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Developing a Bayesian Network risk model to enhance Lean Six Sigma

Yanzhen Li
University of Tennessee

To the Graduate Council:

I am submitting herewith a dissertation written by Yanzhen Li entitled "Developing a Bayesian Network risk model to enhance Lean Six Sigma." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Industrial Engineering.

Rapinder S. Sawhney, Major Professor

We have read this dissertation and recommend its acceptance:

Accepted for the Council:

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Developing a Bayesian Network Risk Model to Enhance Lean Six Sigma

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Yanzhen Li
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Abstract

In today's global market, manufacturing organizations are striving to improve their production performance in order to remain competitive advantages. For the past few decades, many efforts have been conducted by both researchers and practitioners to develop managerial and technical approaches to improve manufacturing processes. Among them, Lean and Six Sigma have become the two most recognized methodologies and together they comprise the primary components of process improvement strategies. However, with the manufacturing system and its external environment becoming more and more complex, a great range of risk factors can affect the results of the Lean Six Sigma initiatives. Consequently, the organization is constantly exposed to risks of not being able to generate a quality product to meet the customer's requirements. The existence of risk is often neglected because there is no easy way to perform the risk analysis for Lean Six Sigma activities due to their complexity. The purpose of this study is to develop a risk-informed model that provides a systematic evaluation for potential risks to enhance the implementation of Lean Six Sigma initiatives. The methodology derives from the Bayesian Network methodology and is incorporated with other risk management techniques. Combining graphical approach to represent cause-and-effect relationships between events of interests and probabilistic inference to estimate their likelihoods, Bayesian Network provides an effective method to evaluate the reliability of Lean Six Sigma. The developed model can be used for assessing the potential risks associated with Lean Six Sigma initiatives and prioritizing efforts to minimize their impacts. The model can serve as a primary component of the decision-making toolbox for maximizing the effectiveness of Lean Six Sigma initiatives and subsequently increasing the competitiveness of a manufacturing firm.

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Chapter 1

Introduction

1.1 Background

Today's U.S. manufacturers are under tremendous pressure of improving their performance in order to stay competitive in the rapidly expanding global economy. The first major issue faced by U.S. manufacturers is the increasingly sophisticated customer demand. Today's customers require more than ever on the design, function, quality, service, and all the other aspects of a product. From the standpoint of manufacturing, the traditional mass production, where high volume is necessary to maximize the individual machine's utilization, is not designed to meet the customers' requirements in the contemporary world. It is each individual customer, rather than customers in general that manufacturers must aim at pleasing. Additionally, any of the special requests, which are really becoming "norm", causes extra costs. However, raising the price in this environment is simply not an option to accommodate the rising costs of production. As a result, the manufacturers have to explore all the possible ways to reduce the cost while at the same time continuing to improve their engineering and production performance.

Another major issue is the influence of globalization in the contemporary world system. The emerging technology of communication, information and transportation has made the national borders disappeared in the business sense, which provides consumers with almost unlimited options when they shop for a certain product. The globalized market is good news for business because the opportunities are unprecedented in scale. As a matter of fact, many U.S. manufacturers have entered the international market and gained great benefits since then. As one of the leading industrialized nations, the United States has the advantages of cutting-edge technologies and well-established infrastructure, which result in great competitiveness of attracting prospective customers and increasing market share globally. However, globalization also poses a great challenge to U.S. manufacturing because it brings more players into the world economy and some of them could potentially become major competitors. Overseas competition normally have advantages on production costs due to cheap labor, material or components. It is no secret that the cost is the chief concern for U.S. manufacturers, which is becoming more and more crucial in today's market.

Furthermore, the recent financial crisis has even made matters worse for manufacturers as global demand plummets. With the outlook having deteriorated considerably, all the manufacturers are taking various actions to lower down the costs. Job cuts are spreading across the manufacturing sectors and, according to Bureau of Labor Statistics [1], the national unemployment rate has rose to 6.5% in October, which is the highest in the five years. During this extremely difficult time, it is even more important to focus on developing and executing the strategies to boost productivity and maintain cost efficiency, which is the only way for a manufacturing firm to keep its most valuable human asset and reduce wastes from the system during the economy downturn.

The purpose of manufacturing is to provide the "value to customer", which is what customers are willing to pay for. It includes design, quality, function, service, and any other aspect that could satisfy the customer's basic requirements and provide extra delight. One consequence of pursuing low-cost competition is the sacrifice of the true "value to customer". Manufacturers may benefit from it for a time, but will most likely suffer bigger losses in a long run. It could be true that certain industries will have to go downsized because of the re-shuffling of economy, but U.S. manufacturers can still remain as the industrial leaders if they can give up the traditional thinking (How should I protect myself from the change?) and establish the new business philosophy (What can I change in this new era to make myself more competitive?).

1.2 Problem Statement

U.S. manufacturers have been using numerous approaches to improve their production performance. The crux of these approaches is the Lean Six Sigma philosophy that has proved to be effective in reducing costs, increasing efficiency, and improving quality. The majority of the manufacturing organizations are developing Lean Six Sigma strategies if they have not already had one in place. However, many companies tumbled this journey and failed to achieve the challenging targets. According to Rubrich [2], 884 U.S. companies responded to a survey conducted by *Industry Week* magazine in 2004. 72 % of them were undergoing the implementation of an improvement strategy such as Lean, Six Sigma, Agile manufacturing, or others. However, "75 % of these companies reported that they had 'no' or just 'some' progress toward their World Class Manufacturing goals". "Only 2% of the companies reported achieving World Class Manufacturing status". The achievement of manufacturing excellence requires major reform of the entire production system as well as organizational culture, which poses great risks to the implementation of Lean Six Sigma strategies.

With the manufacturing system becoming more and more complex, the risks faced by U.S. manufacturers have been significantly increased during the implementation of Lean Six Sigma. *What is risk in Lean Six Sigma*? Risk is incorporated with so many different disciplines that it should come as no surprise that it is defined in different ways. However, they all share common perspectives and yield a general definition that involves different forms of loss in the future due to uncertainties. Simply put, "risk is a measure of the potential loss occurring due to natural or human activities." [3] Based on this concept, the manufacturing system is apt to be under risks caused by different sources and such risks are difficult to control. These sources can be personnel, equipment, material, scheduling and finance. Many efforts have been conducted to address the problems involving risks in engineering. [3–12].

We are living in a world where the future is uncertain no matter how well the plan is prepared and resources are allocated. In the past, decisions regarding potential risks were made primarily based on common senses, travel knowledge, and, in some cases, personal beliefs [13]. Thanks to the development of modern probability theory, systematic and technical approaches have been established to help people extract the most information from the past and make the best decision out of it. These methods are in general called risk analysis. Risk analysis has long been used to deal with uncertainties in order to evaluate and manage risks. It has been largely used in financial disciplines to assess the monetary loss for an investment or transaction, but the concept can also be applied in almost every other area. In engineering field, risk analysis has been deployed to study the reliability of a complex system. However, there is lack of such application to support Lean Six Sigma strategies despite of their popularity in the industry. When management feel a need to evaluate potential risks, they generally do so in an uncontrolled and unfocused manner. A list of action items are normally delivered in a purely reactive way that are not effective in preventing potential hazard from taking place in the implementation of Lean Six Sigma. The pitfalls of current practice can be summarized as follows:

Ineffective in Assessment

The poor decision regarding what to measure is one of the primary reasons leading to the failure of any assessment system. Without a clear understanding of the desired performance as well as the reasons to pursuit it, companies often generate a lengthy list of indicators. Even though such a long list is able to incorporate all the areas of Lean Six Sigma, it requires tremendous amount of efforts, time and resources for developing the model and collecting needed data. It is simply unrealistic to do so and almost impossible to sustain the assessment in a long run.

Ineffective in Implementation

Even when the proper assessment system is developed, the failure can still occur due to the lack of understanding of why and how the system should be utilized. The support of management and the entire workforce plays a critical role in the successful implementation of the risk management strategy. It is also important to translate such strategy into the action to ensure their alignment with overall business objectives.

When implementing Lean Six Sigma strategies, a series of projects are planned and executed to achieve the desired goals. The potential risks could impair the results and even cause failures. The purpose of this study is to develop a risk model to define, identify, analyze, prioritize and mitigate risks that may occur during the course of Lean Six Sigma implementation. The reasons to perform the risk analysis can be summarized as follows:

1. Risk analysis is essential for a complex engineering system because certain information about key project attributes often remain unknown until late in the project.

2. Risk analysis is concerned with the outcome of future events, whose exact outcome is unknown, and with how to deal with these uncertainties. In general, outcomes can be categorized as favorable or unfavorable, and risk analysis is the tool of planning, assessing, handling, and monitoring future events to ensure favorable outcomes or avoid unfavorable ones to the best capability.

3. Risk analysis can provide valuable insights to help plan for risks, alert them of potential risk issues, analyze these issues, and develop, implement, and monitor plans to address the issues long before the issues surface as problems.

1.3 General Guideline

Why Does Risk Need to Be Managed?

According to Deming [14], any system is a "network of interdepdendent components that work together to try to accomplish the aim of a system. A system must have an aim. Without an aim, there is no system." An appropriate risk management system is required to ensure the activities of each entity are being done in compliance with the plan so that the predefined aim can be met. The evaluation system also serves as a communicating mechanism that aligns individual performance with the overall business objectives. A risk management system without specific purposes often turns into a simple collection of data including information that is either unnecessary or irrelevant, which will result in great wastes of resources. To develop a risk model that enhances the Lean Six Sigma strategies, it is important to have an explicitly stated process to determine the measurement objectives through the following tasks:

- Identifying the value that the organization provides to customers.
- Identifying critical metrics in strategic level that enhances the creation of such values.
- Recognizing potential risk factors that could stop such value from being created.
- Decomposing the identified metrics and risk factors into specific operational measures.

What Risks Need to Be Managed?

In order to provide accurate information on the manufacturing performance, appropriate measures must be selected or designed. General principles of risk factor selection have been discussed in the literature review. In practice, however, there are no simple rules for making decisions on what factors should be used. The management has to select the applicable measures based on their understanding of the processes and the overall objectives of Lean Six Sigma strategies.

How Should Risk Be Evaluated?

The effectiveness of a risk management system will be deteriorated by the operational errors and misunderstanding of the workforce. In order to achieve the success, three components need to be examined: human, technical, and business components [15]. The keys to reduce the impact of human component are that, whenever measures are used, they must be understood and accepted by all the people being evaluated and concerned and designed to offer minimal opportunity for manipulation. Technically, the measures must be the ones that truly represent the controllable aspects of the processes. The business component requires that all the measures are objective, timely, result-oriented, and above all they must mean something to those working in and around the process.

The data required for a risk management system are to be collected on a regular base so that the system can be monitored and controlled and corrective actions can be recognized in a timely manner. The frequency of the measurement will be determined by the management according to the short-term and long-term goals of the evaluation. As a result, there may be different reporting frequency for the indicators in different levels. For example, The corporative level measures such as financial indicators are to be reported monthly or even quarterly based on the financial policy and accounting system. On the other hand, the operational level measures need to be investigated more frequently to ensure corrective actions can be taken promptly.

As risk management system has become increasingly crucial to ensure the organizational health and competitiveness, there is a need to assign specific individual or team responsible for the risk evaluation process. This individual or team should directly report to or have access to top management to facilitate the prompt response of corrective actions upon occurrence of problematic issues. It is also important to assign specific responsibilities at departmental and operational level because the information needs to be collected from different functional areas.

How Should Risk Be Reduced?

The purpose of a risk management system is to help one learn about how the organization performs in areas of importance or interests. Once the data has been collected in accordance with the plan, the information needs to be analyzed to ascertain whether the objectives have been met and if not, why not. This will enable the management to be alerted to existing and potential problems and take necessary corrective action or improvement to get the process back on track. Another major issue during this phase is to effectively communicate the results of the risk management system. On a formal level, the results should be reported to executive level and they should also be used internally to guide the organization's operational performance.

The risk management strategy should be developed before any other action is taken. This strategy will be integrated with the overall business. The desired indicators are then selected based on their capability of reflecting the Lean Six Sigma strategy. The irrelevant measures are removed even though some of them appear to be important. After the risk indicators are ready, it should be determined how to implement the risk management system and, more specifically, how and when the indicators should be measured and who should be responsible for the measurement. The analysis of data is then conducted for identifying the weakness and the opportunities for potential improvements.

1.4 General Approach

There are three major steps for developing the Bayesian Network (BN) based risk model to evaluate and control risks in Lean Six Sigma. The first is to define risk and specify the scope of this study. A comprehensive research on both academia and industry is conducted to identify the risk scenarios in the manufacturing environment that deteriorate the effectiveness of Lean Six Sigma strategies. BN methodology is also introduced along with the discussion of its advantages and limitations. Once the risk is defined, the second step is to develop a systematic model to quantify the impact of risks for a given process. By using the quantifiable measures, the efforts to minimize risk impacts can be prioritized. The proposed model should also be able to sustain the monitoring and evaluation of Lean Six Sigma strategies in a long run. The next logic step is then to use a case study to demonstrate its application and validate the effectiveness of the proposed risk model. The general approach can be illustrated in Figure 1.1, followed by the detailed description for each step.

Literature Review

It is critical to define risk in process improvement before it can be evaluated both qualitatively and quantitatively. It must share the generation definition yet be specific for the Lean Six Sigma initiatives. A comprehensive literature search will be conducted in order to provide a thorough understanding on how the concept of risk can be applied in the area of Lean Six Sigma. This includes the risk management methods in both engineering and

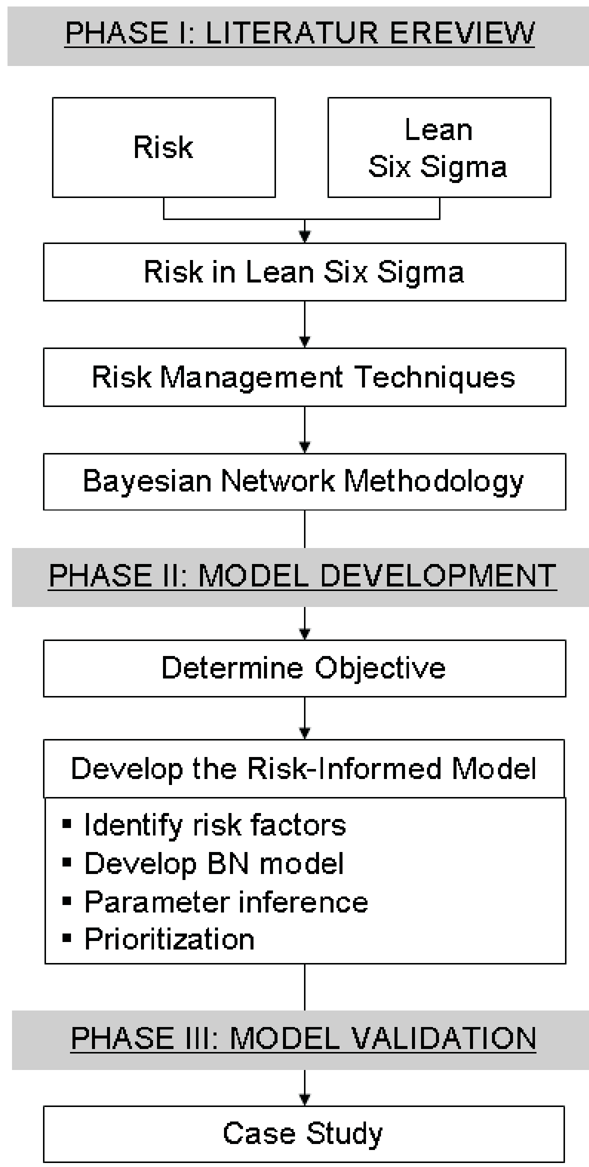


Figure 1.1: General Approach

other disciplines. Another important part of this step is to understand Lean Six Sigma and potential risks associated with it.

The modern risk management techniques were developed based on mathematical theory that makes it possible to study the increasingly complex system. Risk management is a systematic approach to evaluate, monitor and control undesirable uncertainties through risk analysis and it can be used in a variety of disciplines such as financial, military, health care, and engineering. This section summarizes the risk management techniques currently available in different disciplines.

Bayesian method concerns the uncertainty about the unknown parameters. The probability theory is used to quantify such uncertainties and infer the parameters of interests. With the help of relational diagram, Bayesian networks (BN) is a probabilistic graphical tool to obtain the knowledge about uncertainties for a complex system. The theory and applications of BN are introduced in this section as well as basics of Bayesian inference.

Model Development

Based on the understanding of the Lean Six Sigma and the concept of risk, potential risk factors are identified as well as their possible impacts on the overall system. Some of these factors require quantitative analysis and others have to be evaluated in a qualitative manner. It is also possible that some of them are not applicable to the risk analysis. During the development of the risk model, all of these factors will be studied and then selected for the purpose of risk analysis. A structured approach is then established and the risk elements are incorporated with the appropriate consideration. This is to say that the model should not only be a list of all the elements, it ought to present the information in a systematic manner and, more importantly, enable the management to discover any possible risk hazards that hinder the progress of improvement.

The purpose of this study is to develop a complete package that is ready to use for assessing and managing the risk. Ranking the risk elements is one of the most important tasks in risk assessment. As resources are limited, an appropriate ranking can help an organization target the biggest risks and thus minimize potential losses in the most cost-effective manner. Once the risks have been ranked, suitable strategies should be developed to deal with potential risks.

Model Validation

A case study is used to validate the proposed risk model. The selected process undergoes a major transition from traditional mass production to cellular manufacturing. The complexity of this change provides a good example on how BN and other risk management methods can be used to enhance Lean Six Sigma. During the validation, the input from practitioners is important in order to better the model.

1.5 Structure of Dissertation

The dissertation is comprised of five chapters including this introduction chapter. Chapter 1 gives a general introduction to the work. Following the introduction, a comprehensive literature review is conducted in both academia and industry in Chapter 2. Chapter 3 gives a detailed description of the development of the BN based risk model to enhance Lean Six Sigma initiatives. The model is validated and results are discussed in Chapter 4, followed by overall conclusions in the last chapter.

Chapter 2

Literature Review

This chapter presents a review of theoretical literature and empirical applications that inspire research questions and guide methodological direction for this dissertation. The chapter comprises of four sections. The first section is a study of the process improvement methodologies that have been implemented in the manufacturing area. Two major collections of process improvements techniques are Lean Manufacturing and Six Sigma. Lean Manufacturing is utilized to reduce lead-time by eliminating non-value added activities while Six Sigma focuses on analyzing, controlling and reducing variations that exist in the system. Their origins, applications and benefits are discussed in this chapter. Although they have proved to be effective tools to achieve the operational excellence, numerous companies have struggled to implement them and did not experience the desired success. Therefore, this literature review also attempts to shred some light on what can cause failures during the course of process improvement activities.

After a recapitulation in the second section on how risk is defined in different disciplines, the third section provides a summary of the general risk analysis techniques commonly-used to identify, manage, and communicate risk elements. In particular, this section focuses on investigating how these techniques provide insights for an intelligent decision-making system. A review is then given for the methodologies that are used to evaluate and manage risks in manufacturing fields and followed by a discussion of their focuses, applications and how each approach performs to evaluate and control risks. Bayesian Network theory is reviewed and discussed in the fourth section regarding its application, advantages and disadvantages.

2.1 Lean Six Sigma

U.S. manufacturers are under tremendous pressure to improve their production performance and reduce costs in order to stay competitive in the global market. Externally, they face the challenge of satisfying a rapidly-increasing demand from customers while remaining profitable over international competition. The manufacturers are also becoming fragile in the unsteady economic environment when the consumer confidence can be significantly low. Internally, on the other hand, a majority of manufacturers are experiencing operational and cultural transformation to adapt themselves to meet the unprecedented developments taking place in the new era. In many cases, this change could be painful because they require substantial transformation almost on all aspects of the system. It takes the entire system to make it work, but only one component to make it fail.

Over the past several decades, there have been a significant shift toward Lean Six Sigma initiatives that promote the philosophy of continuously identifying opportunities to improve one organization's performance. The major benefit of this strategy is that the manufacturing processes are constantly being evaluated with the focus of maximizing profit by reducing non-value added activities. Lean and Six Sigma are the two major principles that address the efficiency and quality respectively and together they serve as fundamentals of the process improvement strategies. Table 2.1 summarizes a list of methods that are commonly used to improve processes.

2.1.1 Lean Manufacturing

The term Lean production was coined by Womack, Jones and Roos in their book, *The Machine That Changed the Word* [16] based on a five-year study of automobile industry.

Table 2.1: Summary of Lean Six Sigma Tools

LEAN MANUFACTURING
– 5S+Safety and Visual Control System – Value Stream Map (VSM) – Process Mapping – Standard Operating Procedure (SOP) – Pull system – Kanban system – Cellular manufacturing – Setup reduction – Line balancing – Just in Time (JIT) manufacturing – Mistake Proofing – PFEP (Plan for Every Part) material delivery system – Total Preventive Maintenance (TPM) – Kaizen Events – Voice of Customer (VOC)
SIX SIGMA
– DMAIC (Define, Measure, Analyze, Improve, Control) – Process mapping – Cause and Effect diagram – SIPOC (Suppliers, Inputs, Process, Outputs, Customers) diagram – Regression analysis – Measurement System Analysis (MSA) – Design of Experiment (DOE) – Statistical Process Control (SPC) – Quality Function Deployment/House of Quality – Process capability analysis – FMEA/Risk Assessment – Design of Six Sigma – Variation Analysis

Compared to the traditional mass production, Lean production is “lean” because “it uses less of everything compared to mass production – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time. Also, it requires keeping far less than half the needed inventory on site, results in many fewer defects, and produces a greater and ever growing variety of products” [16]. In summary, Lean promotes a constant identification and elimination of any activities that add no values and cause extra costs within the manufacturing system.

Lean is a methodology to help identify and reduce non-value added activities based on the definition of value to customer. According to Lean manufacturing, value is the exchange for which customer is willing to pay. This includes the functions of actual product and any additional delighters such as fast delivery and satisfactory customer service, but not the time spend on transportation, motion, storage, excessive inventory, and any defects and rework. There are a variety of tools utilized in Lean production system, which attempt to address the concern of manufacturing firms that are under pressure to emphasize the improvement on delivery, quality and reduction of costs. The framework of Lean philosophy can be summarized into five steps [17]:

(1) Define value – Specify values from the customer’s perspectives.

(2) Understand the current value system – Identify the current flow of material and information required to make a product to customers.

(3) Design the future flow – Design an optimal sequence of tasks in a manner that non-value added activities are eliminated.

(4) Pull – Develop the production system where a product is made only when it is needed.

(5) Perfection – Sustain the change and continuously identify and implement improvement opportunities.

Since it was introduced in 1990, Lean production techniques have resulted in great benefits to U.S. manufacturing companies. One of the most important contributions brought by lean manufacturing is its strong advocacy of waste elimination as a strategy for continuous improvement [18]. This is different from the traditional manufacturing that focuses on maximizing the machine utilization without considering the value to customer. By eliminating wastes, the quality can be improved and cost be reduced in an efficient and effective manner. Even though the specific wastes vary with different products, processes and organizations, they can be summarized into seven basic categories.

(1) Overproduction: Producing an item before the order is actually made or more than what is required at the time.

(2) Production defects: Work that contains errors, rework, mistakes or lacks something necessary. It has a direct impact on the bottom line because the rework or scrap is a tremendous cost.

(3) Transportation: The unnecessary movement of components, materials or finish goods. The common reason is the poor plant layout or process design that locates the upstream or downstream operations too far apart.

(4) Inventory: Excessive raw materials, work in progress (WIP), or finished products. It increases lead-time, hides quality problems and causes cash flow issues.

(5) Waiting time: Idle time created when materials and goods are not being moved or processed. It can also because of the unavailability of information, people or equipment.

(6) Inappropriate processing: Operation that adds no value from the customer's viewpoint. It may take more resources and not deliver the expected results.

(7) Motion: Unnecessary movement of people. Not only does it add extra time, the additional motion could also cause health and safety issues, which are becoming more of a problem for organizations.

During the transition from traditional manufacturing to Lean system, various strategies have been formulated based on the business objectives and production requirements. Management needs to be very clear of what need to be achieved and by when they could be done. The implementation is a step-by-step process and the Lean tools should be selected wisely. Table 2.2 provides a template plan of Lean implementation.

Table 2.2: Template of Implementation Plan

Implementation Plan of Process Improvement
WORKPLACE DESIGN
SAFETY AND ORGANIZATION BASED ON SAFETY AUDITS AND 5S+1
✓ The area has regular safety audits. ✓ The operators working in the area have appropriate personal protective equipment. ✓ All tools have designated locations. ✓ All tools have appropriate safety features. ✓ The area has a 5S+1 checklist.
MISTAKE PROOFING AND ERGONOMICS
✓ The operators never has to bend or reach abnormally. ✓ There are poke yoke measures built into the operation. ✓ Appropriate jigs, fixtures, templates, etc. are in use.
PARTS PLACEMENT VIA POINT OF USAGE
✓ All parts are delivered to designated areas. ✓ Parts are easily accessible to operators. ✓ Operators never have to go to stock room.
WORKPLACE MANAGEMENT VIA VISUAL CONTROL
✓ The schedule is posted. ✓ All operators can see schedule. ✓ Kit carts and jigs are color-coded according to usage. ✓ All aisle ways and workstations are appropriately marked and stenciled.
WORK STANDARDIZATION
✓ Jobs have work instructions. ✓ Standard hours are correct and validated. ✓ Jobs are balanced. ✓ Visual controls are in place where applicable.
FACILITY LAYOUT
✓ The area is the correct location to support smooth flow of the product. ✓ No monuments exist that impede product flow.
CROSS-FUNCTIONAL TRAINING
✓ Supervisors have a cross-training matrix. ✓ Cross-training matrix is accurate and up-to-date. ✓ Operators are certified for current jobs requirements.
FLOW DESIGN
PRODUCT FAMILY CATEGORIZATION
✓ Group technology is applied to categorize products. ✓ Parts are processed in conformance to families. ✓ Operators understand families have different requirements.

continued on next page

Table 2.2: (Continued)

Implementation Plan of Process Improvement
VALUE STREAM MAP (VSM)
✓ VSMs are conducted. ✓ VSMs are analyzed for improvement opportunities.
SETUP ANALYSIS
✓ Areas have setup program. ✓ Setup programs are appropriate.
LINE BALANCING
✓ Operators work is balanced. ✓ Re-balance is conducted upon production change.
CELLULAR MANUFACTURING
✓ Area is appropriate for cellular work. ✓ Area has appropriate work cells.
PRODUCT CONTROL
✓ Parts are built by schedule. ✓ Product tracking system is in place. ✓ Parts are clearly labelled.
PLAN FOR EVERY PART (PFEP)
✓ Components are delivered per schedule. ✓ All jigs and fixtures are available to operators. ✓ Material delivery routes are designed. ✓ Work instructions for all work are available.
SUPERMARKET DESIGN
✓ Area has a supermarket for parts and materials. ✓ Supermarket is stocked regularly. ✓ Supermarket is easily accessible. ✓ Supermarket is labelled for part numbers, quantities, etc. ✓ Supermarket is clean and organized.
PULL SYSTEM
✓ Process operates with a pull system. ✓ Supermarket is designed to enhance pull system. ✓ Pull system is efficient.
KANBAN SYSTEM
✓ Area utilizes Kanban. ✓ Kanban is efficient. ✓ Kanban quantities are appropriate. ✓ Delivery system of Kanban is efficient.

Much efforts have also been conducted in different aspects of the manufacturing system other than the production line. Some researchers focus on the supply chain system in Lean environment [19]. There is also study on the human issues in the Lean implementation [20]. Because of their advantages in efficiency, cost, quality and flexibility in production, Lean techniques can also contribute to the performance improvements of other industries such as service sector [21], health care [22], construction, and information management.

2.1.2 Six Sigma Methodology

Six Sigma is a collection of technical and managerial tools originally developed by Motorola to reduce variation and eliminate defects in electronic manufacturing processes. This philosophy then received huge successes at industry-leading companies such as General Electric (GE) and Allied Signal. Since then, it has been adopted by a great number of companies and evolved over time to a new way of doing business. “Six Sigma is many things, and it would perhaps be easier to list all the things that Six Sigma quality is not. Six Sigma can be seen as: a vision; a philosophy; a symbol; a metric; a goal; a methodology” [23].

The implementation of Six Sigma can be described by the DMAIC approach that stands for Define, Measure, Analyze, Improve and Control, as shown in Figure 2.1. In the define phase goals and target completion dates are established. Further, resources required for the change and management support are obtained. During the measure phase Critical to Quality (CTQ) – the attributes that are the most important to the customers – and associated measurement systems are designed. Data is collected based on statistical concepts to ensure validity of results. During the analyze phase statistical tools are utilized to identify root cause problems via better process data. This will then allow for one to develop an improvement strategy. The improve phase will select solutions, design implementation plans based on proposed solutions and ensure the support functions available for the implementation plan. The control phase will include standardization and monitoring of processes.

The cornerstone of Six Sigma techniques is the application of scientific principles to manage business processes. Examples of the most widely used methods are Statistical

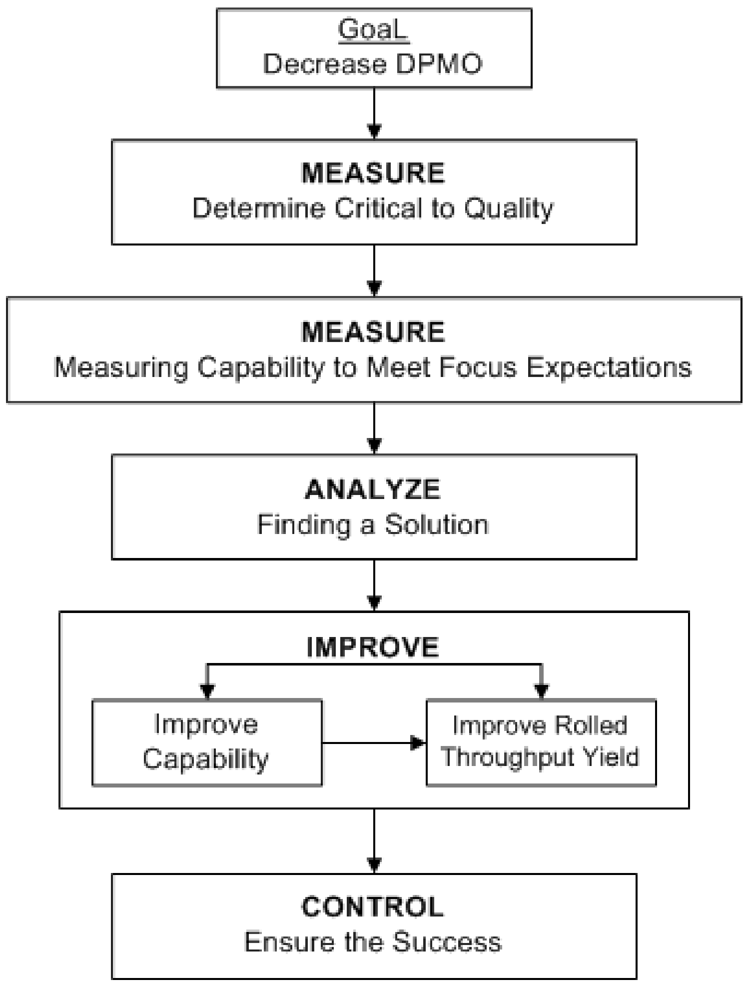


Figure 2.1: Six Sigma Implementation Process

Quality Control (SQC), and Design of Experiments (DOE). Because of the extensive usage of statistical terminology, Six Sigma is frequently considered as a statistics and measurement program. However, in order to achieve the "Six Sigma" performance a systematic management approach needs to be developed to initiate projects, establish teams, monitor progress, and ensure the results. As a result, the organizations determined to use Six Sigma as part of the strategic planning always develop clear visions about how to incorporate Six Sigma principles into the organizational culture. General Electric, for example, specifies the core concepts of Six Sigma as follows [24]:

- Critical to Quality: Attributes most important to the customer.
- Defect: Failing to deliver what the customer wants.
- Process Capability: What your process can deliver.
- Variation: What the customer sees and feels.
- Stable Operations: Ensuring consistent, predictable processes to improve what the customer sees and feels.
- Design for Six Sigma: Designing to meet customer needs and process capability.

2.1.3 Integration of Lean and Six Sigma

In many cases, organizations have selected either Lean or Six Sigma as the primary band to implement a change strategy. Even when organizations have adopted both Lean and Six Sigma, they are normally done from a perspective of implementing two complementary yet distinctly different programs. The main reason is that these two are separate tool kits in practice and an organization can afford only one due to the resource constraints. A number of researchers and practitioners have focused on developing management model to integrate lean manufacturing and Six Sigma techniques. Figure 2.2 provides the general principles of lean and Six Sigma implementation.

Sawhney and Ehie [25, 26] developed a model to integrate lean and Six Sigma. The conceptual framework guides management to first consider the design of the shop floor

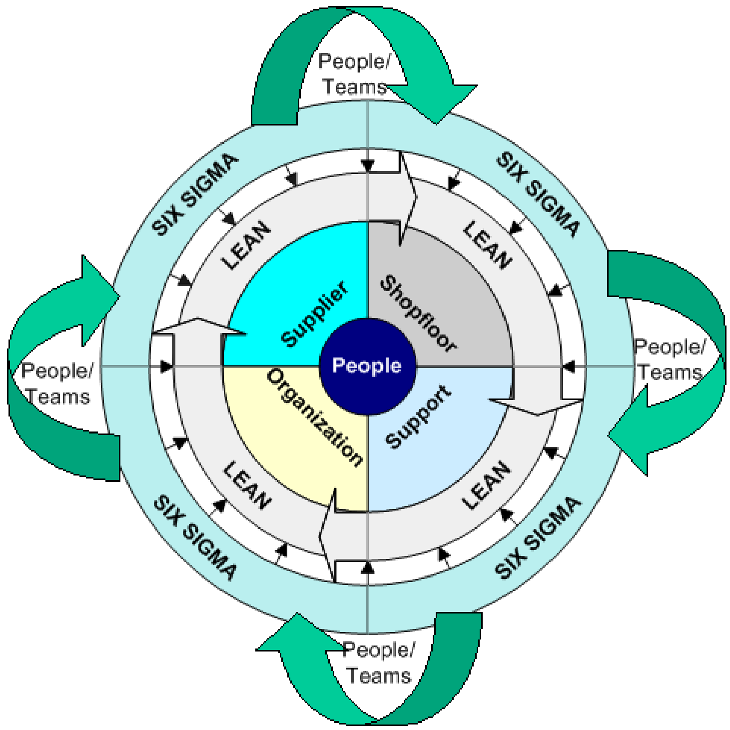


Figure 2.2: Lean and Six Sigma Implementation Circle

production system based on the requirement of the customers. If an evaluation leads to the conclusion that the shop floor is appropriately designed, the management moves to the next domain. This does not imply that shop floor is perfect before any other domain is addressed but rather the focus should be on the domain constraining the ability to meet customer requirements. The ability to make the necessary changes proposed by the conceptual model is explicitly based on developing a people oriented culture. The first step in developing such a culture is to properly plan the change. The essence of each phase is defined below.

(1) Selling the idea: The ability to sell the idea of change is critical. As the human assets are foundation for any change, the key is to communicate the need for change in a manner that is relevant to the specific target group of employees.

(2) Performance measurement System: An organization's performance measurement system strongly affects the behavior of all employees. What is to be measured can be done. There must be an effective evaluation system to monitor and control the process in order for a company to be successful.

(3) Assessment: An assessment must be conducted prior to implementation to provide data for the baseline and analysis to develop a customized strategy for the change.

(4) Communication: Communication within an organization that is proposing change is critical to the success of implementing change. There are two major objectives associated with a communication strategy. First, communication strategy should provide visibility to all employees. Second, the organization selects a unique subset communication mechanisms based on resources, constraints and current culture.

(5) Training: In order for Lean Six Sigma to be understood and implemented by the entire organization, a set of training should be conducted for the entire organization. This training program should be started from the initiation phase of the implementation and designed in such a way that it should involve the entire organization, enhance the techniques and skills for change, and make the idea of change part of the organizational culture.

(6) Implementation: Implementation must be decomposed in a manner that is logical and palatable to the organization. For this reason this phase is delineated into three categories: concept demonstration, focused implementation and implementation proliferation.

2.2 Risk

2.2.1 Definition

The existence of risk is almost as old as human history and the concept of measuring or guessing risks has been around for centuries [13]. The question of what risk is, however, has never been defined with a commonly-accepted term. When used in non-technical contexts, the word "risk" normally refers to situations in which it is possible but not certain that some undesirable event will occur. In 1921, Knight [27] summarized the difference between uncertainty and risk and emphasized that only quantified uncertainty may be considered as risk. After the review of financial literature, Holton [28] argued that the risk should consist of two essential components: exposure and uncertainty. The definition, therefore, is exposure to a proposition of which one is uncertain. Based on philosophical literature, Hannson [29] provides several technical definitions of risk that are used widely across disciplines:

- Risk is an unwanted event which may or may not occur.
- Risk is the cause of an unwanted event which may or may not occur.
- Risk is the probability of an unwanted even which may or may not occur.
- Risk is the statistical expectation value of an unwanted even which may or may not occur.
- Risk is the fact that a decision is made under conditions of known probabilities ("decision under risk" as opposed to "decision under uncertainty").

The study of risk has grown to a major field of research since 1970's and the need of risk analysis can be found in every industry. One of the major breakthroughs of contemporary risk analysis is the use of mathematical notions of probability because it allows a quantitative, rather than quantitative approach to provides a scientific estimation. This is especially important in the process of decision-making when the useful information has to be extracted from scenarios with great uncertainties. Several books have been written to incorporate probability theory with risk analysis [5,30,31]. Accordingly, several definitions of risk were introduced solely based on the probability of an event occurring.

When incorporating the probability theory into risk analysis, the definition of risk depends on the specific research area or industrial application. In most of cases, it contains the elements related to the consequences of a given risk scenario and the likelihood of its occurrence. Accordingly, a common mathematical representation of risk can be formulated as follows [3]:

$$\begin{aligned} \text{Risk}\left(\frac{\text{Consequence}}{\text{Unit of time or space}}\right) &= \text{Frequency}\left(\frac{\text{Event}}{\text{Unit of time or space}}\right) \\ &\quad \times \text{Magnitude}\left(\frac{\text{Consequence}}{\text{Event}}\right) \end{aligned}$$

Another simple definition of risk is commonly used in practical applications where the consequences can be presented in a financial term [32].

Risk = Probability of an accident × Consequence in lost money

Damondaran [32] further argues that the definition of risk should be a combination of danger (crisis) and opportunity, representing both the downside and the upside of risk. This raises up a good point of how an organization should react when facing a crisis. External factors such as globalization and economy are normally out of the manufacturers' control. If the organizations stick to their old strategies, they could lose the competitions. However, pressures can be turned into a driving force and the challenges turned to opportunities. If they make right decisions on what to change under the given circumstances, they will be able to survive the crisis and gain greater advantages when the economy turns around.

2.2.2 Risks in Lean Six Sigma

In the area of manufacturing, the risks may be found through the entire product life cycle from design risks, financial risk, technological risk, safety risk, to operational risk that exist in the production processes. More specifically, the operational risks can be summarized in the following major categories:

- Personnel: all levels of the workforce and their capabilities and skills.
- Equipment: all non-human means for non-value added work.
- Material: any tangible or intangible input that goes through a value-added serve.
- Scheduling: includes forecasting, production planning and control of a system.

For most of the companies that decide to launch Lean Six Sigma initiatives, they are often huge undertakings that require tremendous investment and resources. It often represents the cultural change of an organization's business philosophy because Lean Six Sigma techniques aim at fixing the root causes of problems in a fundamental level. In practice, however, the management sometimes applies selected tools to conduct projects in a short period of time to achieve fast benefits. While such efforts can be very beneficial for making rapid improvements and promoting the process improvement concepts within the organization, they can easily lose the achieved benefits or even fall into failure if there is no system in place to make them sustainable.

Several common risks that could exist during the implementation of Lean Six Sigma initiatives are as follows:

- The improvement initiatives don't fit into the organizational missions or goals. Lean Six Sigma provides a broad collection of tools and the systematic approach to use them. However, the effectiveness of these tools depends on their alignment with the overall business objectives. One of the biggest mistakes companies normally make is to initiate the process improvement activities without a well-planned strategies to define why it is necessary.
- The final results of the improvement projects haven't achieve the goals as originally planned. There could be a variety of reasons for this such as poor planning, poor execution, and lack of sustaining program.
- The improvement project significantly changes the work flow of the organization. The various components of Lean such as elimination of buffers, Just-in-Time, pull system, one piece flow and Kanban system could makes the manufacturing processes more fragile.
- The decisions related to the project are based on politics.
- Lack of experience with change management. The transition of process improvement is a change process, which could be extremely difficult. Knoster [33] provides a framework to manage the complex change (Figure 2.3)

Just like an individual's financial investment, what hurt us the most could be something unknown and unexpected at the time of making decision. While the risks can not always be avoided, a well-established program should reduce the consequences to a minimal level. This may seem like an obvious statement, yet so often the processes that could prevent or mitigate the unknown risks are ignored because the lack of thorough understanding of potential risks.

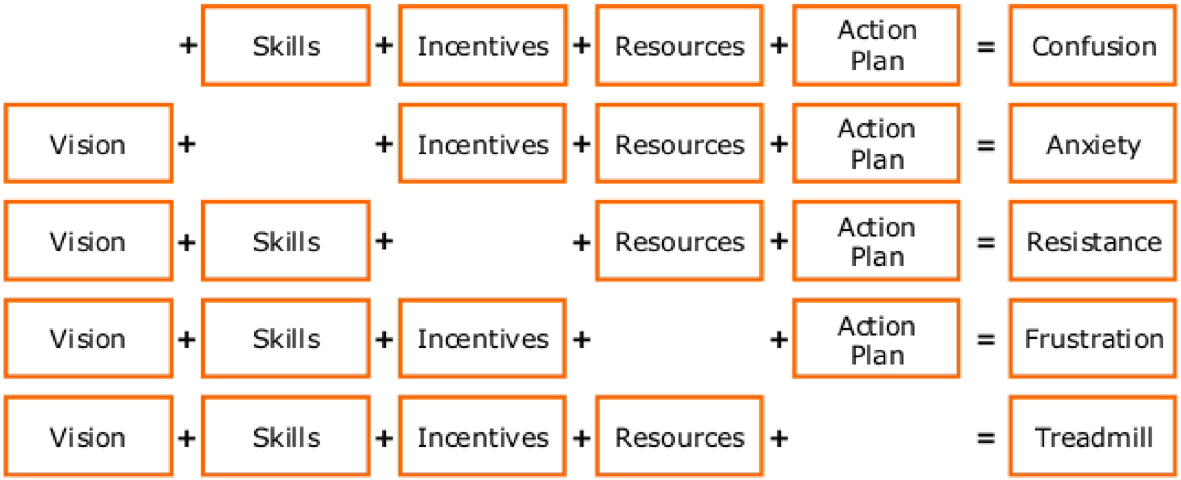


Figure 2.3: A Framework for Managing Change

2.3 Risk Management

2.3.1 General Perspective

The concept of risk analysis can be traced back to the beginning of human history. At the time when the world was advancing fairly slowly and economy was relatively simple, it seemed to be enough that risk was evaluated solely based on guessing, belief and personal experience. Since in the 1960s and 1970s, the pace has started to accelerate and the business system has become far more complex. Furthermore, many catastrophic events have taken place since the beginning of this century, which had made people realize the importance of studying risks. Risk management was, therefore, becoming an important topic especially for the financial sector. In addition, the advance of mathematical theory made it possible to provide scientific evaluate for potential risks.

Risk management is a systematic approach to evaluate, monitor and control undesirable uncertainties through risk analysis. Risk analysis is a "body of knowledge (methodology) that evaluates and derives a probability of an adverse effect of an agent (chemical, physical, or other), industrial process, technology, or natural process" [34]. Some traditional risk management techniques focus on physical causes such as natural disasters, accidents, and death while financial risk management focuses on the risks in the field of investment and trading, which can be managed using financial tools. Another important aspect of risk management, which is commonly neglected in practice, is how to maximize the results when risk occurs. Cooper *et al.* [35] state that "The purpose of project risk management is to minimize the risks of not achieving the objectives of the project and the stakeholders with an interest in it, and to identify and take advantages of opportunities. In particular, risks management assists project managers in setting priorities, allocating resources and implementing actions and processes that reduce the risk of the project not achieving its objectives."

According to National Research Council, three primary components of risk analysis are risk assessment, risk management, and risk communication [36]. Risk assessment is a process to determine the quantitative or qualitative value of risk (including probability or frequency of a failure and the magnitude of the failure) related to a concrete situation and given resources. Risk management focuses on integrating recognition of risk, risk assessment, developing strategies to prevent, control, and minimize losses due to a risk exposure. Risk communication refers to all activities of communicating the knowledge of risk, risk assessment results, and risk management methods among decision makers and stakeholders.

Various researchers and practitioners have developed frameworks to implement risk management techniques. The Space and Naval Warfare (SPAWAR) Systems Center (SSC) San Diego Systems Engineering Process Office (SEPO) [37] developed a process that will help identify project risks as early as possible and to periodically reassess and manage those risks, as shown in Figure 2.4.

With organizations having recognized the necessity to include risk management at the highest level and thus promoting its usage for the entire business, it has been clear that the traditional and reactive approach must be replaced by a dynamic and proactive vision aimed at achieving the organization's mission. One major evolution was to develop a quantified method. Condamin [38] discussed that a risk can be defined by three elements:

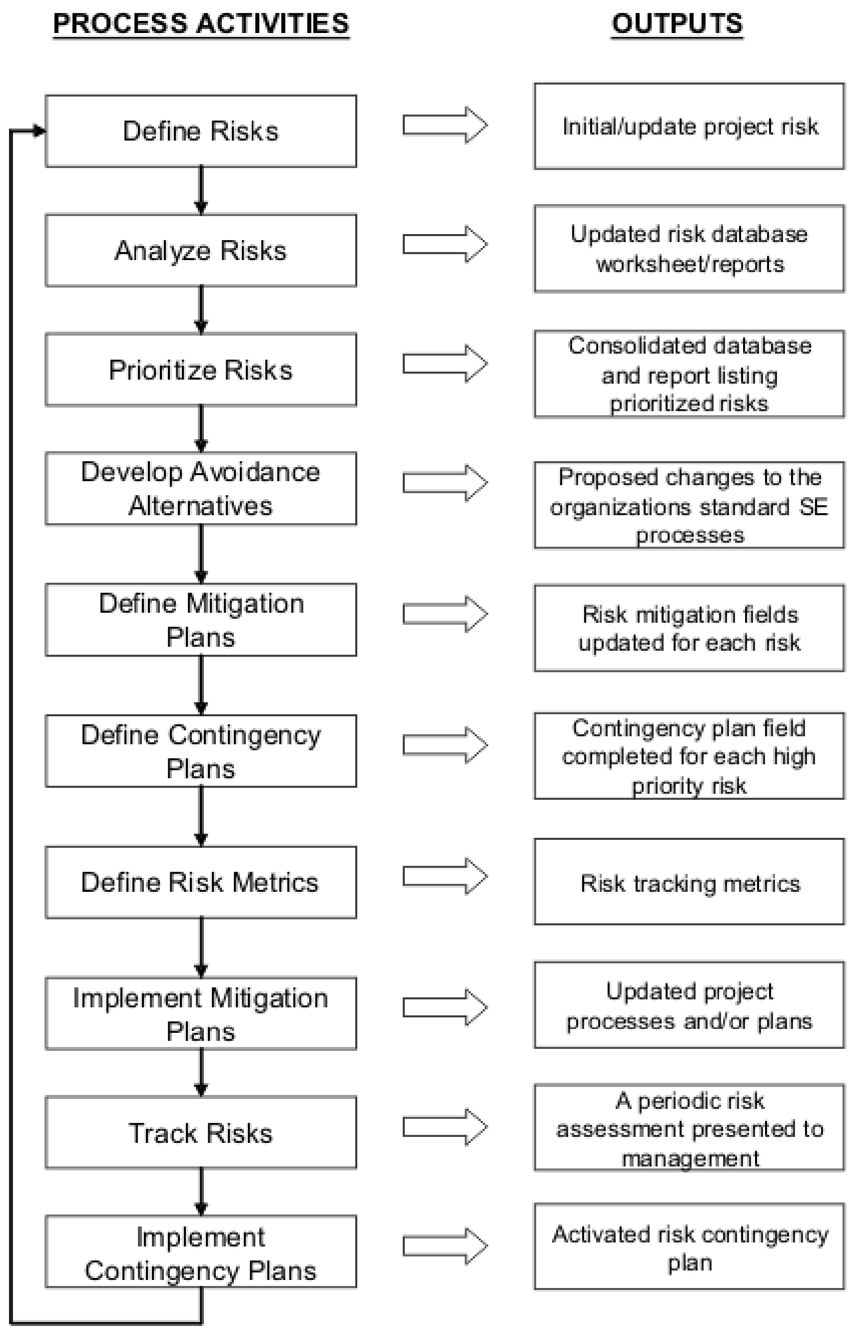


Figure 2.4: Risk Management Process Overview

- The resource at risk, or risk object. This is quantified by exposure.
- The peril or random event to which the resource is exposed. This is quantified by a probability of occurrence.
- The consequence when the resource is "hit" by the peril. This is quantified by a severity or impact indicator.

Condamin [38] further addressed that exposure, occurrence, and impact are the three random variables that fully define a risk and quantifying these variables is the first step or risk quantification. This assessment is probabilistic as each of these variables is potentially random. Probability theory is the fundamental mathematical tool to quantify uncertainties. The tool box normally contains methods such as basic probability and statistic theory, bayesian theory, and simulation.

2.3.2 Risk Analysis in Manufacturing

In the manufacturing system, the loss due to potential risks could be external such as warranty cost, losing a customers or eventually the market. It can also be internal to the system itself. The poor product design could cause excessive resources in the later manufacturing process. The unpredictable prices of materials could make it difficult to lower the cost. Safety and health is another important issue in the manufacturing environment. Risk analysis tools have been used in the manufacturing to evaluate technical risk and hazard and several major techniques are listed as follows:

Fault Tree and Event Tree Analysis

Fault Tree Analysis (FTA) is a "deductive process by means of which an undesirable event, called the top event, is postulated, and the possible ways for this event to occur are systematically deducted" [3]. It is basically a graphic description of the state of the system in order to identify potential accidents and predict the most likely system failures. In practice, a smaller subsystem is usually analyzed before it is integrated into the entire system.

Event Tree Analysis (ETA) is used to “model the patterns of events and consequences that may follow from one or more initiating events” [35]. It is closely linked with FTA and fault trees are often used to quantify system events that are part of event tree sequences.

Probabilistic Risk Assessment

Probabilistic risk assessment (PRA) was initially developed to evaluate risk associated with a complex engineered technological entity such as nuclear power plants and spacecraft. ”The primary value of a PRA is to highlight the system design and operational deficiencies and optimize resources that can be invested on improving the design and operation of the system” [3]. As an integrated method of various risk analysis techniques such as FTA and ETA, PRA provides a systematic and comprehensive methodology to evaluate and manage risks. The NASA PRA guide [39] summarized components of PRA as following:

(1) Objectives and methodology definition

(2) Familiarization and information assembly

(3) Identification of initiating events

(4) Sequence or scenario development

(5) Logic modeling

(6) Failure data collection, analysis and performance assessment

(7) Quantification and integration

(8) Uncertainty analysis

(9) Sensitivity analysis

(10) Risk ranking and importance analysis

(11) Interpretation of results

In addition to the methods mentioned above, PRA studies include special yet important tools such as Human Reliability Analysis (HRA). Hannaman and Spurgin [40] developed an approach to evaluate human reliability and it is called systematic human action reliability procedure (SHARP). According the SHARP procedure, there are seven steps to perform an analysis on risks related to human reliability: definition, screening, qualitative analysis, representation, impact assessment, quantification, and documentation. The methodology developed in this study is to adopt this framework and analyze assembly process reliability based on the following procedures.

(1) Definition: Define all different types of sources that may cause the assembly process to fail.

(2) Screening: Conduct a statistical analysis and performance assessment analysis to select sources that have the most significant impact on the system reliability.

(3) Qualitative analysis: Develop a detailed description for important factors.

(4) Representation: Select and apply techniques to model process errors.

(5) Impact assessment: Determine the significance of the impact from each factor.

(6) Quantification: Use appropriate data to suitable models to calculate probabilities for various resources.

(7) Documentation: Include all necessary information and prioritize the sources under consideration.

Cause and Effect Diagram

Cause and Effect Diagram (CED), also known as Ishikawa diagram, is an analytical tool to identify the underlying factors that have impact on the parameter of interest. Figure 2.5 provides a study of why there exist a great of deal of motion waste in the process. This is normally done in a brainstorming session by a team that consists of employees from different areas of the process.

Failure Mode and Effect Analysis

Failure Mode and Effect Analysis (FMEA) is a systematic approach to evaluate the potential failure modes by considering its severity, likelihood and detection. It is widely used

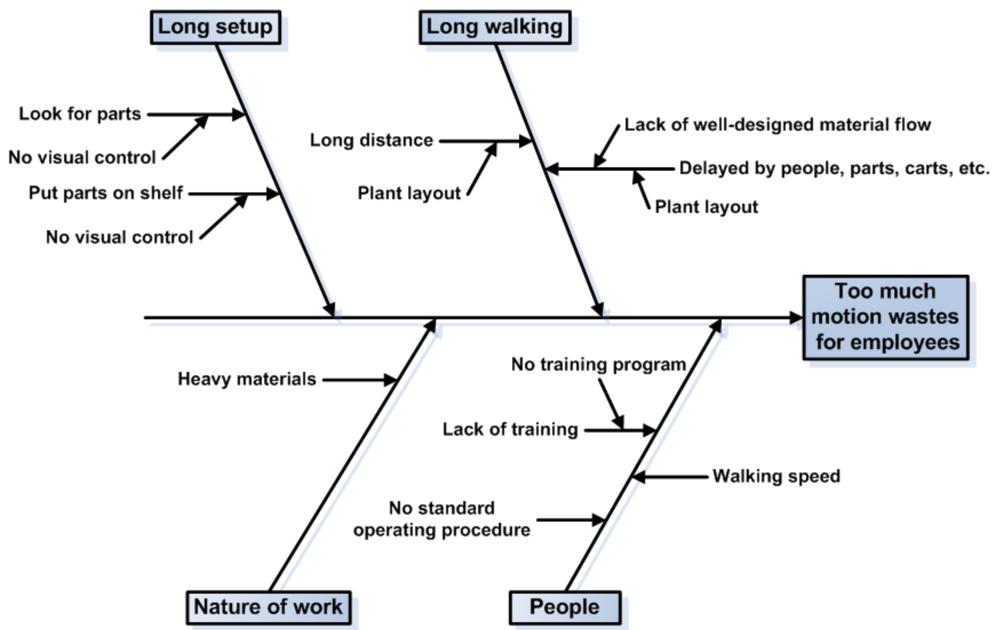


Figure 2.5: Cause and Effect Diagram

in various stages of a product's life cycle to identify errors or defects in the process. Two major applications of FMEA are Design FMEA and Process FMEA. Design FMEA is used during the design phase to identify any issues that may cause system failures for manufacture, assembly, service and functional requirements. Process FMEA, on the other hand, is applied to evaluate the manufacturing and assembly process. Other types of FMEA include Concept FMEA, Equipment FMEA, Service FMEA, System FMEA, and Software FMEA.

Tixier [41] reviewed 62 risk analysis methodologies used in industrial plants at the time and classified them in to four categories: deterministic, probabilistic, qualitative, and quantitative. He argued that, no matter which method is used, three kinds of elements are required: expected output data, available input data, and Selected method. He further provided a detailed sub-categories for each elements and presented the linkage between input data, output data, and the selected method (See Figure 2.6).

Apostolakis [42] reinforced the benefits of quantitative risk assessment (QRA) by reviewing its successful application in industry. He further stated that "QRA results are

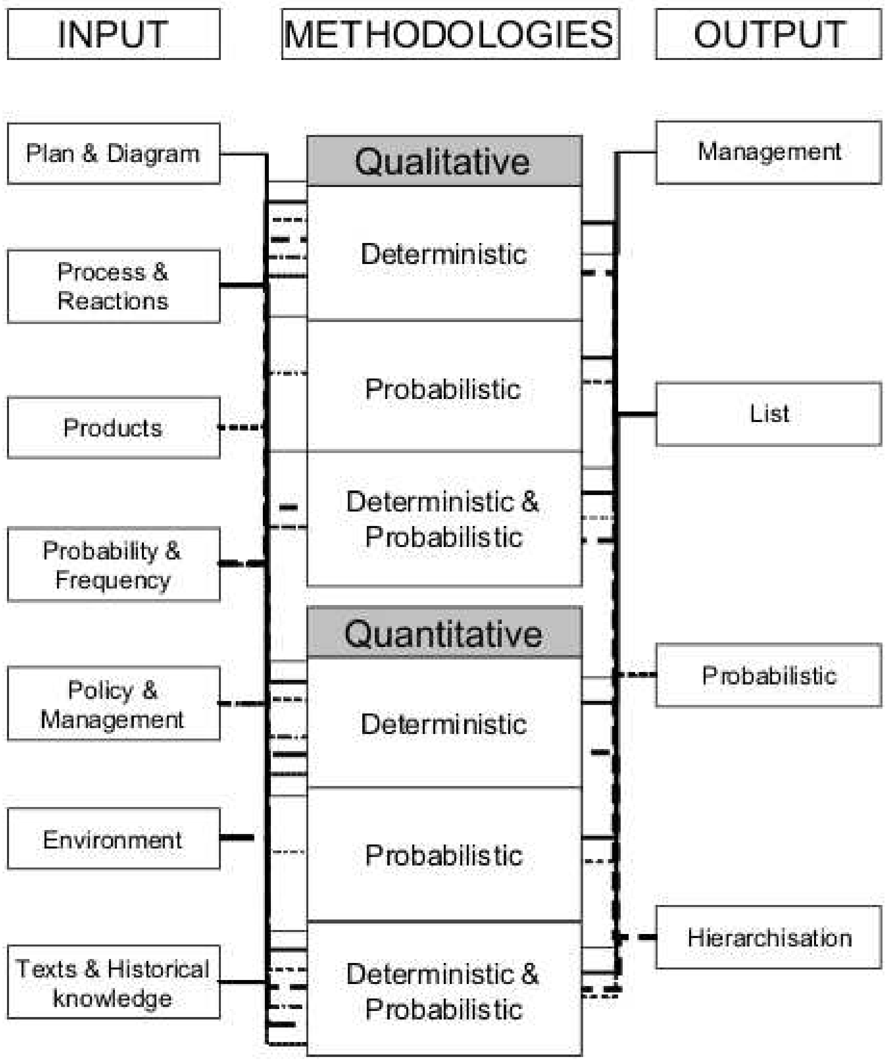


Figure 2.6: Links Between Input Data, Method, And Output Data

nenver the sole basis for decision making by responsible groups". In other words, it is important to incorporate other tools to provide a comprehensive package to support decision-making regarding risks. As a result, risk management has developed to a sophisticated system based on quantitative analysis yet embedding with other business tools.

2.3.3 Risk Analysis and Reliability Analysis

The concept of reliability is firstly used in the engineering field. Reliability is a broad term that focuses on the ability of a product to perform its intended function. Accordingly, reliability engineering consists of the systematic application of time-related engineering principles and techniques throughout a product life cycle. The goal of reliability engineering is to evaluate the inherent reliability of a product or process and pinpoint potential areas for reliability improvement.

Risk analysis is a closely-related subject. It contains methods for the assessment, characterization, and management of risk. The definition of risk has never been agreed with a commonly-accepted term. When used in non-technical context, it normally refers to situations in which it is possible but not certain that some undesirable even will occur. Risk analysis is widely used in economic and financial areas to minimize the monetary loss associated with uncertainties. In engineering, "Risk" is generally taken to be the product of the probability of an event and the loss caused by the events. Risks are often associated with failures of systems, and thus the quantitative treatment of risk has much in common with reliability analysis.

Reliability and risk analysis share a lot of common principles and, in some cases, they could be used interchangeably or as complement to each other to achieve the intended objectives. The synergy between the fields of reliability and risk analysis can be summarized as follows:

- Objectives: Both reliability and risk analysis are techniques to deal with uncertainties in order to evaluate and minimize the effects of those undesirables. In general, outcomes can be categorized as favorable or unfavorable. The goals of both reliability and risk analysis are to plan, assess, handle, and monitor future events to ensure favorable outcomes or avoid unfavorable ones to the best capability.

- Theory fundamentals: They share the same mathematical fundamentals: probability and statistical theory. The basic statistical principles are the same for these two methods. Reliability normally deals with life data and performs a statistical analysis of failure and usage data in order to mathematically model the reliability and failure characteristics of a product. Risk analysis deals with data with greater varieties and evaluates the impacts of these uncertainties. The statistical analysis aims at utilizing existing data to model the potential losses due to uncertainties.
- Applications: Reliability analysis is commonly used in engineering field. Risk analysis is primarily used in financial disciplines, but more and more applications can be found in engineering field. Both techniques are to ensure a product or a process can achieve the expected functions. In addition, risk analysis involves a more comprehensive range of factors and aims at providing insights to minimize potential unfavorable results.

2.4 Bayesian Theory and Application

There are two main philosophical approaches to statistics [43]. One is referred to as frequentist method of inference. It assumes that the parameter is unknown but fixed and the procedure allows to estimate the parameter with certain confidence. The prediction is based on the estimated parameter value. The second approach is Bayesian method, which incorporates the uncertainty about the unknown parameter. The probability theory is used to quantify this uncertainty and predict the parameters. Compared to the conventional frequentist perspective, the Bayesian perspective has the following advantages [43].

- The "objectivity" of frequentist statistics has been obtained by disregarding any prior knowledge about the process being measured. In practice, there is usually some knowledge about the process and it can be valuable during the implementation of process improvement.

- The Bayesian approach allows direct probability statements about the parameters. Compared to the confidence interval used by frequentist statistics, Bayesian method allows customers to use a perspective to make the interpretation that is useful to them.
- Bayesian statistics has a single tool, Bayes' theorem, which is used in all situations. Compared to many different tools required in the frequestist procedure, Bayesian statistics provides a single mathematical representation to incorporate the prior knowledge to the study.
- Bayesian methods often outperform frequentist methods, even when judged by frequentist criteria.
- Bayesian statistics has a straightforward way of dealing with nuisance parameters. They are often marginalized out of the joint posterior distribution.
- Bayesian theorem gives the way to find the predictive distribution of future observations. This can not be easily done in a frequentist way.

2.4.1 Bayes' Theorem

In probability theory, Bayes' theorem is used to compute conditional probabilities of events. It is a way of understanding the likelihoods of certain random events when the evidence of others is present. When we analyze a complex system where one event is dependent on another, the occurrence of one event may have impact on the possibilities of other components within the system. Therefore, our existing belief on the variables that we are interested in could be changed given the new evidence. Bayes' Theorem provides a power tool to re-evaluate the system scientifically.

Given two events A and B such that $P(A) \neq 0$ and $P(B) \neq 0$,

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)} \tag{2.1}$$

where,

$P(B\|A)$	=	Conditional probability of B, given A.
$P(A\|B)$	=	Conditional probability of A, given B.
$P(B)$	=	Prior probability or marginal probability of event B.
$P(A)$	=	Prior probability or marginal probability of event A

More generally, for given n mutually exclusive and exhaustive events $B_1, B_2, ..., B_j$ such that $P(B_j) \neq 0$ for all j, the statement of Bayes' Theorem can be described as follows.

$$P(B_i|A) = \frac{P(A|B_i)P(B_i)}{\sum_{j=1}^{n} P(A|B_j)P(B_j)} \tag{2.2}$$

2.4.2 Bayesian Network

Bayesian inference is fairly simple when it involves only a few variables. However, when the model becomes much more complex and a great number of variables are involved, it gets difficult to make the inference with many related variables. The Bayesian network techniques are designed to solve such problems in a more efficient manner. They emerged from artificial intelligence research and have been applied to many areas, ranging from bioinformatics [44, 45], image processing [46], and forensic science [47].

Bayesian networks (BN) is a probabilistic graphical tool to study the knowledge about uncertainties. It is illustrated in the form of an acyclic graph consisting of nodes and directed links where each node represents a random variable and the links stand for the probabilistic dependencies among the corresponding random variables. This graphic presentation is also a common approach in the process improvement to understand the relations among the variables within the system. A great amount of research efforts have been conducted on developing Bayesian networks such as brief networks, causal networks, and influence diagrams.

Friedman [48] provides a formal definition for Bayesian networks. "A Bayesian network is an annotated directed acyclic graph that encodes a joint probability distribution over a set of random variables **U**". Formally, a BN for **U** is a pair $B =< G, \Theta >$. The first component, G, is a directed acyclic graph whose vertices correspond to the random variables $X_1, X_2, ..., X_n$, and whose edges represent direct dependencies between the variables. The graph G encodes independence assumptions: each variable X_i is independent of its nondescendants given its parents in G. The second component of the pair, namely Θ, represents the set of parameters that quantifies the network. It contains a parameter $\theta_{x_i|\Pi_{x_i}} = P_B(x_i|\Pi_{x_i})$ for each possible value x_i of X_i, and Π_{x_i} of Π_{X_i}, where Π_{X_i} denotes the set of parents of X_i in G. A Bayesian network B defines a unique joint probability distribution over **U** given by

$$P_B(X_1, ..., X_n) = \prod_{i=1}^{n} P_B(X_i|\Pi_{X_i})P_B(\Pi_{X_i}) \tag{2.3}$$

Jenson [49] summarizes that a Bayesian Network should consist of the following:

- A set of variables and a set of directed edges between variables.
- Each variable has a finite set of mutually exclusive states.
- The variables together with the directed form a directed acyclic graph (DAG). (A directed graph is acyclic if there is no directed path $A_1 \longrightarrow \cdots \longrightarrow A_n.s.t.A_1 = A_n$.)
- To each variable A with parents $B_1, ..., B_n$, there is attached the potential table $P(A|B_1, ..., B_n)$.

Langseth [50] argues that two sources of information are to be relied on when building a BN: Input from domain experts and statistical plan. He also discussed the phases that need to be proceeded through for building a BN model. Based on this framework, the major phases for a BN analysis are as follows:

1. Decide what to model: Define the project boundaries and select what should be selected in the scope and what to be left out. This is especially critical for process improvement initiatives because the resources can be very limited. Besides, there is normally a strict timeline for a project to be finished.

2. Define variables: Select the important variables in the model based on the defined scopes. The range of the continuous variables and the states of the discrete variables should also be determined at this point.

3. The qualitative part: The graphical structure is defined to connect the variables selected from the previous step.

4. The quantitative part: To define the quantitative part, one must select distributional families for all variables and fix parameters to specify the distribution.

5. Verification: Verification should be performed both through sensitivity analysis and by testing how the model behaves when analyzing well-known scenarios.

Bayesian network techniques have become increasingly popular to model uncertain and complex system and proved to be an effective tool to solve this kind of problems. Uusitalo [51] summarized the advantages of applying Bayesian network techniques in environment engineering, which also equally apply for other disciplines such as manufacturing.

- Suitable for small and incomplete data sets. There is no minimum sample sizes required to perform and Bayesian network analysis. This can be very important when dealing with a problem in the process improvement domain because the most difficult part is data collection.
- Combining different sources of knowledge. An important contribution of Bayesian method is to use prior information from various sources. In manufacturing, a lot of information are available from the knowledge of subject matter experts. It will be very beneficial to incorporate such information when the study of the system is performed.
- Structural learning possible. The Bayesian method also allows to use data to learn the structure of Bayesian network. Besides the prior knowledge, Bayesian network can provide insights on finding the optimal model structure.
- Explicit treatment of uncertainty and support for decision analysis. Bayesian networks can be used to support decision-making process by providing the information on variables of the model including their costs and consequences associated

with these decisions and their outcomes. These models naturally focus on the relationship between actions, knowledge and uncertainty; the consequences of various management decisions can be studied not only from the perspective of expected values, but also with regard to the risks of highly undesirable outcomes.

- Fast responses. Because Bayesian networks are solved analytically, they can provide fast responses to queries once the model is compiled. The compiled form of a Bayesian network contains a conditional probability distribution for every combination of variable values, and can thus provide any distribution instantly.

Chapter 3

The Bayesian Network Risk Model to Enhance Lean Six Sigma

Lean Six Sigma has become the most effective strategy to increase a manufacturing organization's competitiveness by improving its productivity and reducing excessive costs. Many companies have invested large sums of money as well as other business resources in launching various projects to achieve the desired goals. They also develop training programs to foster a culture of change within the entire organization. However, just like an individual's financial investment, the return can not always be guaranteed. There can be many reasons why people fail in their finance such as lack of knowledge, poor decisions, insufficient planning, lack of disciplines, and, more importantly, "something you don't know that will hurt you". Similarly, a company's efforts can also turn into failure due to a variety of reasons.

This study focuses on the risks existing in the manufacturing processes that are uncertain during the implementation of Lean Six Sigma strategies. In practice, such risks are often neglected because there is no easy way to estimate their impact and subsequently establish procedures to mitigate the severe consequences. A number of companies have realized the importance of having a project control procedure to ensure the success of Lean Six Sigma initiatives. However, such control plans are mostly designed for ensuring the schedule and budget. The specific risks faced by individual projects are not taken into account even though it is commonly recognized that the uncertain factors can put the implementation into jeopardy.

The purpose of this study is to develop the Bayesian network based risk model for Lean Six Sigma that systematically identify the risks, evaluate their impacts in order to enhance the reliability of Lean Six Sigma system. DMAIC (Define, Measure, Analyze, Improve and Control), developed in Six Sigma for problem solving, is used to systematically develop the framework of proposed model. Figure 3.1 provides an overview of the proposed methodology.

3.1 Define Risk in Lean Six Sigma

The risks in Lean Six Sigma vary from different organizations, work environments, and processes. Their definitions, however, share the same perspective. Therefore, it is crucial to develop a systematic framework to analyze them. Kaplan and Garrick [52] posed three questions that should be answered in order to define the risk:

(1) What can go wrong that could lead to a hazard (risk) exposure outcome?

(2) How likely is this to happen?

(3) If it happens, what consequences are expected?

The answer to the first question is a list of all the possible scenarios that are undesirable and could cause negative impact to the targeted goal. This essential step requires a thorough understanding of the entire system including the management function, the manufacturing process, and all the other areas that are related to the overall business objectives. For instance, Jeynes [53] summaries 10 elements of operation that represent the main risk areas to the success of a business: premises, product, purchasing, people, procedures, protection, processes, performance, planning, and policy. It also requires a well-established goal to specify the objective, scope, and importance of conducting a risk analysis. The second question requires assessment of the likelihood for each of these scenarios and the third

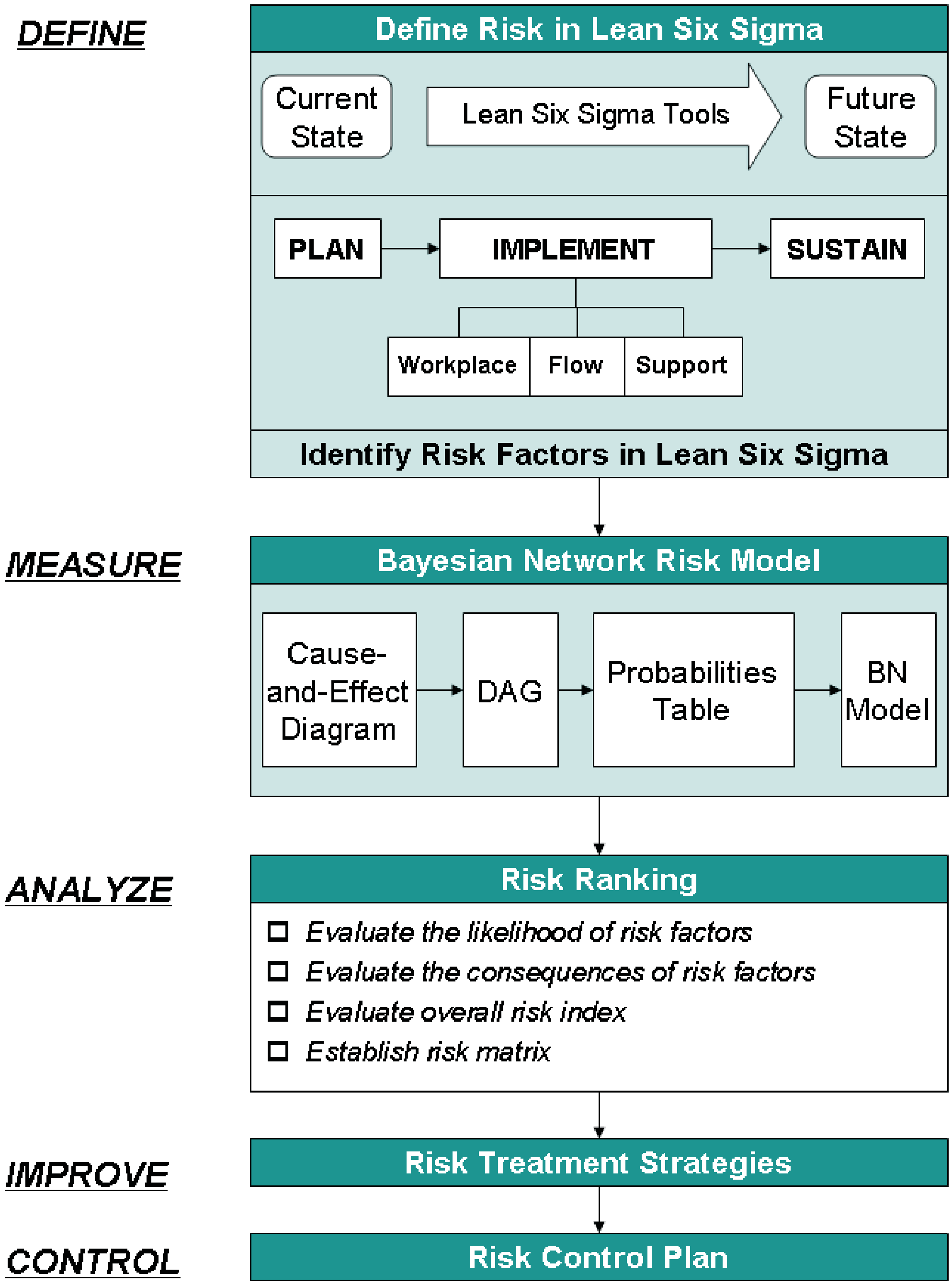


Figure 3.1: General Methodology

estimates the magnitude of potential losses when certain scenario does occur. Depending on the specific scenarios, these two factors could be evaluated in either qualitative or quantitative manner. As a result, the simple mathematical representation of risk can be formulated as follows:

$$R = S_i P_i C_i, \quad i = 1, 2, ..., n \tag{3.1}$$

where,

S_i = Scenario i that leads to hazard exposure.

P_i = Likelihood of scenario i.

C_i = Consequence due to occurrence of events in scenario i.

Risk in Lean Six Sigma

During the implementation of Lean Six Sigma strategies, the general approach can be summarized into four steps. The first step is to study the current state of the system using Value Stream Map. The key is to reveal the existing problems that impede the process from meeting the internal requirements or customers' expectations in an efficient and effective manner. Once we have a better understanding on the current status, the potential opportunities are identified for the second step when the future state is designed to meet the business objectives. The third step is then to select applicable tools to tackle the problems and improve the process. One of the major contributions of Lean Six Sigma is that it provides a variety of tools for problem solving in different areas such as line balancing, setup reduction, inventory reduction, statistical process control and so forth. The last step is then to control the process and make the improvement sustain. This step is normally the most difficult yet extremely important component to ensure the success of the entire Lean Six Sigma strategies.

In Lean Six Sigma, risk factors refer to all the uncertain scenarios existing in the manufacturing system that could inhibit the designed future state from being achieved. Such variables have a finite set of mutually exclusive states, some of which are preferable and others not. For instance, the part needed to fabricate a product can be either good or defect. Obviously, getting a good part is the desired state. Once we decide what risk scenarios should be taken into account, further study needs to be carried out to understand how likely each scenario will take place and their consequences in order to evaluate the potential risks in the Lean Six Sigma implementation. With this information, the next logic step is to calculate the risk index that considers occurrence, likelihood and consequence. Based on this concept, the risk index for the Lean Six Sigma can be defined as follows.

Risk index for a given risk factor,

$$R_{ij} = S_{ij} P_{ij} C_{ij} \tag{3.2}$$

where,

R_{ij}	=	Risk index of the risk factor E_{ij}
i	=	The ith risk category, i=1,2,3,...,m
j	=	The jth risk event within the risk category, j=1,2,3,...,n_i
S_{ij}	=	The existence of the risk factor E_{ij}, $S_{ij} = 1$ or 0
P_{ij}	=	Likelihood of risk factor E_{ij}
C_{ij}	=	Consequence due to occurrence of risk factor E_{ij}

Accumulating score for each category of risk factors,

$$R_i = \sum_{j=1}^{n} R_{ij} \tag{3.3}$$

Total risk index of a process improvement project,

$$R = \sum_{i=1}^{m} \sum_{j=1}^{n} R_{ij} \tag{3.4}$$

where,

R	=	Total risk index of a given project
R_{ij}	=	The risk index of a given risk factor

While the BN techniques will be introduced in the rest of the chapter, Figure 3.2 summarizes the mathematical formulation of the proposed model. The details will be discussed through this chapter.

3.2 Identify Risk Factors

A manufacturing system is a complex combination of all activities and functions that are inter-connected and together contribute to the finish of a quality product. When the Lean Six Sigma strategy is initiated, it normally targets on selected components of a given process. The success of such projects depends on various factors including the accountability of top management, communication of middle management, and the understanding and performance of the entire workforce. It takes the entire organization to make it succeed, but only one component to make it fail. The first task of risk management in Lean Six

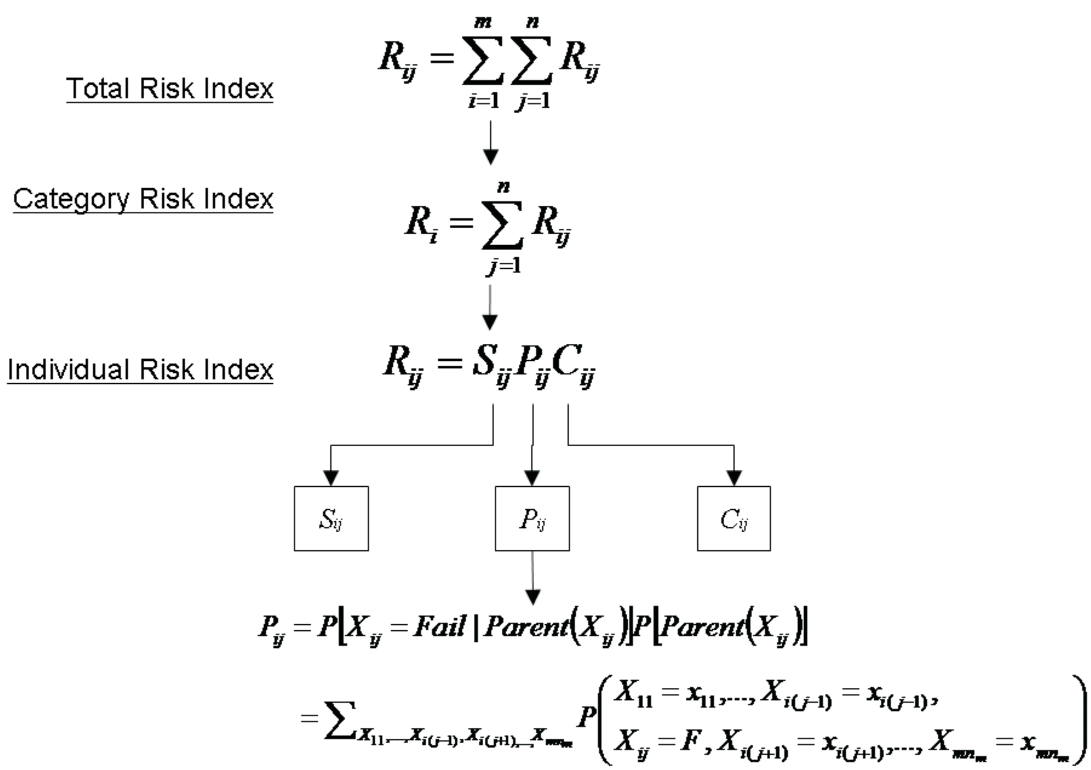


Figure 3.2: Mathematical Formulation

Sigma, therefore, is to list all the possible risk factors during the implementation of Lean Six Sigma strategy.

The breakdown of the elements is based the general framework of Lean Six Sigma implementation. Figure 3.3 illustrates a general system of the transition from the current state to the future state by implementing Lean Six Sigma initiatives. It starts with a plan to determine the overall strategy that guide through the course of implementation. The plan phase is critical for the success of Lean Six Sigma as it involves getting support from the entire organization and fostering a culture of change. An appropriate set of performance metrics must be developed and communicated to provide a baseline and subsequently identify areas of improvement opportunity within an organization.

During the implementation phase, three tasks need to be conducted in sequence: workplace, flow, and supportive functions. Workplace improvement is associated with modifying workplace to ensure that the workplace is safe and organized, the work is performed according to standard operating procedures, and processes are mistake proof to reduce chances of errors. The basic techniques include 5S, visual control, and standard operating procedure (SOP). The major problem existing in the traditional manufacturing is the inefficiency of flow that doesn't focus on the value for customer. The Lean Six Sigma strategy helps an organization achieve the work flow with the minimal non-value added activities. This stage is associated with developing the basis to flow product through the process in an efficient manner. The activities include setup reduction, cellular manufacturing, line balancing, small lot production, lean material handling, and implementing pull systems. The support function involves designing the functional support systems to actually support the production systems. The activities include scheduling systems, maintenance, supplier development, and training program.

At last, the sustain phase applies continuous improvement philosophy to ensure the lasting effectiveness of the implementation. Even though there is no direct research on the failure rate of Lean Six Sigma initiatives, it has been widely-observed that the efforts could wane without an effective system to sustain the change. This is due to the fact that the successful Lean Six Sigma strategies requires fundamental transformation of the entire organization.

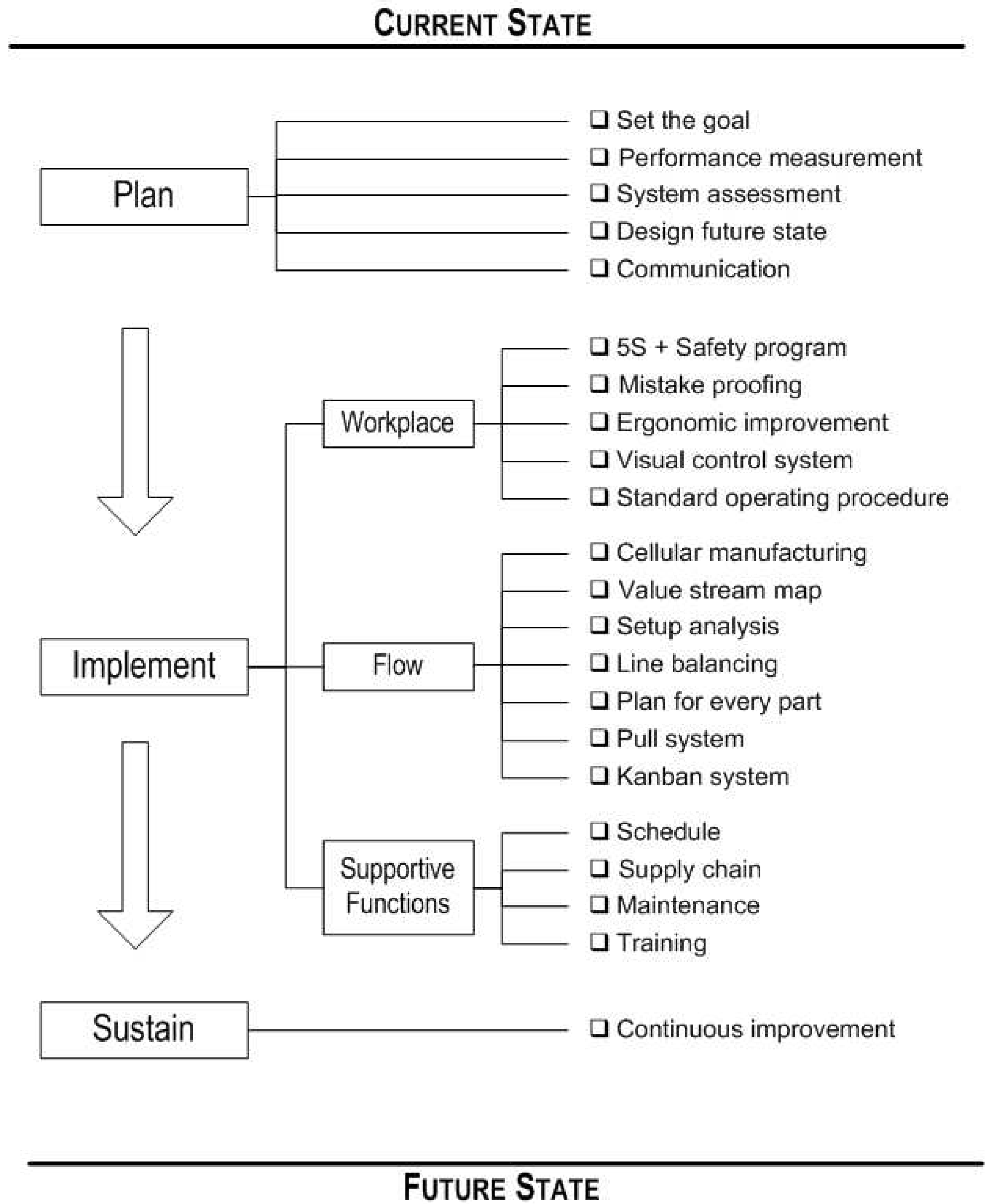


Figure 3.3: The Framework of Process Improvement Implementation

In practice, the major focus of a Lean Six Sigma projects could be a collection of these elements. Yet the general frameworks follows plan, implement (workplace, flow, and supportive function), and sustain. Based on this framework, one can systematically review the entire process and identify all the potential risks that can impact the Lean Six Sigma strategies. The risk factors existing during the implementation of Lean Six Sigma can be categorized as Table 3.1.

3.3 Risk Analysis

Once the risk factors are identified, their likelihood and consequence functions need to be determined. Depending on the nature of risk factors and availability of data, two approaches can be used to determine their potential impacts. Quantitative method is used for those factors that have historical data or established failure model to estimate probability and impacts and qualitative method is used for those that are difficult to quantify or resource-consuming to do so.

3.3.1 Qualitative Approach

In some cases, the precise information is not required or difficult to obtain. Rank-ordered approximations can be applied. In some cases, when the exact data is not necessary for a rough estimation, the qualitative approach can also be very useful. Table 3.2, for example, provides a common method to rank the likelihood one even may take place. Even though we may not know the exact probability, the subject matter experts can normally provides a rough estimate based their experience and the current performance of the system. Table 3.3, on the other hand, provides an example of how the consequence is evaluated for individual risk factors in the similar manner. This ranking is usually related to the general objectives of the system and each risk factor is ranked according to their impacts on the bottom line. The advantage of this approach is that it doesn't require extensive data collection, which can be very difficult in the reality. Additionally, the subject matter experts can normally provide good estimate on the data needed to conduct a rank-ordered approximation.

Table 3.1: Risk Factors in Lean Six Sigma Implementation

PLAN
Conflict with overall business objective
Inappropriate improvement strategy
Alteration of plan
Lack of top down management support
Lack of middle management/supervisor buy-in
Lack of improvement measures
Insufficient communication among different functional areas
IMPLEMENT
Workplace
Insufficient 5S program
Insufficient visual control system
Insufficient standard operating procedure
Operational errors
Inadequate work instructions
Flow
Not considering risks in Value Stream Map
Unexpected operational changes
Miscalculation of process capacity
Insufficient skills/expertise to perform the task
Insufficient resources
Design change
Supportive Function
Demand change
Capability of the designed process
Misalignment of process with product family
Facility layout
Vendor-related issues
Machine availability
Lack of maintenance management system
Wrong material supply
Poor quality of material supply
Accuracy of inventory
SUSTAIN
Lack of continuous improvement initiatives
Insufficient training
Absenteeism
Employee turnover
Lack of responsibility and accountability

Table 3.2: Qualitative Probability Categories

Categories	Description
Almost certain	Likely to occur very often during a given time period
Likely	Likely to occur several times during a given time period
Possible	Likely to occur sometime during a given time period
Unlikely	Very unlikely to occur during a given time period
Rare	Not expected to occur during a given time period

Table 3.3: Severity Description from Exposure of the Failure

Categories	Description
Catastrophic	CNG release involving catastrophic fire or explosion
Critical	Unconfirmed CNG release with critical fire or explosive potential
Marginal	Small CNG release with marginal ignition potential or fire effects
Minor	Failure with minor fire potential and only loss of system operation

3.3.2 Quantitative Approach

When the likelihood of risk factors can be estimated quantitatively, it normally yields the following formula. It should be well defined and maintained to ensure the consistency through the entire analytical process. It should also be noted that the expert knowledge in that area are often used to obtain the probabilities if the data is not currently available and difficult to collect.

$$P_i = \left(\frac{\mathrm{n}}{\mathrm{N}}\right) \tag{3.5}$$

where,

P_i = Probability of event i.

n = Total number of times of event i occurring during a given period.

N = Total number of times of all events occurring during a given period.

In the real world, the occurrence of one event often relies on another. Therefore, it is important to gain the information about likelihoods given that certain evidence has been observed.

The consequence of risks can also be quantified. If able to be estimated quantitatively, the severity of each factor is based on historical data or product specifications. It is also common practice to calculate the financial loss due to the failures if related information is available or can be obtained.

3.3.3 Bayesian Network

Another major component of the quantitative analysis is to estimate the probabilities of events based on their interrelationship. In probability theory, Bayes' theorem is used to compute conditional probabilities of events. It is a way of understanding the likelihoods of certain random events when the evidence of others is present.

Bayes Formula

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{3.6}$$

where,

$P(A)$	=	Prior probability of A.
$P(A\|B)$	=	Conditional probability of A, given B.
$P(B\|A)$	=	Conditional probability of B, given A.
$P(B)$	=	Prior probability of B.

More generally, when we deal with a collection of alternatives A_1, A_2, ..., A_n,

$$P(A_i|B) = \frac{P(A_i \bigcap B)}{P(B)} = \frac{P(B|A_i)P(A_i)}{P(B)} \tag{3.7}$$

According to law of total probability, for an event B,

$$P(B) = P(B|A_i)P(A_i) + \cdots + P(B|A_n)P(A_k) \tag{3.8}$$

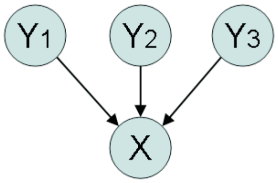
Bayesian inference is simple when it involves only a few variables. However, when there are too many related events in the analysis, the calculation of probabilities gets very complicated. Bayesian network (BN) techniques provides an effective method for such problems. BNs are a set of tools for graphical representation and probabilistic calculation for problems involving uncertainty. They consist of a set of variables and directed edges that represent the relationship between variables. If an edge points from node Y to X, we say that Y is a "parent" variable of X and X is a "child" variable of Y. The variables that have no parents are called root variables. Because "parent" variables affect the states of "child" variables, Bayesian networks provides an effective representation of possible cause-and-effect relationships.

When the BNs deals with discrete variables, each variable has a finite set of mutually exclusive states. The states of the child variable X_i with parents $Y_1, Y_2, ..., Y_n (n > 1)$ are described by an attached conditional probability table $P(X_i|Y_1, Y_2, ..., Y_n)$. For the variables $X_1, X_2, ..., X_n$ of a Bayesian Network the probability of the joint event $X_1 \wedge X_2 \wedge ... \wedge X_n$ is given by

$$P(X_1, X_2, ..., X_n) = \prod_{i=1}^{n} P[X_i|Parent(X_i)]P[Parent(X_i)] \tag{3.9}$$

where $Parent(Xi)$ is the set of parent variables of the variable X_i. Maglogiannis [54] provides a simple example in Fig 3.4, in which a simple BN with discrete variables is depicted with three parents and one child node.

Maglogiannis [54] states that building and using a BN is essentially a three-stage process. The first stage is to identify all the involved variables and their cause-and-effect relationships. The second stage involves specifying the conditional probabilities for the states of each variable, given the states of their parents variables. The inference is made in the third stage, during which the input data is entered to the BN model and the probabilities for all the network variables are calculated based on the cause-and-effect relationships. "Furthermore, Bayesian inference includes the calculation of the posterior probabilities for the variable states given a system fault or a certain combination of events, the joint



(a)

Y_1		State1				State2			
Y_2		State1		State2		State1		State2	
Y_3		State1	State2	State1	State2	State1	State2	State1	State2
X	State1	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8
	State2	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}

(b)

Figure 3.4: (a) A simple Bayesian network with three parents nodes (Y_1, Y_2, Y_3) and one child node (X). (b) The conditional probability table of X.

probability of combination of variable states and the determination of the most probable combination of variable states."

3.3.4 Risk Model Using BN Techniques

In the arena of Lean Six Sigma, finding cause-and-effect relationships is a commonly-utilized approach to understand the complex system and identify the root cause of the problem. Such exercise can always lead to a large network that involves enormous components and their relations due to the complexity of manufacturing systems. For instance, a common method applied to systematically study the cause-and-effect relations is 4Ms methodologies [55] derived from Ishikawa's ideas [56]. The 4Ms stand for man, machine, material, and method. "Man" include all the employees involved in manufacturing. They could be shop floor operators who actually perform the job or management whose commitment and guidance have great influence on the system. "Machine" refers to equipment and tools used to manufacture a product. "Material" refers to issues related to raw materials required for the production. The availability and accuracy of inventory have key impacts on today's manufacturing. And the last, "Method", is to indicate the right methods are used to ensure the performance of a manufacturing system. While it ensures the involvement of all possible factors, the resulted structure can be quite extensive.

For most Lean Six Sigma initiatives, the investigation normally stops at this level when the root causes have been identified. Therefore, the analysis is mostly carried out in the qualitative manner. When there is a need to decide which factors have the most impact on the end results and therefore should be focused on, the most common approach is to rely on the subjective judgment of the decision makers. This works well if there is an obvious critical issue or all the problems will be resolved over time. However, there are usually more than one cause that have equally significant impact and, unfortunately, the resources to tackle them are quite limited. Under these circumstances, it is of interest to know which causes can most likely result in failures. Thus the risks exposed can be evaluated based on their possibilities and consequences.

Understand the Process

In this section, a brief example will be used along with the description of proposed model to demonstrate how to use BN techniques and other risk management techniques in the area of Lean Six Sigma. This example represents an inventory problem in the fabrication process. The manufacturing can be a very dynamic environment where the change is constant due to customers' expectations or internal requirements. If such information is not communicated well, the shop floor employees can get the wrong part for the production, which causes unnecessary wastes within the process. Several technical terms are introduced as follows:

- Engineering Change (E): Engineering change refers to a documented change in the design of product development or manufacturing process. Such change can occur frequently due to continuously evolving product development, technological advances, customer requirements, and fluctuations in the availability of components and raw materials.
- Inventory Audit (I): Inventory audit, or cycle counting, is a necessary action in inventory management. The implication of wrong inventory can be grave for a company. In our case, the process of inventory audit includes physically counting the parts and recording the counted results in the pre-designed system.
- Nesting (N): In manufacturing environment, nesting refers to the process of efficiently cutting parts from flat raw material. There are various nesting software

Table 3.4: States of Variables

E=Engineering Change	
E=True	EC Communicated
E=False	EC Not Communicated
I=Inventory Audit	
I=True	There is no error in the inventory sheets
I=False	There is error in the inventory sheets
N=Nesting	
N=True	There is no error in the nesting process
N=False	There is error in the nesting process
P=Part	
P=True	Part is correct
P=False	Part is incorrect

available in the market and SigmaNest® is one of the commonly-used commercial packages that use proprietary algorithms to determine how to lay the parts out in such a way as to produce the required quantities of parts, while minimizing the amount of raw material wasted and achieving maximized material yield.

- Part Accuracy (P): If the engineering change is not communicated, the parts cut from the router could be different from the ones as they are supposed to be. As a result, the wrong part may be cut and sent to the work station.

The first step to establish the BN is to identify the variables for the system of interests. The elements described above are used as the variables being modelled. There are two kinds of variables: continuous variables and discrete variables. The continuous variable, such as length, weight, and temperature, can take on any of a range of values. Discrete variable, on the other hand, are those for which subjects or observations can be categorized. In our study, discrete variables are used. For each variable, the set of outcomes or states are to be defined. This set is referred to in the mathematical literature as "mutually exclusive and exhaustive", meaning that it must cover all possibilities for each variable and no important distinctions are shared between states. Table 3.4 provides the descriptions of the states for each variable.

Create BN Graphical Model

The next step is to create the graphical model to represent the dependent relationships between the selected variables. There are three possible connections by which information can travel through a variable in a directed graph: diverging, serial and converging connections. A diverging connection is an appropriate graphical model whenever it is believed that one variable is relevant for other variables and those other variables are conditionally independent the given variable. A serial connection is an appropriate graphical model whenever it is believed that one variable is relevant for a second variable, that this second variable is relevant for the third one, and the first and the third are conditionally independent the second variable. A converging connection is an appropriate graphical model whenever it is believed that A and B are both relevant for C, A is not relevant for B, but it does become relevant if the state of C is known.

Figure 3.5 illustrates the causal dependency relationships between the variables where the issue is the excessive or incorrect inventory due to either insufficient nesting or incorrect inventory audit system. These two variables are affected by the process of engineering change. Under some circumstances, engineering design needs to be changed due to various reasons. If it is not communicated through the related departments, the information on inventory management and nesting system could be wrong. The person who does the nesting may not know he needs to change the geometric data of the parts, or the quantity to cut, or remove the part from nesting. For the inventory control, on the other hand, may not know the inventory audit sheets need to be updated. Consequently, the part that will be delivered to the production line is incorrect.

Define Conditional Probabilities

Conditional probability is the probability of some event A, given the occurrence of some other event B. Once the diagram is developed to represent the relevance and causality we can start analyzing the uncertainties in the system, giving the quantitative information between parameters under different circumstances. As indicated earlier, this is normally

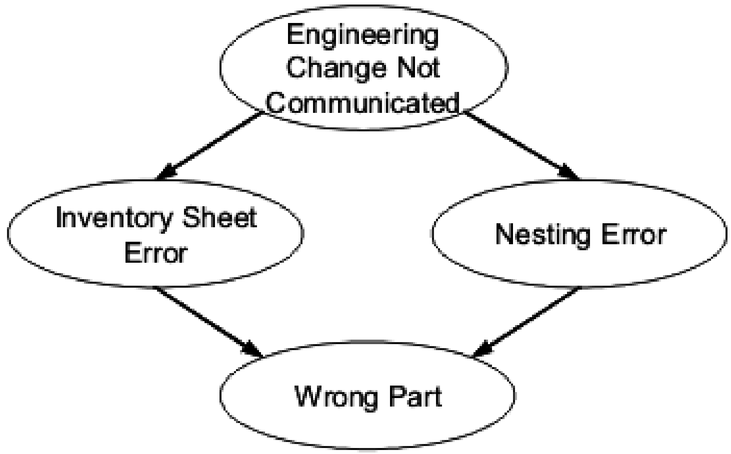


Figure 3.5: Bayesian Network Example

where the study is ended because the difficulty to quantify the existing uncertainties. Management has to make a decision based on the experience or subjective judgement. However, if there are more than one possible major risks existing in the system and it not realistic to solve all of them, a scientific approach is required to provide more insights for the decision making process.

BN theory addresses the network of great complexity, which consists of a number of variables that are connected. A key step is to specify the conditional probability of one event based on other events it relates. This provides a base for making inference on one event given that any other events take place. Table 3.5 provides the conditional probabilities in the BN example.

Inference

The BN model can be used to answer the questions of probabilistic queries regarding the variables. For example, the network can be used to study the updated information of the outcome of a subset of variables when other variables are observed. This process of computing the posterior probabilities of variables given observed information is called probabilistic inference. This is especially important because the occurrence of one event

Table 3.5: Probabilities Table

Pr(E)				
True: EC Communicated	0.75			
False: EC Not Communicated	0.25			
***Pr*(*I*|*E*)**				
	E=True	E=False		
True: Inventory Accurate	0.65	0.05		
False: Inventory Inaccurate	0.35	0.95		
***Pr*(*N*|*E*)**				
	E=True	E=False		
True: Nesting Accurate	0.90	0.40		
False: Nesting Inaccurate	0.10	0.60		
***Pr*(*P*|*I*, *N*)**				
	I=True		I=False	
	N=True	N=False	N=True	N=False
True: Part Accurate	0.85	0.25	0.10	0.01
False: Part Inaccurate	0.15	0.75	0.90	0.99

can significantly change one's belief. The manufacturing environment is quite dynamic and variables are constantly changing due to different reasons. Therefore, the decisions may need to be adjusted with the occurrence of new evidence. In practice, this approach allows management to make more intelligent decisions based on the dynamically-evolving information.

From the standpoint of probability theory, the questions concerned with probabilities can be summarized into three major categories. By computing these probabilities, one can gain useful insights given the circumstances.

- Marginal probability.
- Joint probability.
- Conditional probability

Marginal Probabilities

Marginal probability is the unconditional probability of an event. This represents how likely this event takes place regardless of whether other events related occur or not. In the network we developed, a probability table is established based on historical data and expert opinion. Some may want to understand the performance of the inventory control system. The question is what the probability is that the right part can be obtained in the process. The following discusses how to compute the marginal probability of part being correct.

First of all, we need to calculate the marginal probability for $Pr(I = T)$, which represents the unconditional probability of inventory information being correct regardless of the occurrence of any other events. Since engineering change is the only variable that impacts inventory information and it has two states: communicated ($Pr(E = T)$) and not communicated ($Pr(E = F)$), the marginal probability of $Pr(I = T)$ may be computed based on Bayes' Theorem as follows:

$$\begin{aligned} Pr(I = T) &= Pr(I = T|E = T)Pr(E = T) + Pr(I = T|E = F)Pr(E = F) \\ &= 0.65 \times 0.75 + 0.05 \times 0.25 = 0.50 \end{aligned}$$

The probability of inventory being incorrect is therefore

$$Pr(I = F) = 1 - Pr(I = T) = 1 - 0.50 = 0.50$$

Next, we will calculate the marginal probability for $Pr(P = T)$, which represents the probability of part being correct, not contingent on any prior or related events.

$$\begin{aligned} Pr(P = T) = Pr(&P = T|I = T, N = T)Pr(I = T, N = T) \\ &+Pr(P = T|I = T, N = F)Pr(I = T, N = F) \\ &+Pr(P = T|I = F, N = T)Pr(I = F, N = T) \\ &+Pr(P = T|I = F, N = F)Pr(I = F, N = F) \end{aligned}$$

Taking the first section of the equation,

$$\begin{aligned} &Pr(P = T|I = T, N = T)Pr(I = T, N = T) \\ &\quad = Pr(P = T|I = T, N = T) \end{aligned}$$

$$
\begin{aligned}
&\times[Pr(I=T,N=T|E=T)Pr(E=T)\\
&\quad +Pr(I=T,N=T|E=F)Pr(E=F)]\\
&= Pr(P=T|I=T,N=T)\\
&\quad\times[Pr(I=T|E=T)Pr(N=T|E=T)Pr(E=T)\\
&\quad\quad +Pr(I=T|E=F)Pr(N=T|E=F)Pr(E=F)]\\
&= Pr(P=T|I=T,N=T)Pr(I=T|E=T)Pr(N=T|E=T)Pr(E=T)\\
&\quad +Pr(P=T|I=T,N=T)Pr(I=T|E=F)Pr(N=T|E=F)Pr(E=F)
\end{aligned}
$$

The marginal probability for $Pr(P=T)$ can therefore be re-written as follows.

$$
\begin{aligned}
Pr(P=T) &= Pr(P=T|I=T,N=T)Pr(I=T,N=T)\\
&\quad +Pr(P=T|I=T,N=F)Pr(I=T,N=F)\\
&\quad +Pr(P=T|I=F,N=T)Pr(I=F,N=T)\\
&\quad +Pr(P=T|I=F,N=F)Pr(I=F,N=F)\\
&= Pr(P=T|I=T,N=T)Pr(I=T|E=T)Pr(N=T|E=T)Pr(E=T)\\
&\quad +Pr(P=T|I=T,N=T)Pr(I=T|E=F)Pr(N=T|E=F)Pr(E=F)\\
&\quad +Pr(P=T|I=T,N=F)Pr(I=T|E=T)Pr(N=F|E=T)Pr(E=T)\\
&\quad +Pr(P=T|I=T,N=F)Pr(I=T|E=F)Pr(N=F|E=F)Pr(E=F)\\
&\quad +Pr(P=T|I=F,N=T)Pr(I=F|E=T)Pr(N=T|E=T)Pr(E=T)\\
&\quad +Pr(P=T|I=F,N=T)Pr(I=F|E=F)Pr(N=T|E=F)Pr(E=F)\\
&\quad +Pr(P=T|I=F,N=F)Pr(I=F|E=T)Pr(N=F|E=T)Pr(E=T)\\
&\quad +Pr(P=T|I=F,N=F)Pr(I=F|E=F)Pr(N=F|E=F)Pr(E=F)\\
&= 0.85\times 0.65\times 0.90\times 0.75 + 0.85\times 0.05\times 0.40\times 0.25\\
&\quad +0.25\times 0.65\times 0.10\times 0.75 + 0.25\times 0.05\times 0.60\times 0.25\\
&\quad +0.01\times 0.35\times 0.90\times 0.75 + 0.10\times 0.95\times 0.40\times 0.25\\
&\quad +0.01\times 0.35\times 0.10\times 0.75 + 0.01\times 0.95\times 0.60\times 0.25\\
&= 0.3729 + 0.0043 + 0.0122 + 0.0019 + 0.0236 + 0.0095 + 0.0003 + 0.0014\\
&= 0.4261
\end{aligned}
$$

As we can see, the computation is quite lengthy and tedious. To make it easier, the computation can be formulated in Equation 3.10. The probabilities used in this equation are the conditional probabilities of one event depending on their parents variables. The computation can also be summarized in Table 3.6.

$$Pr(P = T) = \sum_{e,i,n} Pr(E = e, I = i, N = n, P = T) \tag{3.10}$$

Accordingly, the probability of getting an incorrect part is

$Pr(P = F) = 1 - Pr(P = T) = 1 - 0.4261 = 0.5739$

As we can imagine from the example, when the number of variables is getting bigger, the network becomes more complex and so does the computation of probabilities. This calls for a more efficient method, which can be achieved by BN techniques. The marginal probabilities are summarized as follows for all the events in the network of case study.

$Pr(E = T) = 0.75, Pr(E = F) = 0.25$
$Pr(I = T) = 0.5, Pr(I = F) = 0.5$
$Pr(N = T) = 0.775, Pr(N = F) = 0.225$
$Pr(P = T) = 0.4261, Pr(P = F) = 0.5739$

Joint Probabilities

Table 3.6: Computation of $Pr(P = T)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	T(0.85)	$0.75 \times 0.65 \times 0.90 \times 0.85 = 0.3729$
T(0.75)	T(0.65)	F(0.10)	T(0.25)	$0.75 \times 0.65 \times 0.10 \times 0.25 = 0.0122$
T(0.75)	F(0.35)	T(0.90)	T(0.10)	$0.75 \times 0.35 \times 0.90 \times 0.10 = 0.0236$
T(0.75)	F(0.35)	F(0.10)	T(0.01)	$0.75 \times 0.35 \times 0.10 \times 0.01 = 0.0003$
F(0.25)	T(0.05)	T(0.40)	T(0.85)	$0.25 \times 0.05 \times 0.40 \times 0.85 = 0.0043$
F(0.25)	T(0.05)	F(0.60)	T(0.25)	$0.25 \times 0.05 \times 0.60 \times 0.25 = 0.0019$
F(0.25)	F(0.95)	T(0.40)	T(0.10)	$0.25 \times 0.95 \times 0.40 \times 0.10 = 0.0095$
F(0.25)	F(0.95)	F(0.60)	T(0.01)	$0.25 \times 0.95 \times 0.60 \times 0.01 = 0.0014$
				$\sum = 0.4261$

Table 3.7: Joint Probabilities

Pr		**E**		**I**		**N**		**P**	
		T	*F*	*T*	*F*	*T*	*F*	*T*	*F*
E	*T*			0.4875	0.2625	0.6750	0.0750	0.4091	0.3410
	F			0.0125	0.2375	0.1000	0.1500	0.1171	0.2330
I	*T*	0.4875	0.0125			0.4438	0.0563	0.3913	0.1088
	F	0.2625	0.2375			0.3313	0.1688	0.0348	0.4652
N	*T*	0.6750	0.1000	0.4438	0.3313			0.4103	0.3647
	F	0.0750	0.1500	0.0563	0.1688			0.0158	0.2093
P	*T*	0.4091	0.1171	0.3913	0.0348	0.4103	0.0158		
	F	0.3410	0.2330	0.1088	0.4652	0.3647	0.2093		

Joint probability specifies the likelihood of more than one events occur in conjunction. It is possible that the jointly occurrence of two or more events have much more significant impact than anyone of them. Under such circumstance, the knowledge of joint probability becomes crucial. In our example, some may be interested in finding out the joint probability of engineering change well-communicated and part being correct.

$$
\begin{aligned}
Pr(P=T,E=T) = \textstyle\sum_{e,i,n} Pr(E=T,I=i,N=n,P=T) \\
&= Pr(P=T|I=T,N=T)Pr(I=T|E=T)Pr(N=T|E=T)Pr(E=T) \\
&\quad +Pr(P=T|I=T,N=F)Pr(I=T|E=T)Pr(N=F|E=T)Pr(E=T) \\
&\quad +Pr(P=T|I=F,N=T)Pr(I=F|E=T)Pr(N=T|E=T)Pr(E=T) \\
&\quad +Pr(P=T|I=F,N=F)Pr(I=F|E=T)Pr(N=F|E=T)Pr(E=T) \\
&= 0.85\times0.65\times0.90\times0.75+0.25\times0.65\times0.10\times0.75 \\
&\quad +0.10\times0.35\times0.90\times0.75+0.01\times0.35\times0.10\times0.75 \\
&= 0.3729+0.0122+0.0236+0.0003 \\
&= 0.4090
\end{aligned}
$$

Table 3.7 provides a summary of the joint probabilities of any two given events for all the events in the network.

Conditional Probabilities

Conditional probability represents the possibility of one event given the occurrence of some other events. It is noted that several prior conditional probabilities have been provided.In practice, it is normally easier to compute or estimate of certain conditional probabilities based on historical data or expert knowledge. Such information provides prior information to obtain other important conditional probabilities. In our example, suppose that the wrong parts are observed. There are two possible causes: the inventory sheets contain errors or the nesting is not correct. Both of these events are caused by the lack of communication on engineering change. To understand the likelihoods about the engineering change given the parts's information is known, Bayes' rule could be used to compute the posterior probability of each explanation.

$$Pr(E=T|P=T) = \frac{Pr(P=T,E=T)}{Pr(P=T)} = \frac{0.4091}{0.4261} = 0.9601$$

$$Pr(E=F|P=T) = 1 - 0.9601 = 0.0399$$

$$Pr(E=T|P=F) = \frac{Pr(P=T,E=F)}{Pr(P=F)} = \frac{0.3410}{0.5739} = 0.5942$$

$$Pr(E=F|P=F) = 1 - 0.5942 = 0.4058$$

We can see that, when the part supplied is correct, the engineering change appears to be communicated very well. Table 3.8 provides a summary of the conditional probabilities for all the events in the network. For further details on how to compute the probabilities related to the scenario when the part is incorrect, please refer to Appendix.

Explanation

The most common task we wish to solve using BN is to conduct probabilistic inference when certain information is given. In the inventory accuracy example used in this study, there are two possible causes to cause the generation of an incorrect part: either inventory audit is incorrect, or nesting has been not adjusted. Suppose that we observe that the

Table 3.8: Conditional Probabilities

Pr		**GIVEN EVENTS**							
		E		**I**		**N**		**P**	
		T	*F*	*T*	*F*	*T*	*F*	*T*	*F*
E	*T*			0.9750	0.5250	0.8710	0.3333	0.9601	0.5942
	F			0.0250	0.4750	0.1290	0.6667	0.2748	0.4060
I	*T*	0.6500	0.0500			0.5726	0.2502	0.9183	0.1896
	F	0.3500	0.9500			0.4275	0.7502	0.0817	0.8106
N	*T*	0.9000	0.4000	0.8876	0.6626			0.9629	0.6355
	F	0.1000	0.6000	0.1126	0.3376			0.0371	0.3647
P	*T*	0.5455	0.4684	0.7826	0.0696	0.5294	0.0702		
	F	0.4547	0.9320	0.2176	0.9304	0.4706	0.9302		

wrong part is delivered to the production, the posterior probability can be computed for each scenario.

According to the results in Table 3.8, we can have the conditional probabilities as follows:

$$Pr(I = F|P = F) = 0.8109$$

$$Pr(N = F|P = F) = 0.3647$$

We see that, in this example, the reason why a wrong part is produced is more likely due to incorrect inventory audit rather than insufficient nesting. Figure 3.6 summarizes the posterior probabilities of various events given that the wrong part has been produced as well as their unconditional probabilities. As indicated in this figure, the occurrence of incorrect part can change our perspective on other variables within the system. When an incorrect part is observed, the probability of inventory being incorrect is increased significantly.

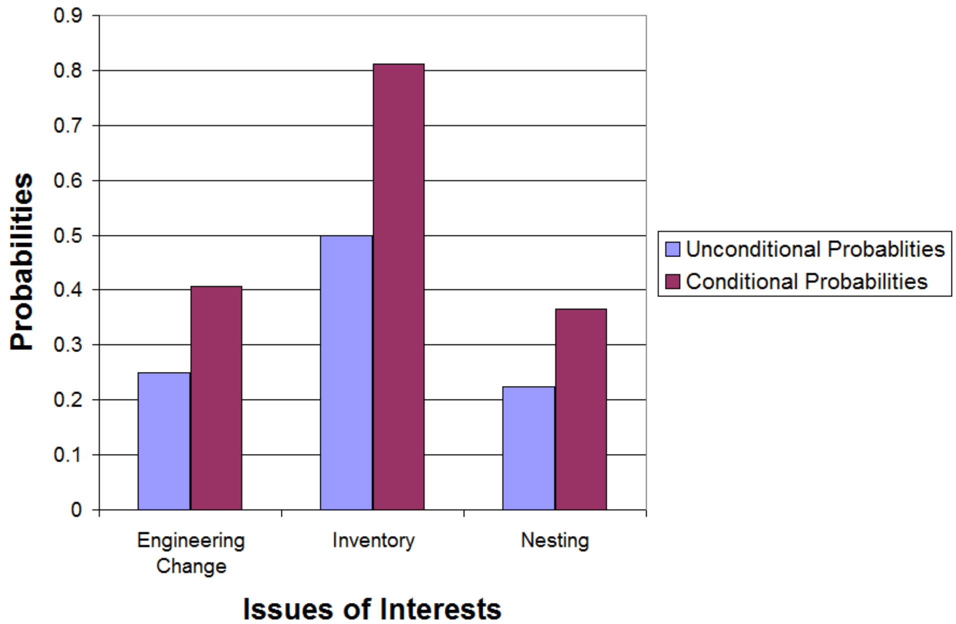


Figure 3.6: Comparison of Probabilities

3.4 Risk Ranking

3.4.1 Risk Index

As described in Equation 3.2, the risk index can be computed as $R_{ij} = S_{ij}P_{ij}C_{ij}$ where S_{ij} shows where this risk factor should be included, P_{ij} represents how likely it will take place, and C_{ij} addresses the severity of the consequence. In the example, the probabilities computed by BN method are used for P_{ij}. To calculate the risk index of an individual risk factor, the equation 3.2 can be rewritten as follows:

$$R_{ij} = S_{ij}P_{ij}C_{ij} = S_{ij}\left\{P[X_{ij} = \text{Fail}|Parent(X_{ij})]P[Parent(X_{ij})]\right\}C_{ij} \tag{3.11}$$

Where,

$$\begin{aligned} P_{ij} \quad &= \textstyle\sum_{X_{11},\ldots,X_{i(j-1)},X_{i(j+1)},\ldots,X_{mn_m}} Pr(\quad X_{11} = x_{11}, ..., X_{i(j-1)} = x_{i(j-1)}, \\ &\qquad\qquad\qquad\qquad\qquad X_{ij} = F, X_{i(j+1)} = x_{i(j+1)}, ..., X_{mn_m} = x_{mn_m}) \end{aligned}$$

We can define the S_{ij} and C_{ij} in the following framework.

<u>Occurrence</u>

1 This risk exists

0 This risk does not exist

<u>Consequence</u>

1 The impact is insignificant

2 The impact is minor

3 The impact is moderate

4 The impact is major

5 The impact is catastrophic

In the example we used in this chapter, suppose all the three events, lack of communication of engineering change, insufficient inventory system, and incorrect nesting, lead to incorrect part. Therefore, their impact are the same. Because the incorrect part cause interruption of production, it will be considered as major risk. Their unconditional probabilities are $Pr(E = F) = 0.25$, $Pr(I = F) = 0.5$, $Pr(N = F) = 0.225$. Table 3.9 summarizes the ranking of the risk factors presented in the simple example introduced in this section.

3.4.2 Risk Matrix

Risk Matrix provides another method to rank the risk factors, in which the risk factors are ranked according to their likelihood and consequences. The combination of both likelihood

Table 3.9: Risk Ranking by Risk Indices

RISK FACTORS	S_{ij}	P_{ij}	C_{ij}	R_{ij}
Engineering Change	1	0.25	4	1.00
Inventory Audit	1	0.5	4	2.00
Nesting System	1	0.225	4	0.90

and consequence gives an estimate of risk ranking. Figure 3.7 provides an example of Risk Matrix. The risks on the lower left corner represent the risk factors that are less like to take place and have minimal impact on the process. They can be easily managed by developing standard operating or auditing procedure to mitigate risks. The upper right corner refers to the risk factors that are very likely to happen and have significant impact on the objectives. For each risk factor in this area, a detailed plan should be developed regarding how to control these risks.

3.5 Risk Treatment

Once the risk have been identified, it needs to be determined what actions should be taken in order to reduce the risks or lower them to a minimum level. Cooper *et al.* [35] describes the process of selecting and developing effective risk treatments.

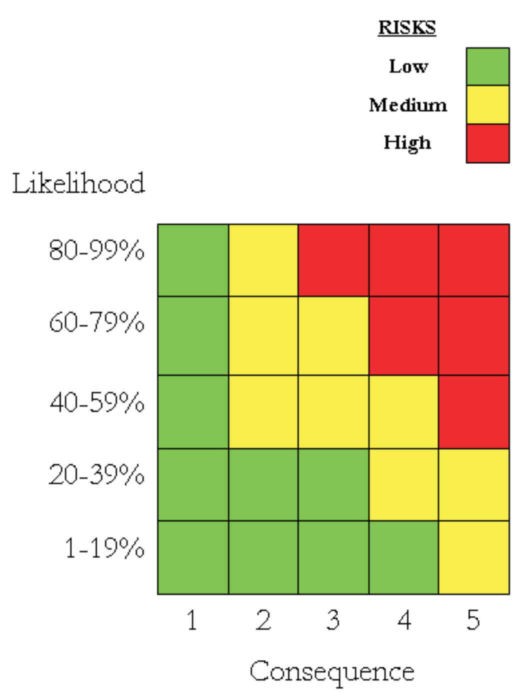


Figure 3.7: Risk Ranking Metrics

(1) Identify the options for reducing the likelihood or consequences of each Extreme or High risk;

(2) Determine the potential benefits and costs of each option, including the possible impact on the organization if the risk occurred, the reduced level of risk if the option were implemented, the potential benefits of the reduced level of risk, and the costs of achieving those benefits, including both direct and indirect costs and the effects of any schedule delays;

(3) Select the best options for the project;

(4) For options that have the form of contingency plans, specify the symptoms or trigger points at which the option might be implemented;

(5) Identify links to related processes or activities within or outside the project; and

(6) Develop detailed Risk Action Plans.

In a general perspective, the risk treatment strategies can be summarized into the following categories.

Risk Prevention/Avoidance Risk prevention/avoidance strategies aims at eliminating the sources of risks and reducing the possibility of their occurrence. one common action is not to perform the activities that may cause the risks. While such solution certainly prevents the risks from taking places, it will also lose any gains from the activities by taking the risk. In practice, the possible damages of risks are compared to the potential gains and, if it is not worthy to take the risks, related activities should be removed from the action items immediately.

Risk Mitigation If the risks can not be avoided, the consequences could be minimized by appropriate risk mitigation strategies to reduce the severity of the loss or the likelihood of the loss from occurring. This could be the most common strategy for managing risks because it is usually impossible to choose not to take actions on certain items. It normally refers to the additional efforts that need to be taken by management to lower the likelihood of the risk occurring and/or to minimize the impact on the process if the risk does occur. A successful risk mitigation plan normally include the following:

- Which departments should be included to develop and implement such strategies.
- The roles and responsibilities of each party involved.
- The timelines to execute the mitigation plan when risks take place.
- Signals to trigger the plan and the conditions present in order for risk level to be acceptable.
- Resources required to carry out the planned action items.

Risk Sharing Some risks can be shared among different parties. "A general principle of risk management is that risks should be the responsibility of those best able to control and manage them" [35]. Therefore, by sharing the risks, it can be decided in the early stage that which party should deal with the potential risks. This strategy requires all the parties to work together with a clear understanding on their roles and responsibilities.

Risk Transfer and Risk Retension Risk can be transferred to another party that accept it. Insurance is a common example of risk transfer strategies. Some risks can not be avoided, shared or transferred, or the costs of doing so would be too high. To take any actions for such risks often leads to little or no profit. Therefore, the companies may become risk takers.

Chapter 4

Case Study

The developed model needs to be validated with an industrial case for its accuracy and applicability. Assessing the quality of the model is called data validation. It should represent the real picture of risk management activities for Lean Six Sigma strategies. The factors adopted in the model ought to be able to internally reflect an organization's perspectives to support Lean Six Sigma strategy and externally as a benchmark tool to identify the best practices for management. The analytical procedure should transfer the data collected into the useful information so that decision-makers can use it as guideline to address potential risks.

The major purpose of the proposed model is to provide a practical tool for companies to evaluate, monitor, and manage the risk, and subsequently improve the performance of production process. The developed model will help determine the optimum solution to minimize potential risks. It should be able to demonstrate the effectiveness of the Lean Six Sigma initiatives. The model is expected to be part of the process improvement program that would help sustain the change within the organization. Therefore, it is critical to investigate the applicability of the proposed model and, specifically, whether it could work well in the practical scenario. The risk factors should be applicable to the general process initiatives. The data required would be readily available from existing system or require only limited amount of work to develop or calculate.

The following case study uses a study of selected manufacturing process to validate the developed risk model as it is used to enhance Lean Six Sigma initiatives. The general flow is described and followed by the discussion of how to apply Lean Six Sigma techniques to reduce the wastes within the system. The risk model is then used to identify the risks within the process and quantify their likelihoods and consequences and consequently calculate the risk indices. BN methods are utilized to provide an intelligent approach to compute the likelihoods in a dynamic environment.

4.1 Business Case

U.S. manufacturers are facing great challenges in the rapidly expanding global economy. A chief concern of U.S. manufacturers is the cheap labor and other associated costs offered by abroad competitors. The furniture industry is still labor-intensive where the product is fabricated by employees manually with the assistance of necessary tools and equipment. The manufacturers of residential wood furniture are, therefore, suffering an even greater challenge to stay competitive. By the year of 2002, U.S. residential industry has lost one-third of the market share to oversea competitors [57] and the imports have been rapidly increasing during the past decade (Figure 4.1).

This situation has forced U.S. manufacturers to rethink their business strategies in order to stay competitive in both domestic and global business. Compared to industries that more machine- or technology-oriented, furniture manufacturers are more struggling to compete with oversea competitors. The Lean Six Sigma techniques were originally used by automotive industry where the processes are heavily based on machine operations. However, the core philosophy, which is to reduce any non-value added activities or wastes in the manufacturing process, can be utilized in a much wider scope. As a matter of fact, it is very common to find their applications even in non-manufacturing industries such as service, health care and military. A number of researchers have carried out studies on people issues during the implementation of process improvement and it has been recognized that human factors play a critical role to the success of process improvement.

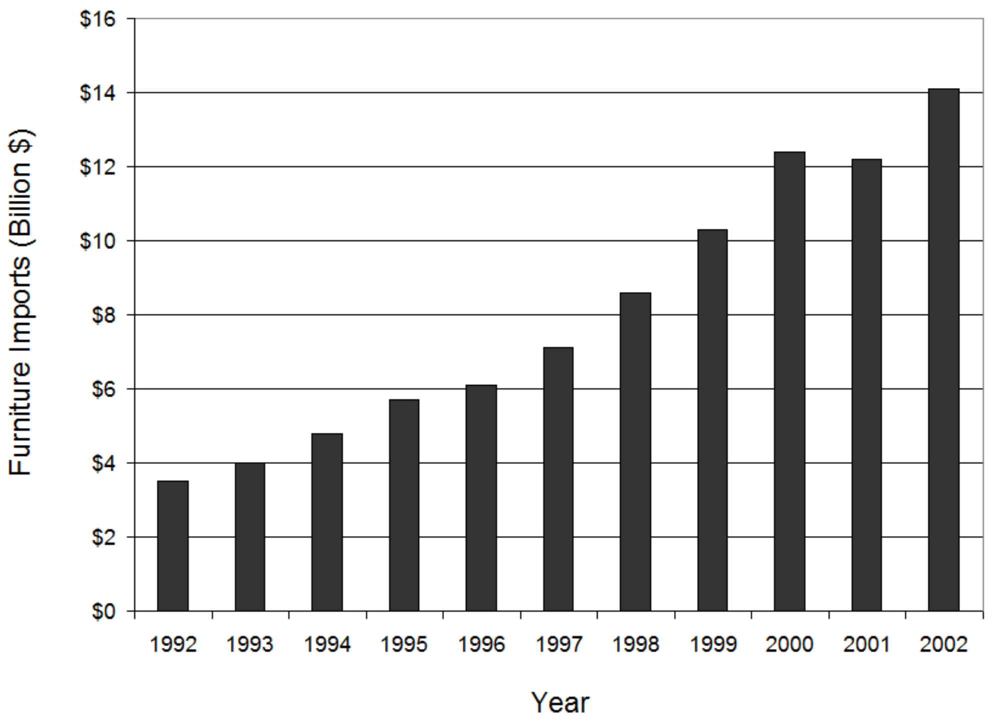


Figure 4.1: Total U.S. Furniture Imports

As a result, a number of furniture manufactures have started their journeys to apply Lean Six Sigma techniques to improve their production performance. These initiatives are normally great undertakings as they require the fundamental change of the entire organizational culture in stead of just certain operations or processes. Throughout the implementation, a great deal of non-value added activities can be identified and then eliminated. It has been commonly agreed that Lean Six Sigma strategies can bring the following benefits to the organization.

- Improve quality: After batch production is eliminated, there will be less opportunity to manufacture defects. The Lean Six Sigma techniques provide an effective way for the communication and help identify and eliminate the possible defects in an early stage.
- Reduce lead time: After the unnecessary steps are The streamlined process will significantly reduce the time taken from raw material to a quality final product.

- Reduce cost: The inventory will be reduced as single piece flow is implemented and the cost related to the non-value added activities can also be reduced.
- Enhances overall manufacturing flexibility: In a leaner flow environment, since we operate with less inventory and shorter lead times, more time can be spent on reacting to customer orders in an efficient and effective manner.
- Ensures a safer work environment: Less inventory means less clutter and a better lay out for equipment and tools. Also, since the standard work procedure is established, there is less opportunity for unexpected movements, which increase the chances of accidents.
- Improve financial capability: By uncovering and eliminating non-value added activities, the stock and in-process materials can be reduced and therefore reducing the capital used, increasing cash flow, and improving return on investment. As a result, the bottom line will be improved by reducing production costs.

However, the nature of the furniture manufacturing process, which relies heavily on the people, makes it more fragile to the potential risks when Lean Six Sigma techniques are implemented. Removal of safety buffer requires the minimal interruption of the flow due to issues related to materials and equipments. Another example is the imbalanced flow, which is especially usual when most of work is done by people. It has long been recognized that human performance has a substantial impact on the reliability of complex systems [3]. Modarres [3] further summarizes the limitations and difficulties in current methodologies of studying human reliability in the engineering system.

- Human behavior is a complex subject that cannot be described as a simple component in a system. Human performance can be affected by social, environmental, psychological, and physical factors that are difficult to quantify.
- Human actions cannot be considered to have binary success and failure states. There exist a full range of human interactions that make it impossible to develop an effective mathematical model for evaluation.
- There are more variations in the labor-oriented manufacturing process. For example, the process time taken to complete one task can never be consistent especially when there are great contents in each job.

- The most difficult problem is the lack of appropriate data on human behavior.

4.2 Business Plan

4.2.1 Current State

This case study introduces an assembly process to produce residential furniture. It is comprised of cutting, sewing, cushion stuffing, framing, and assembly. In a traditional manufacturing environment, these elements belong to separate departments. Because each department aims at maximizing their efficiency and productivity locally, weeks or even months of inventory are generated between departments. Besides, when a quality problem is discovered at the end of the process, which may have occurred at early stages of the process, it would already have been late and lead to missing the delivery date. The steps of production can be summarized into the following.

1. The fabric or leather is cut by computer-driven cutting machines that are loaded with the cutting programs. The cut fabric or leather is removed from the machine, sorted, marked, and stored for delivery to sewers.
2. The cut pieces of upholstery are delivered to the sewers, who work on industrial grade sewing machines, to stitch all pieces of the covers for the foam seats together. The empty cushion covers are then sent to the cataloguer, who stores the cushions for the upholsterer.
3. The frame is hand-constructed of planed, measured, shaped, and assembled wood by employees. Rigid frames are put together with nuts, bolts, nails, and/or staples. The framing is laborious work. The frame is sent to a holding area, where it will await further assembly.
4. Foam bodies for the upholstered parts (arm, back and seat) are sculpted from a rigid foam, such as polyurethane, by cutting, slicing, or shaping with electronic saws to conform with a desired profile.

5. Next is upholstery assembly, in which polyurethane foam, polyester fiberfill, die-cut fiberboard, and covers or seats are sent to the upholsterer. Edges are softened by gluing padding of some sort, often polyester fiberfill, to the hard edges of the foam. The air bubbles are sucked out of the foam bodies, thus compressing them. The foam bodies are then pushed into the sewn cushion in order to fill it out neatly. The upholstery covers are nailed and stapled to the seats and backs.
6. During final assembly, the backs and seats are assembled to the seat frame, the activating mechanism is attached to the frame, the decorative skirt is added (depending on the style of the recliner), and final inspection occurs.

The current state Value Stream Map (VSM) is illustrated in Figure 4.2. As discussed before, VSM is a valuable tool to uncover the non-value added activities in the system. It represents the material and information flow from the perspective of customer and identifies the excessive inventory, waiting, transportation, motion, unnecessary process, defects and overproduction.

4.2.2 Future State

The traditional way of manufacturing is designed to maximize the efficiency and productivity of each single machine individually. The cost is expected to be lowered by having the machines produce as many parts as possible. However, this approach has appeared to be inefficient and ineffective in converting materials to a quality product. First of all, it takes a long time to deliver the product to customers. One advantage provided by the domestic manufacturers is a quick communication with the customers. The customers can go online or step into any of the galleries to pick their favorite options including color, pattern, style, electronics, etc. However, it creates a lot of issues to manufacturers as there are much higher requirements on the process's capability and flexibility for production of greater varieties.

Secondly, a lot of quality issues exist in the system when each functional department focuses only on their own activities trying to get products pushed to the next area. As a

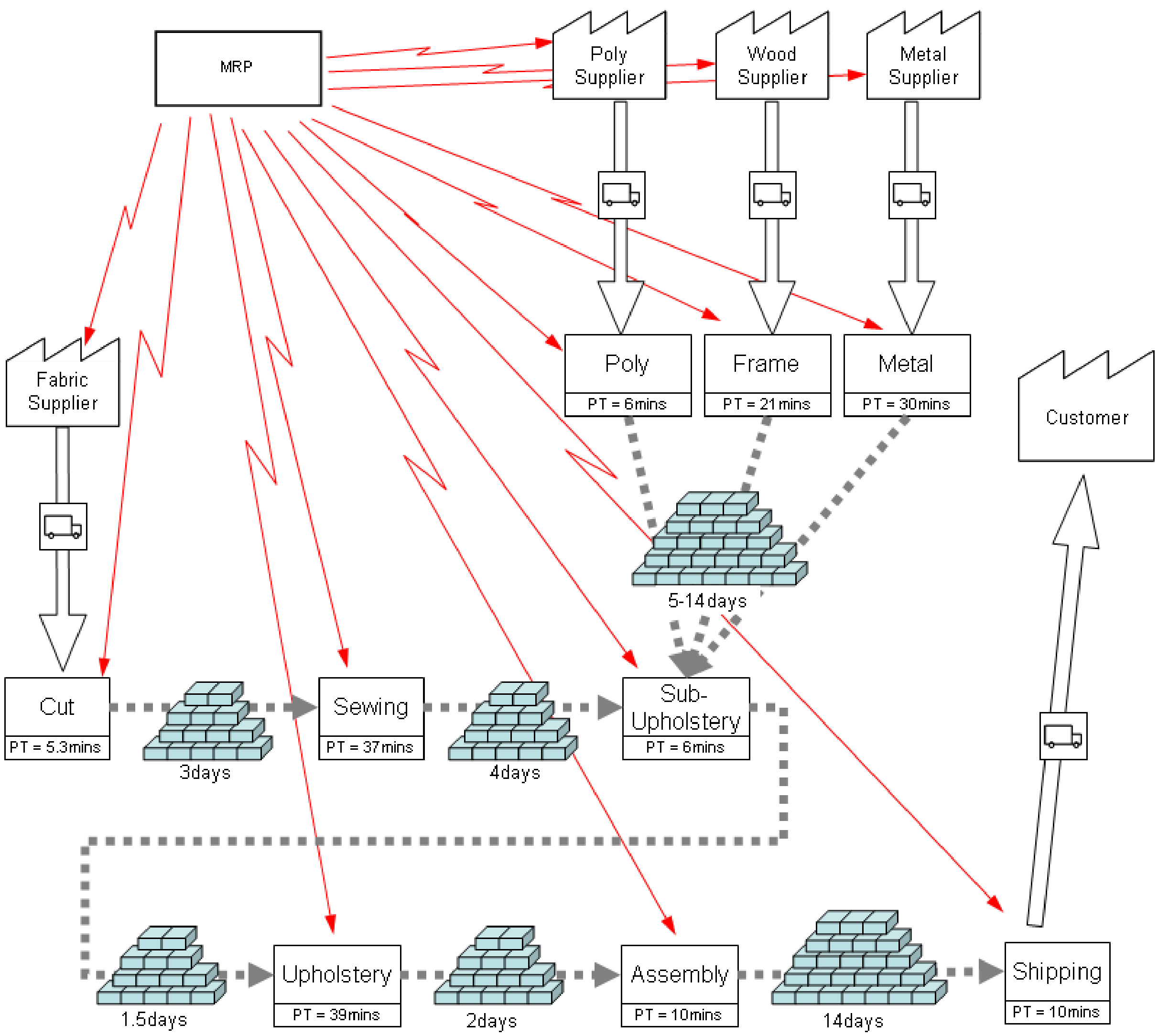


Figure 4.2: Current State Value Stream Map

result, the defects cannot be discovered until the end of the entire process. Till then, the defects may take significantly longer to fix it compared to if they can be found immediately. The lack of communication between the departments is another important reason why the classical manufacturing is not capable of meeting customer's demand in today's manufacturing environments.

The last but the least is the extensive inventory and unnecessary costs associated with it. When each department is trying to push the production with any consideration of what the downstream station actually needs, the buildup of inventory is unavoidable. Large amount of excess inventory often accumulate between the departments because of the batch processing. Inventory means cash, which is very important to an organization's financial performance. In addition, the products must be transported from one department to another, which is another major category of wastes in Lean manufacturing.

As mentioned above, there is a need of change in order for the organization to remain competitive advantages. The purpose of this process improvement initiative is to transfer traditional batch-and-queue method to cellular manufacturing. With this new method, a work cell manufactures the product starting with cushion stuffing all the way to completion. The work cell represents a new way of arranging stations, materials, and resources to improve the quality, speed and cost of the process. The design of the work cell can be summarized as follows:

1. Select products: The design of work cells is product-specific. Therefore, it is necessary to select which product or product family needs to be considered first to design the work cells. The same procedure can then be applied to other products.
2. Determine resource requirements: The work content that is included in the work cells needs to be specified in terms of the number of operators, machine requirements and other resources.
3. Design process and layout: The tasks are normally executed in a sequential manner. This step is to decide how to lay out the work stations.

4. Design supportive function: The necessary supportive functions are critical to the smooth operations of work cells. The major functions are material delivery system, maintenance program, scheduling, etc.

Figure 4.3 illustrates the future state of the process. The work cells will contain operations of sewing, framing, stuffing, upholstery, assembly and boxing. Due to the space and capacity constraints of cutting machine, the cutting operation is left out. Cellular manufacturing allows moving products through the entire process one piece at at time, at a rate based on the customers' orders.

The major benefit of having a work cell is its flexibility to accommodate spikes in the ordering processes. When there is order change, it takes less efforts to shift processes or employees. The one-piece flow production results in less inventory and quicker response to the customer. Because work stations are located adjacent to each other, the communication is much easier, which makes it possible to uncover the defects earlier. There are also ergonomic benefits due to the shorter travel distance and less twist motions.

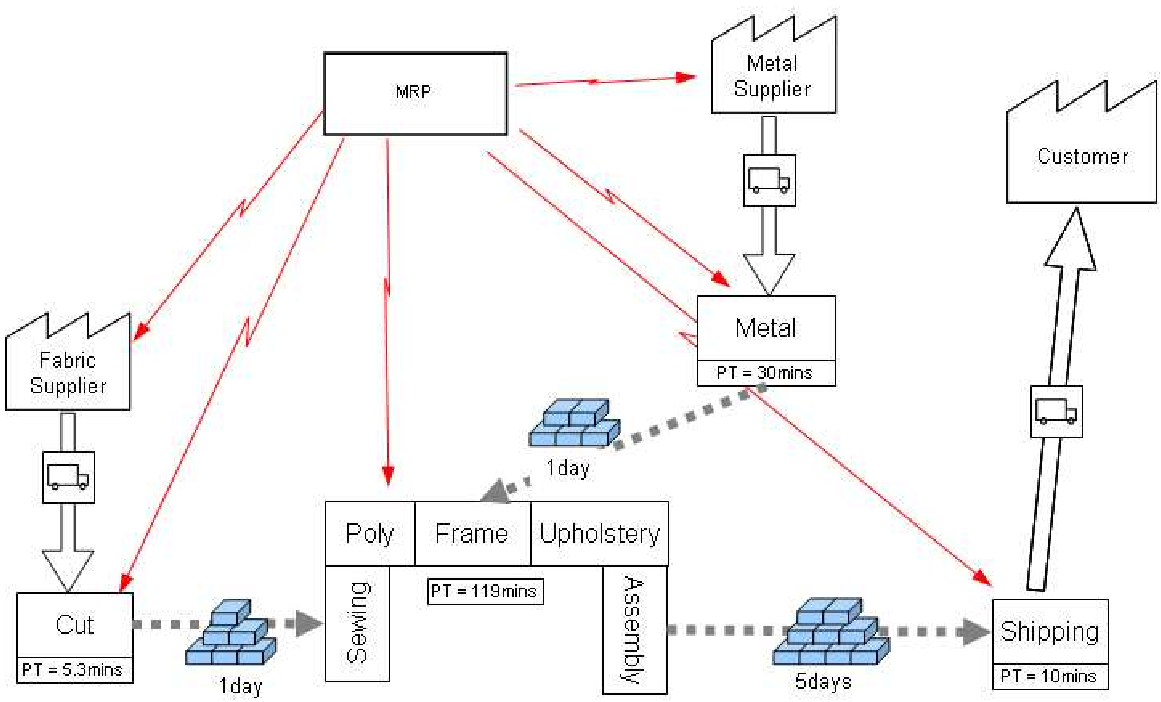


Figure 4.3: Future State Value Stream Map

4.2.3 Implementation Plan

The implementation of process improvement initiatives is based on the concept that there is sequential set of events: planning, creating the fundamental work environment for improvement, designing efficient flow through the shop floor, designing support systems to actually support production, reducing the variation in all designed processes, and developing systems that sustain improvement. As discussed earlier, the implementation of process improvement strategies requires fundamental change of the entire organization. The above mentioned steps ensure such change can be conducted in an efficient and effective manner. The Lean implementation scheme is therefore defined by the following sequence of events.

Planning The planning phase is associated with initiating the implementation through well-designed preparation. The process improvement strategies must be aligned with the overall business objectives. The first activity is the development of an improvement policy, which includes understanding the baseline of the process, developing metrics for evaluate the performance, and establishing a strategy for improvement. Value Stream Map (VSM) is used to analyze the current status of the manufacturing process and identify any potential improvement opportunities. Another important task to develop a culture that emphasizes the change within the organization, which includes reporting structure, resource allocation, and team development. A training and communication strategy needs also be developed during this stage.

Workplace This phase is associated with designing a workplace that enhance the implementation of process improvement initiatives. 5S principles (Sorting, Straightening, Shining, Standardizing, and Sustaining) is a common tool to provide an organized infrastructure in the manufacturing environment. It focuses on modifying the workplace and reducing variation in the manner that work is being performed to a point at which one explicitly understands the flow through the workplace. The activities include ensuring that the workplace is safe, the workplace is organized, the work is performed according to standard operating procedures, work can be managed by visual controls, and processes are mistake proofed to reduce chances of errors.

Flow One of the major drawbacks of the traditional manufacturing processes is the inefficient flow that creates non-value added activities and cause excessive costs. This phase is associated with developing the basis to flow product through the process in an efficient manner. The Takt time sets the pace time in which the product flow is expected to follow. The activities include

- Design the work cell or other appropriate layout that determines the locations and sequence of stations to promote a smooth flow for materials handling and product fabrication.
- Reduce setup time to allow a more efficient flow and higher flexibility in the case of product changeover.
- Design the process and balance the production line to match with Takt time. When the line is not able to be balanced, the concept of supermarket should be used.
- Develop one piece flow production that allows each station to manufacture product only when needed.
- Develop material and labor requirements for cellular design.
- Develop lean material delivery system, which should be able to ensure the on-time delivery of materials and parts to cell.

Support This phase is associated with designing the functional support systems to actually support the production systems. Such systems are critical to the success of process improvement. As a matter of fact, from the perspective of risk management, they are just as important as process design. The activities include scheduling system, maintenance, supplier development, production control, and training.

Consistency This phase is associated with reducing variation from design production and support processes. In order to make the process stay efficient in a long run, the variability must be reduced. Activities include defining variation, measuring variation, analyzing variation, improving processes by reducing variation, and controlling processes.

Sustain This phase is associated with sustain improvements and the continuous improvement effort. This has appeared to be the most critical yet difficult stage for the entire implementation of process improvement initiatives. Figure 4.4 provides a simplified visual for the strategy, given the understanding that each phase is not necessarily sequential and that there are overlaps and parallel processing of various phases.

4.3 Develop Risk-Informed Model

The transition of process improvement is normally a major undertaking that requires great resources and aims at potentially changing all aspects of the business. The benefits include not only to save costs and improve manufacturing process, but also to foster an organizational culture that makes the business more successful through the competition. While a well-planned program can certainly help avoid unnecessary problems during the implementation, a great range of risks can have impact on the implementation of process

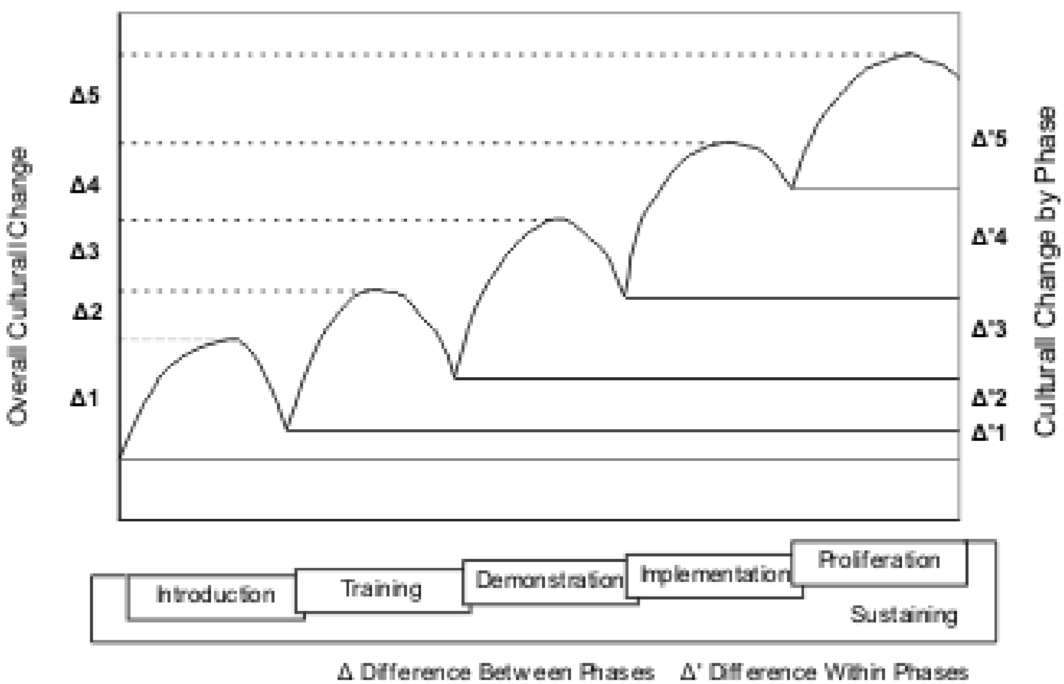


Figure 4.4: Overall Cultural Change in the Lean Implementation

improvement initiatives. Therefore, there is a need to develop a model to identify the possible risks, evaluate their impacts and subsequently develop risk treatment strategies to ensure the success of process improvement implementation. The developed model starts with a thorough investigation on the entire process to study what impact the results of process improvement strategies. The causal independence of the identified variables are illustrated and their probabilistic relationships are specified. Their overall effects are then evaluated with the consequences on the implementation.

4.3.1 Identify Risk Factors

As indicated earlier, the manufacturing system is quite complex. The first step to develop the risk-informed model is to identify the possible risk factors during the implementation of process improvement. In the manufacturing process present in the case study, the implementation of process improvement initiatives is carried out in the following steps.

- Planning
- Workplace
- Flow
- Supportive function
- Sustain

There exist a variety of factors for each step and through the entire process that could cause potential failures to the process improvement strategies. Table 4.1 summarizes the list of all risk factors that could exist.

Inadequate plan can lead to misalignment of process improvement strategies with overall business objectives. It is very important for the designer to thoroughly understand the current process and existing problems before selecting proper tools to tackle them. The reasons of change need to be communicated with the entire workforce. Well-designed workplace environment provides necessary infrastructure for process improvement. The wastes

Table 4.1: Risk Factors in Process

ID	RISK FACTORS
	PLAN
1	Conflict with overall business objective
2	Inappropriate improvement strategy
3	Insufficient plan
4	Insufficient communication
	IMPLEMENT
	Workplace
5	Insufficient 5S program
6	Insufficient visual control system
7	Insufficient standard operating procedure
8	Inadequate work instructions
9	Operational errors
	Flow
10	Imbalanced line
11	Capability of designed process
12	Insufficient skills/expertise to perform the task
13	Insufficient resources
14	Insufficient design
15	Design changes
	Supportive Functions
16	Demand change
17	Vendor-related issue
18	Machine availability
19	Lack of maintenance management system
20	Insufficient material supply
21	Quality and accuracy of material supply
	SUSTAIN
22	Insufficient training
23	Absenteeism
24	Employee turnover
25	Lack of responsibility and accountability

that are relatively obvious can also be uncovered through the workplace improvement. It helps gain employees' buy-in, which is the key to any change, and promote a better communication through the entire organization by providing a more organized and ergonomic environment.

One of the major purposes of process improvement is to streamline the process. Therefore, inefficient flow simply means failure. There are a variety of reasons that can impact the operating of processes. For example, a well-designed work cell requires an optimized configuration of resources. In other words, no extra resource is allowed in order to gain the benefits of cellular manufacturing. Therefore, if any resource is not provided, the entire system will be interrupted. Supportive functions are just as important. Maintenance program, for example, ensures the availability and reliability of machines because the focus of manufactures on delivery, quality and cost is highly dependent upon the proper functioning of physical assets within the organization.

At last, the most difficult step is to sustain the achievement of process improvement strategies. The necessary training program is required to ensure the knowledge and skill sets to perform the tasks. Absenteeism and employee turnover can severely affect the results of process improvement initiatives. In addition, how to foster a system that makes the concept of change part of the organizational culture is particularly important.

4.3.2 Develop Bayesian Network

Develop Dependency Diagram

The next step is to create the graphical model to represent the relationships between the identified risk factors. During the implementation of process improvement strategies, the occurrence of one event may have impact on the rest of the components in the system. Some components have more significant impact on the overall effectiveness of process improvement. For example, if the goal of process improvement is not aligned with the overall business objectives, the end results will most certainly lead to failures. Figure 4.5 illustrates the cause independence diagram for the risk factors selected in the previous section.

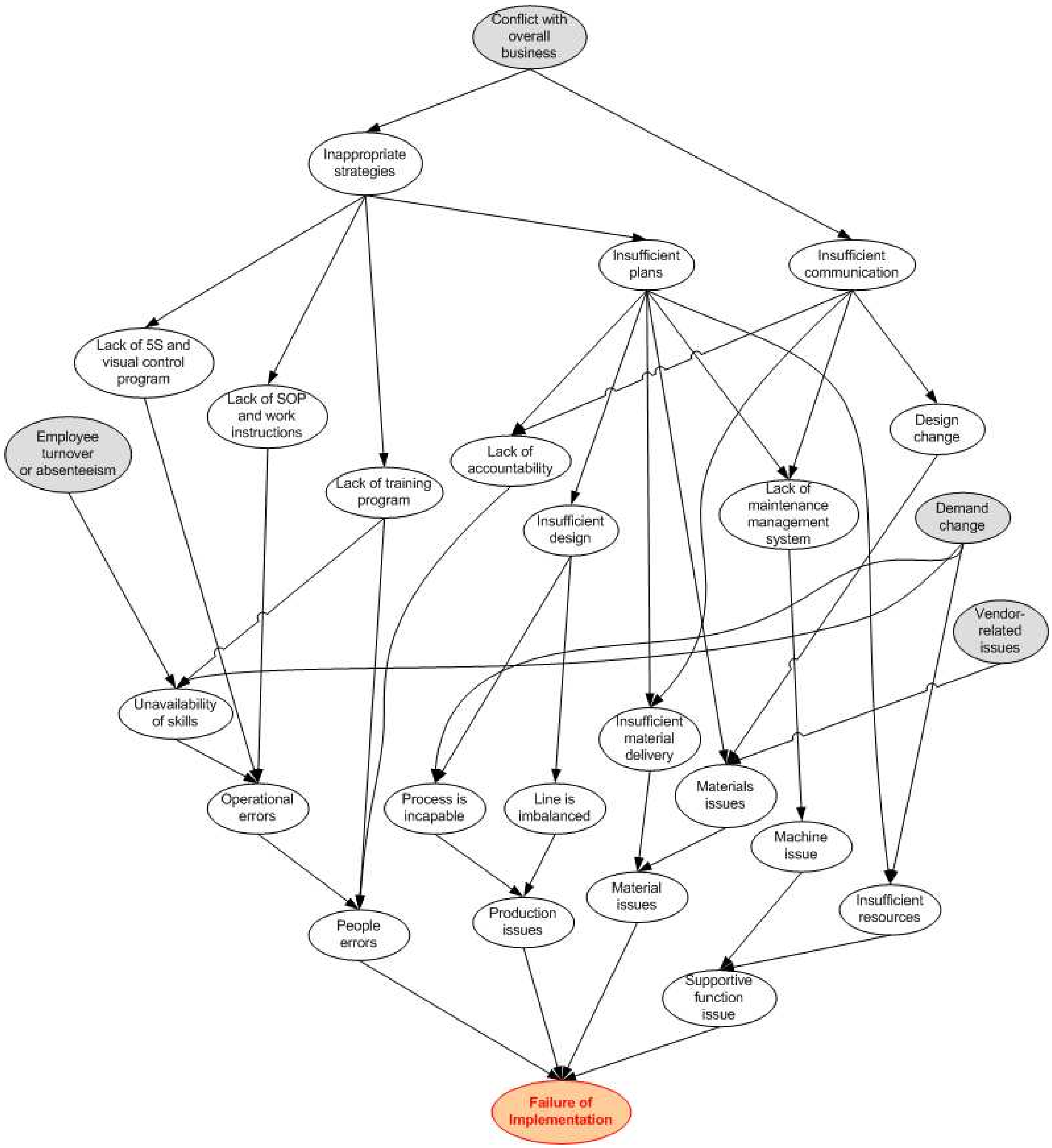


Figure 4.5: Causal Network

The purpose of the graphic model is to study these relationships between the components in the system. The procedure of cause and effect diagrams can be used to develop the graphic model. It help one think think through causes of a program thoroughly. Its major benefit is that we can consider all possible causes rather than just those that are the most obvious. A specialized team may need to formalized that include appropriate parties involved. A brainstorming is also a good approach to solve the problem. The exact problem needs to specified in detail and all the factors that may contribute to the problem are identified. For each of these factors, brainstorm possible causes of them. Where a cause is complex, it may be necessary to break it down into sub-causes of various levels.

In practice, the causality may not always be obvious. The developed model provides a communication language, which is easy for process improvement team to read. It is also a well-defined syntax to communicate with a computer for a detailed analysis.

Create BN Graphic Model

Once the dependency relationships have been identified for all the variables in the system, they need to be translated into the language of graphic model. Figure 4.6 illustrates the graphic model developed based on the dependency diagram. Notice that each variable is assigned an ID number for the convenience of programming. Table 4.2 populates those relations.

Define Conditional Probabilities

Once the diagram has been completed to represent the relevance and causality, the probability table needs to be created to represent the likelihood for given factors. The information needed is the conditional probability of the child node given the occurrence of the parent node. Table 4.3 provides the conditional probabilities for the case study. In order to keep them consistence, **True** is defined as the factor is successfully achieved and **False** represents the negative impact.

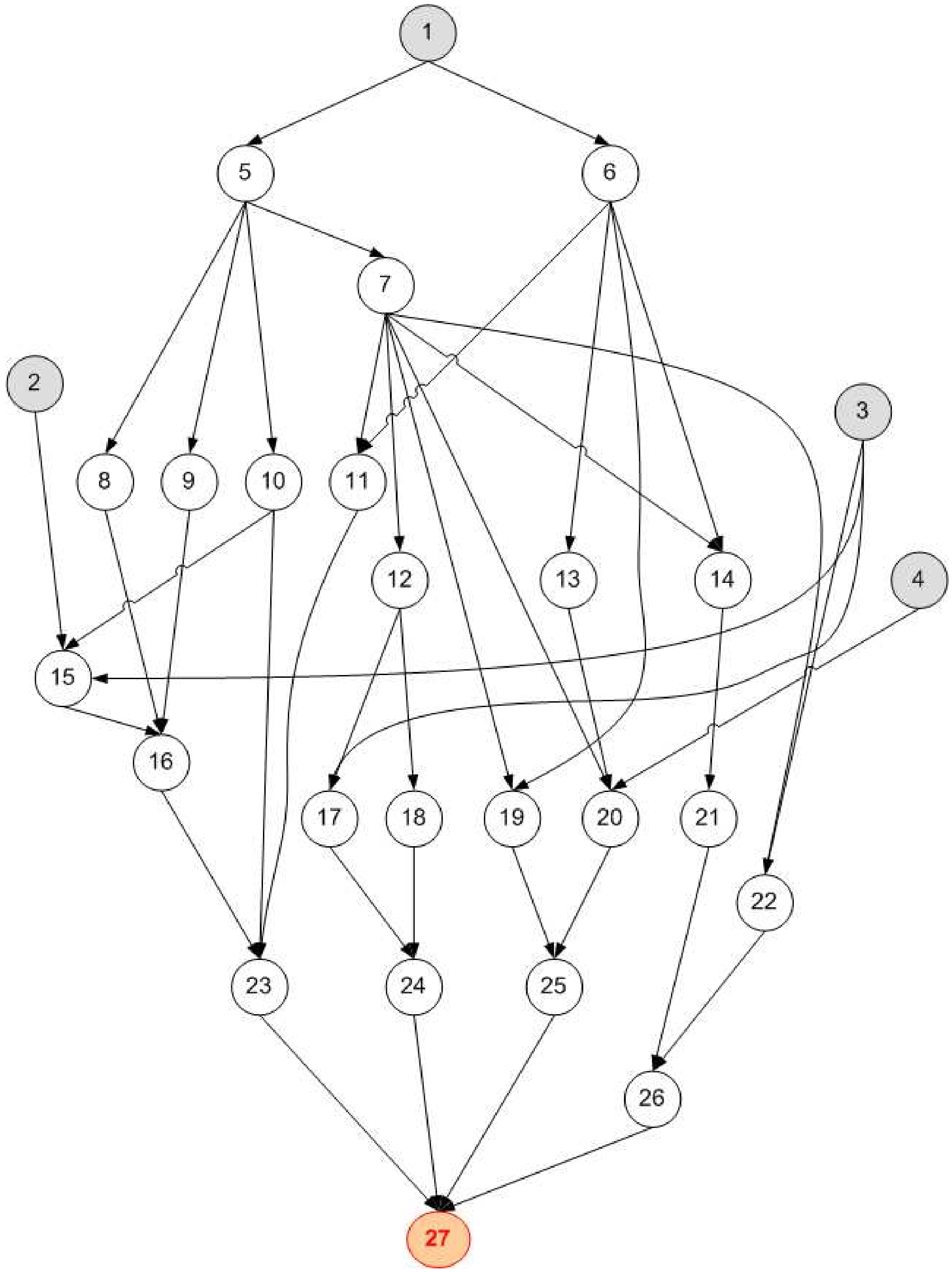


Figure 4.6: BN Graphic Model

Table 4.2: Dependency Relations of Variables

ID	RISK FACTORS	PREDECESSORS
(1)	Conflict with overall business objective	N/A
(2)	Employee turnover or absenteeism	N/A
(3)	Demand change	N/A
(4)	Vendor-related issue	N/A
(5)	Inappropriate improvement strategy	(1)
(6)	Insufficient communication	(1)
(7)	Insufficient plan	(5)
(8)	Insufficient 5S and visual control program	(5)
(9)	Insufficient SOP and work instructions	(5)
(10)	Insufficient training	(5)
(11)	Lack of responsibility and accountability	(6)(7)
(12)	Insufficient design	(7)
(13)	Design changes	(6)
(14)	Lack of maintenance management system	(6)(7)
(15)	Insufficient skills/expertise	(2)(3)(10)
(16)	Operational errors	(8)(9)(15)
(17)	Capability of designed process	(3)(12)
(18)	Imbalanced line	(12)
(19)	Insufficient material supply	(6)(7)
(20)	Material quality	(4)(7)(13)
(21)	Machine availability	(14)
(22)	Insufficient resources	(3)(7)
(23)	People issues	(10)(11)(16)
(24)	Production issues	(17)(18)
(25)	Material issues	(19)(20)
(26)	Supportive function issues	(21)(22)
(27)	Failure of implementation	(23)(24)(25)(26)

Table 4.3: Table of Conditional Probabilities

Factors	Predecessors			Probabilities	
(5) Strategy	(1)			T	F
	T			0.90	0.10
	F			0.01	0.99
(6) Communication	(1)			T	F
	T			0.80	0.20
	F			0.01	0.99
(7) Plan	(5)			T	F
	T			0.90	0.10
	F			0.01	0.99
(8) 5S and visual control	(5)			T	F
	T			0.75	0.25
	F			0.10	0.90
(9) SOP and work instructions	(5)			T	F
	T			0.75	0.25
	F			0.10	0.90
(10) Training program	(5)			T	F
	T			0.95	0.05
	F			0.10	0.90
(11) Accountability	(6)	(7)		T	F
	T	T		0.95	0.05
	T	F		0.50	0.50
	F	T		0.60	0.40
	F	F		0.05	0.95
(12) Insufficient design	(7)			T	F
	T			0.75	0.25
	F			0.10	0.90
(13) Design change	(6)			T	F
	T			0.85	0.15
	F			0.05	0.95
(14) Maintenance	(6)	(7)		T	F
	T	T		0.95	0.05
	T	F		0.50	0.50
	F	T		0.60	0.40
	F	F		0.05	0.95
(15) Skill/Expertise	(2)	(3)	(10)	T	F
	T	T	T	0.90	0.10
	T	T	F	0.80	0.20
	T	F	T	0.80	0.20
	T	F	F	0.60	0.40
	F	T	T	0.40	0.60
	F	T	F	0.35	0.65

continued on next page

Table 4.3: (Continued)

Factors	Predecessors			Probabilities	
	F	F	T	0.20	0.80
	F	F	F	0.10	0.90
(16)	(8)	(9)	(15)	T	F
Operational errors	T	T	T	0.85	0.15
	T	T	F	0.75	0.25
	T	F	T	0.70	0.30
	T	F	F	0.40	0.60
	F	T	T	0.70	0.30
	F	T	F	0.60	0.40
	F	F	T	0.60	0.40
	F	F	F	0.10	0.90
(17)	(3)	(12)		T	F
Process capability	T	T		0.85	0.15
	T	F		0.05	0.95
	F	T		0.90	0.10
	F	F		0.05	0.95
(18)	(12)			T	F
Imbalanced line	T			0.90	0.10
	F			0.05	0.95
(19)	(6)	(7)		T	F
Material supply	T	T		0.80	0.20
	T	F		0.70	0.30
	F	T		0.70	0.30
	F	F		0.40	0.60
(20)	(4)	(7)	(13)	T	F
Material quality	T	T	T	0.90	0.10
	T	T	F	0.80	0.20
	T	F	T	0.75	0.25
	T	F	F	0.70	0.30
	F	T	T	0.15	0.85
	F	T	F	0.10	0.90
	F	F	T	0.10	0.90
	F	F	F	0.10	0.90
(21)	(14)			T	F
Machine availability	T			0.90	0.10
	F			0.05	0.95
(22)	(3)	(7)		T	F
Resources	T	T		0.90	0.10
	T	F		0.40	0.60
	F	T		0.30	0.70
	F	F		0.05	0.95
(23)	(10)	(11)	(16)	T	F

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Table 4.3: (Continued)

Factors	Predecessors				Probabilities	
People issues	T	T	T		0.90	0.10
	T	T	F		0.80	0.20
	T	F	T		0.25	0.75
	T	F	F		0.20	0.80
	F	T	T		0.45	0.55
	F	T	F		0.40	0.60
	F	F	T		0.35	0.65
	F	F	F		0.01	0.99
(24)	(17)	(18)			T	F
Production issues	T	T			0.85	0.15
	T	F			0.35	0.65
	F	T			0.45	0.55
	F	F			0.10	0.90
(25)	(19)	(20)			T	F
Material issues	T	T			0.95	0.05
	T	F			0.30	0.70
	F	T			0.35	0.65
	F	F			0.05	0.95
(26)	(21)	(22)			T	F
Supportive function issues	T	T			0.90	0.10
	T	F			0.60	0.40
	F	T			0.40	0.60
	F	F			0.05	0.95
(27)	(23)	(24)	(25)	(26)	T	F
Implementation failure	T	T	T	T	0.95	0.05
	T	T	T	F	0.60	0.40
	T	T	F	T	0.70	0.30
	T	T	F	F	0.45	0.55
	T	F	T	T	0.35	0.65
	T	F	T	F	0.30	0.70
	T	F	F	T	0.35	0.65
	T	F	F	F	0.55	0.45
	F	T	T	T	0.30	0.70
	F	T	T	F	0.20	0.80
	F	T	F	T	0.20	0.80
	F	T	F	F	0.15	0.85
	F	F	T	T	0.10	0.90
	F	F	T	F	0.05	0.95
	F	F	F	T	0.10	0.90
	F	F	F	F	0.01	0.99

4.3.3 Risk Ranking

Probabilities Ranking from BN

The major purpose of having a risk model is to provide management with some insights on what they should focus on first given the limited resources. Therefore, how to rank potential risks becomes very important. Bayesian Network provides a quantitative approach to rank the risk factors based on the probabilities.

The rapid development of BN techniques has been accompanied by a number of BN software tools. In this study, we used *MSBNx* the package developed by Microsoft Research. *MSBNx* is " a component-based Windows application for creating, assessing, and evaluating Bayesian Networks" [58]. With the help of *MSBNx*, Figure 4.7 summarizes the unconditional probabilities computed based on the dependency relationships and quantitative parameters in the model. We can easily list the top five variables that yield the largest probabilities of undesirable outcomes.

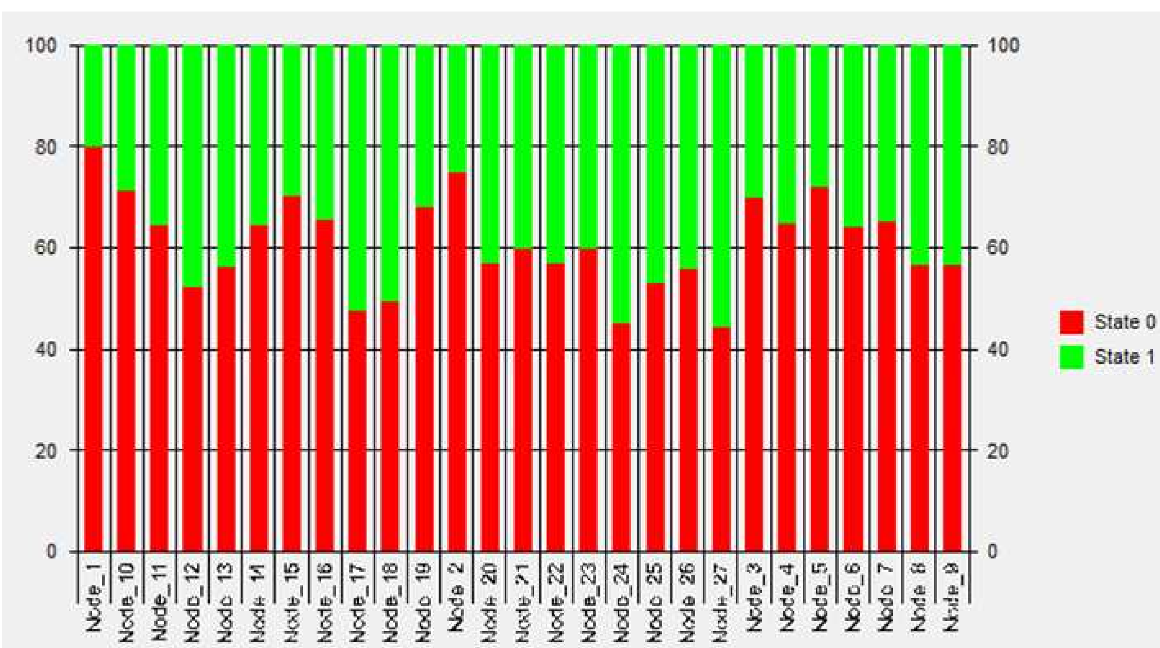


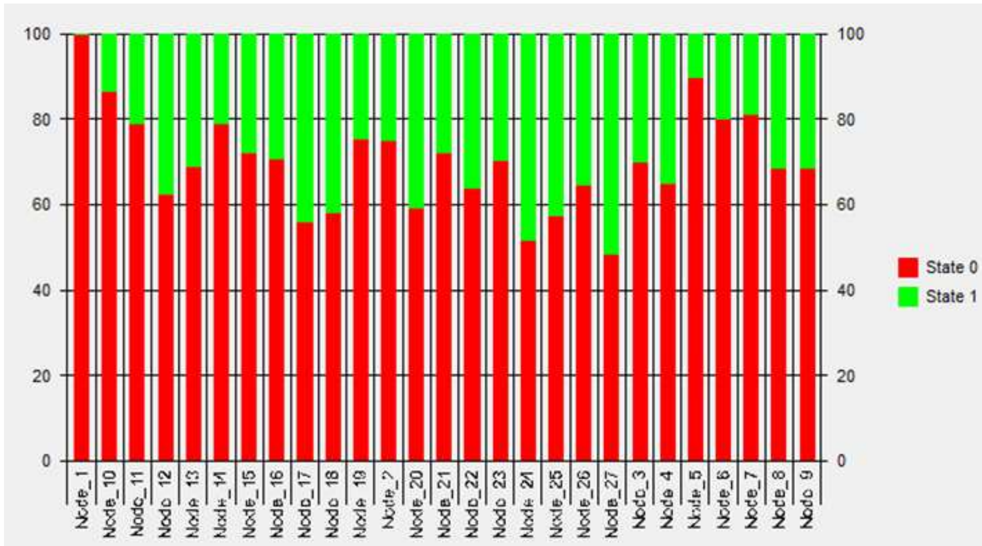
Figure 4.7: Unconditional Probabilities of All Events

- Node 17: Incapable designed process (52.28%)
- Node 18: Imbalanced line (50.44%)
- Node 12: Insufficient design (47.58%)
- Node 13: Design changes (43.64%)
- Node 22: Insufficient resources (42.77%)

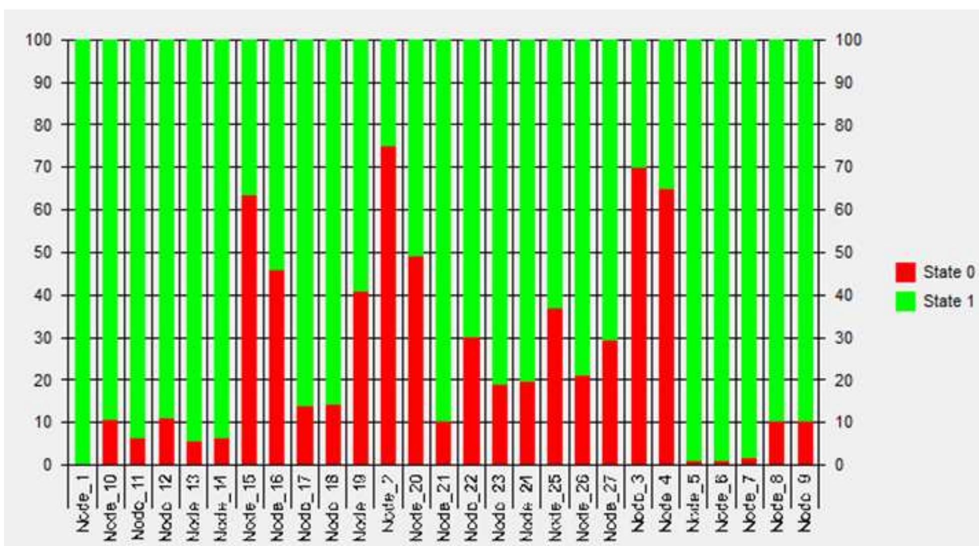
The major benefit of BN technique is to perform a statistical inference, or model evaluation, to update probabilities of certain variables given the information known about other factors. When the new evidence is observed, it can be applied to a Bayesian model by changing the state of given factors. *MSBNx* or any other BN software packages will then perform a mathematical analysis to compute the probabilities of all other variables. In doing so, the posterior probabilities regarding the system can be adjusted accordingly to reflect the levels of belief computed in light of the new evidence. For example, Figure 4.8(a) summarizes the results. If it is evident that the Lean Six Sigma strategies are aligned with the overall business goals, the probabilities of all the events may change based on the new evidence. The top five variables then become

- Node 17: Incapable designed process (43.86%)
- Node 18: Imbalanced line (41.69%)
- Node 20: Material quality (40.69%)
- Node 12: Insufficient design (37.29%)
- Node 22: Insufficient resources (36.03%)

On the other hand, we may also be interested in the scenario when the Lean Six Sigma strategy is conflicted with the business goals (Figure 4.8(b)), the top five factors can be changed to the following. The factors that are related to whether Lean Six Sigma is conflicted with the business have risen to the top critical factors. In addition, design change and maintenance also appear very important, which may not be that obvious to a lot of people.



(a)



(b)

Figure 4.8: (a) Conditional probabilities of all events given event 1 is favorable. (b) Conditional probabilities of all events given even 1 is unfavorable.

- Node 5: Inappropriate improvement strategy (99.00%)
- Node 6: Insufficient communication(99.00%)
- Node 7: Insufficient plan (98.11%)
- Node 13: Design change (94.20%)
- Node 14: Maintenance (93.51%)

As we can see in the figures, if the Lean Six Sigma is aligned with the overall business objectives, the probabilities of failures drop. However, if there is conflict, the probabilities of failures will increase significantly. In addition, some factors appear to be more likely to happen when the new evidence is discovered. In terms of likelihood, the rank of risk factors can be changed.

Risk Index

Table 4.4 provide the ranking of consequences utilized in this case study, which is provided by the subject matter experts who are familiar with the production process. With this information, we will be able to calculate the risk indices that incorporate both likelihoods and consequences. Table 4.5 calculated the risk indices for all the risk factors that incorporate information on both likelihoods and consequences. When certain risk factors are not considered, the S_{ij} is given as 0.

Table 4.4: Consequence Ranking

Ranking	Categories	Description
5	Extreme	The project will fail
4	Major	Critical event, potential for major costs and damages
3	Moderate	Large impact, but can be managed
2	Minor	Minor impact that can be managed through routine procedure
1	Insignificant	The risks can be ignored

Table 4.5: Results of Risk Analysis

ID	RISK FACTORS	S_{ij}	P_{ij}	C_{ij}	R_{ij}
	PLAN				
1	Conflict with overall business objective	1	0.20	5	1.00
2	Inappropriate improvement strategy	1	0.28	4	1.12
3	Insufficient plan	1	0.35	5	1.75
4	Insufficient communication	1	0.36	4	1.44
	IMPLEMENT				
	Workspace				
5	Insufficient 5S program	1	0.43	2	0.86
6	Insufficient visual control system	1	0.43	2	0.86
7	Insufficient standard operating procedure	1	0.43	4	1.72
8	Inadequate work instructions	1	0.43	4	1.72
9	Operational errors	1	0.34	3	1.02
	Flow				
10	Imbalanced line	1	0.50	4	2.00
11	Capability of designed process	1	0.52	5	1.60
12	Insufficient skills/expertise to perform the task	1	0.30	4	1.20
13	Insufficient resources	1	0.43	4	1.72
14	Insufficient design	1	0.48	4	1.92
15	Design changes	1	0.44	5	2.20
	Supportive Functions				
16	Demand change	0	0.30	4	0.00
17	Vendor-related issue	1	0.35	2	0.70
18	Machine availability	1	0.40	4	1.60
19	Lack of maintenance management system	1	0.35	2	0.70
20	Insufficient material supply	1	0.32	3	0.96
21	Quality and accuracy of material supply	1	0.43	3	1.29
	SUSTAIN				
22	Insufficient training	1	0.29	5	1.40
23	Absenteeism	1	0.25	3	0.75
24	Employee turnover	0	0.25	5	0.00
25	Lack of responsibility and accountability	1	0.35	4	1.40

Risk Matrix

Once the risk indices are determined for each risk factor, they can be used with the risk matrix to define how each risk factor should be treated. Figure 4.9 provides the risk matrix for the given case study. The general strategy for each categories is described as follows:

- **Extreme area**: Detailed risk treatment action is required.
- **Problem area**: Risks in this area have high likelihoods, but moderate to low impacts. Treatment actions can often be directed to improving management systems and procedures. This area typically receives a lot of management attention because of the high frequency and may result in an over-allocation of resources.
- **Catastrophe area**: Risks in this area have low likelihoods but potentially high impacts. Effective preparation and crisis management or contingency plans are often valuable options for the catastrophic residual risk.
- **Routine area**: Risks in this area can often be managed by standard processes, systems and procedures, or on an ad hoc basis.

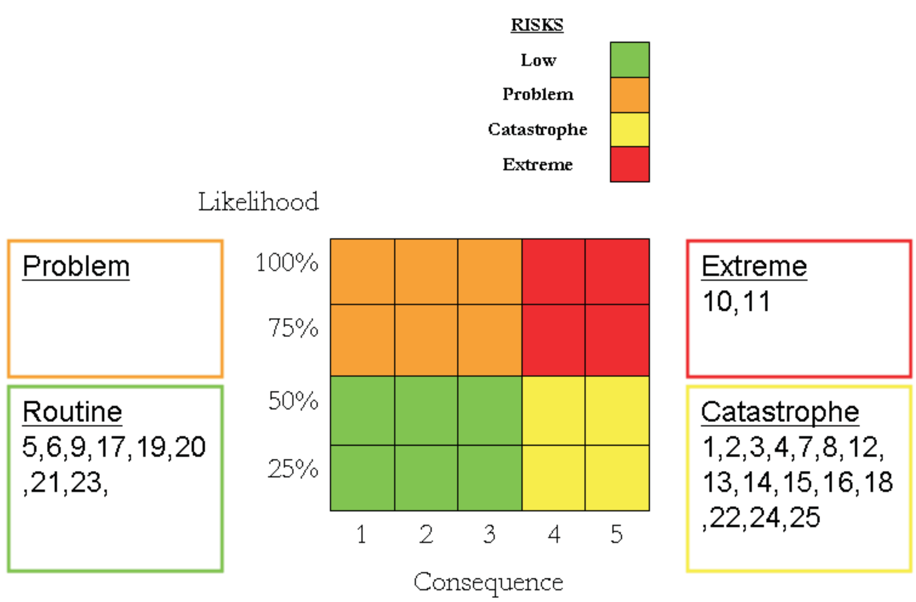


Figure 4.9: Results of Risk Ranking Metrics

Chapter 5

Conclusions

5.1 Summary of Findings

The improvement of a production process cannot succeed without considering potential risks caused by various uncertainties in the system. The purpose of this study is to develop a methodology of risk evaluation for auditing current system behavior and minimizing risk exposure in an efficient and effective manner. The developed model is validated through the case study in terms of its applicability in practice and compatibility to overall decision-making system. The following major conclusions can be drawn from the empirical validation carried out by this study.

Conclusion 1: The BN risk model provides insights to ensure the success of Lean Six Sigma.

The model has been applied to a case study of manufacturing organizations that are undergoing major transition from traditional manufacturing to Lean Six Sigma philosophy. Such major change leads to a very complex system that involves a great number of uncertain variables. With so many risk factors that can impact the success of the transition, it is difficult for management to determine which one(s) have the most impact and should be focused on first. BN risk model allows them to quantify the likelihoods and consequences of all the risk factors and therefore to prioritize the efforts to reduce risks to ensure the success of Lean Six Sigma. As the risk factors are selected from a comprehensive list of all possible risks related to Lean Six Sigma, the inclusive coverage is assured to provide a thorough evaluation.

Conclusion 2: The BN risk model provides an effective approach to utilize expert knowledge within the system.

The success of Lean Six Sigma hinges upon the development of a culture that embraces change. The foundation in developing such a culture is the human asset of an organization. However, a lot of expert knowledge focused on only limited areas. For example, each subject matter expert can normally provide detailed information of the operations they are working on and present a fairly good estimate on the probability of certain events. However, it can often lead to the local optimization without considering the entire system. With the help of BN method, the expert knowledge can be best utilized to provide a systematic and quantitative estimates for the variables of interests.

Conclusion 3: The BN risk model provides an efficient and effective method to optimize resource allocation for risk reduction efforts.

With the help of BN tools available for both academia and industry, the developed model approves to be practically easy to use. The application of expert knowledge has ensured that the risk factors that are relevant to the Lean Six Sigma implementation. The BN risk model achieves the balance of results reliability and resource efficiency. It requires limited resources for one organization or a trained individual to obtain the data needed for the model, which has tremendously reduced the labor work, cost, time and other necessary resources. Therefore, the application of model can be completed with satisfactory results in a time-efficient and cost-effective manner.

The BN risk model introduces a new approach to integrate risk management strategy with the objectives of Lean Six Sigma initiatives and translate such strategy to quantifiable measures. Both likelihood and consequence indicators are included, where consequence measures are aligned with business strategy and likelihood measures provide guidance for risk treatment strategies.

The BN risk model utilizes quantitative analysis to provide intelligent insight through the proposed model and enables management to track down the performance of process improvement implementation and identify the root causes of current problems. The feature provides great advantages for practitioners as the ultimate goal is to recognize the strengths and weaknesses and identify opportunities for improvement.

5.2 Benefits of The Developed Model

The developed risk-informed model aims at providing a practical tool for manufacturing organizations to evaluate, monitor, and manage the risk, and thus improve the performance of the production process. This model is expected to be a major component of the decision-making toolbox that would help determine the optimum solution to minimize potential risks. The potential applications of the risk-informed model can be summarized as follows:

(1) The risk-informed model provides an integrated and comprehensive examination of a broad set of design and operational features of a complex manufacturing system. This provides a solid infrastructure for risk analysis. A thorough and accurate understanding of the system is required for developing an approach to investigate, monitor, control and minimize the risks.

(2) The BN risk model provides a process for the explicit consideration of uncertainties that exist throughout the entire system. It could be used to estimate the level of risk exposure one system can face given the existing knowledge. It is especially useful when there is a great deal of uncertainties involved from both external and internal environment.

(3) The BN risk model model provides insights on the possibilities of achieving success when a new product or process is to be launched. By collecting data and analyzing the potential impacts, one can predict the possible operational risks that could affect the entire process. Through selected risk-reduction tools, certain risks are expected to be reduced to the minimal level with the least amount of efforts.

(4) The BN risk model model provides a model for incorporating operating experience with the mathematical formulation of complex system. It also allows dynamically updating risk estimates for risk monitor and control. The developed model quantifies uncertainties exposed in the engineering process by applying appropriate mathematical formulation. As a result, the risk factors could be ranked and the improvement opportunities could be prioritized according to their importance.

(5) The BN risk model model enables the organization to estimate the potential risks before any major change is implemented. Today's manufacturers are striving for implementing all possible methodologies to improve their performance. These initiatives could possibility increase the risk for the entire system. By performing appropriate risk analysis, one should be able to attain information on whether the improvement initiatives could put the organization into to higher risk.

(6) The BN risk model model could be used to benchmark best practice. Benchmark is a process to discover the strength and weakness of an organization by comparing certain variables with the best performance or the strongest competitors in the industry. Knowing the best methodologies or minimizing potential risks could certainly help one select appropriate risk management tools.

(7) The BN risk model model permits the analysis of sensitivity analysis. When a given variable or attribute is changed, one should be able to see the impact on the overall risk value. This is important to an engineering system when one organization needs to evaluate various alternatives to determine the best solution.

5.3 Concluding Remarks

This dissertation intends to explore a different point of view in how to enhance the success of Lean Six Sigma initiatives. That is to develop a BN risk model to evaluate, control and reduce the potential risks that exist during the course of process improvement implementation. Extant risk management techniques and statistical analysis, particularly Bayesian network, were utilized to identify the risks and quantify their impacts, which provides both theoretical and managerial implications.

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Appendix

Computation of Probabilities in BN Example

Marginal Probabilities

$$\begin{aligned}
Pr(E = T) &= 0.75 \\
Pr(E = F) &= 0.25
\end{aligned}$$

$$\begin{aligned}
Pr(I = T) &= Pr(I = T|E = T) \times Pr(E = T) \\
&\quad + Pr(I = T|E = F) \times Pr(E = F) \\
&= 0.65 \times 0.75 + 0.05 \times 0.25 = 0.4875 + 0.0125 = 0.50 \\
Pr(I = F) &= Pr(I = F|E = T) \times Pr(E = T) \\
&\quad + Pr(I = F|E = F) \times Pr(E = F) \\
&= 0.35 \times 0.75 + 0.95 \times 0.25 = 0.2625 + 0.2375 = 0.50
\end{aligned}$$

$$\begin{aligned}
Pr(N = T) &= Pr(N = T|E = T) \times Pr(E = T) \\
&\quad + Pr(N = T|E = F) \times Pr(E = F) \\
&= 0.90 \times 0.75 + 0.40 \times 0.25 = 0.675 + 0.1 = 0.775 \\
Pr(N = F) &= Pr(N = F|E = T) \times Pr(E = T) \\
&\quad + Pr(N = F|E = F) \times Pr(E = F) \\
&= 0.10 \times 0.75 + 0.60 \times 0.25 = 0.075 + 0.15 = 0.225
\end{aligned}$$

$$Pr(P = T) = \sum_{e,i,n} Pr(E = e, I = i, N = n, P = T)$$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	T(0.85)	$0.75 \times 0.65 \times 0.90 \times 0.85 = 0.3729$
T(0.75)	T(0.65)	F(0.10)	T(0.25)	$0.75 \times 0.65 \times 0.10 \times 0.25 = 0.0122$
T(0.75)	F(0.35)	T(0.90)	T(0.10)	$0.75 \times 0.35 \times 0.90 \times 0.10 = 0.0236$
T(0.75)	F(0.35)	F(0.10)	T(0.01)	$0.75 \times 0.35 \times 0.10 \times 0.01 = 0.0003$
F(0.25)	T(0.05)	T(0.40)	T(0.85)	$0.25 \times 0.05 \times 0.40 \times 0.85 = 0.0043$
F(0.25)	T(0.05)	F(0.60)	T(0.25)	$0.25 \times 0.05 \times 0.60 \times 0.25 = 0.0019$
F(0.25)	F(0.95)	T(0.40)	T(0.10)	$0.25 \times 0.95 \times 0.40 \times 0.10 = 0.0095$
F(0.25)	F(0.95)	F(0.60)	T(0.01)	$0.25 \times 0.95 \times 0.60 \times 0.01 = 0.0014$
				$\sum = 0.4261$

$Pr(P = F) = \sum_{e,i,n} Pr(E = e, I = i, N = n, P = F)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	F(0.15)	$0.75 \times 0.65 \times 0.90 \times 0.15 = 0.0658$
T(0.75)	T(0.65)	F(0.10)	F(0.75)	$0.75 \times 0.65 \times 0.10 \times 0.75 = 0.0366$
T(0.75)	F(0.35)	T(0.90)	F(0.90)	$0.75 \times 0.35 \times 0.90 \times 0.90 = 0.2126$
T(0.75)	F(0.35)	F(0.10)	F(0.99)	$0.75 \times 0.35 \times 0.10 \times 0.99 = 0.0260$
F(0.25)	T(0.65)	T(0.40)	F(0.15)	$0.25 \times 0.65 \times 0.40 \times 0.15 = 0.0008$
F(0.25)	T(0.75)	F(0.60)	F(0.75)	$0.25 \times 0.65 \times 0.60 \times 0.75 = 0.0056$
F(0.25)	F(0.35)	T(0.40)	F(0.90)	$0.25 \times 0.35 \times 0.40 \times 0.90 = 0.0855$
F(0.25)	F(0.35)	F(0.60)	F(0.99)	$0.25 \times 0.35 \times 0.60 \times 0.99 = 0.1411$
				$\sum = 0.5739$

Joint Probabilities

$Pr(P = T, E = T) = \sum_{i,n} Pr(E = T, I = i, N = n, P = T)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	T(0.85)	$0.75 \times 0.65 \times 0.90 \times 0.85 = 0.3729$
T(0.75)	T(0.65)	F(0.10)	T(0.25)	$0.75 \times 0.65 \times 0.10 \times 0.25 = 0.0122$
T(0.75)	F(0.35)	T(0.90)	T(0.10)	$0.75 \times 0.35 \times 0.90 \times 0.10 = 0.0236$
T(0.75)	F(0.35)	F(0.10)	T(0.01)	$0.75 \times 0.35 \times 0.10 \times 0.01 = 0.0003$
				$\sum = 0.4090$

$Pr(P = T, E = F) = \sum_{n,p} Pr(E = e, I = i, N = T, P = T)$

E	I	N	P	Pr
F(0.25)	T(0.05)	T(0.40)	T(0.85)	$0.25 \times 0.05 \times 0.40 \times 0.85 = 0.0043$
F(0.25)	T(0.05)	F(0.60)	T(0.25)	$0.25 \times 0.05 \times 0.60 \times 0.25 = 0.0019$
F(0.25)	F(0.95)	T(0.40)	T(0.10)	$0.25 \times 0.95 \times 0.40 \times 0.10 = 0.0095$
F(0.25)	F(0.95)	F(0.60)	T(0.01)	$0.25 \times 0.95 \times 0.60 \times 0.01 = 0.0014$
				$\sum = 0.0171$

$Pr(P = T, I = T) = \sum_{e,i,n} Pr(E = e, I = T, N = n, P = T)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	T(0.85)	$0.75 \times 0.65 \times 0.90 \times 0.85 = 0.3729$
T(0.75)	T(0.65)	F(0.10)	T(0.25)	$0.75 \times 0.65 \times 0.10 \times 0.25 = 0.0122$
F(0.25)	T(0.05)	T(0.40)	T(0.85)	$0.25 \times 0.05 \times 0.40 \times 0.85 = 0.0043$
F(0.25)	T(0.05)	F(0.60)	T(0.25)	$0.25 \times 0.05 \times 0.60 \times 0.25 = 0.0019$
				$\sum = 0.3913$

$Pr(P = T, I = F) = \sum_{e,i,n} Pr(E = e, I = F, N = n, P = T)$

E	I	N	P	Pr
T(0.75)	T(0.35)	T(0.90)	T(0.10)	$0.75 \times 0.35 \times 0.90 \times 0.10 = 0.0236$
T(0.75)	T(0.35)	F(0.10)	T(0.01)	$0.75 \times 0.35 \times 0.10 \times 0.01 = 0.0003$
F(0.25)	T(0.95)	T(0.40)	T(0.10)	$0.25 \times 0.95 \times 0.40 \times 0.10 = 0.0095$
F(0.25)	T(0.95)	F(0.60)	T(0.01)	$0.25 \times 0.95 \times 0.60 \times 0.01 = 0.0014$
				$\sum = 0.0348$

$Pr(P=T, N=T) = \sum_{e,i,n} Pr(E=e, I=i, N=T, P=T)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	T(0.85)	$0.75 \times 0.65 \times 0.90 \times 0.85 = 0.3729$
T(0.75)	F(0.35)	T(0.90)	T(0.10)	$0.75 \times 0.35 \times 0.90 \times 0.10 = 0.0236$
F(0.25)	T(0.05)	T(0.40)	T(0.85)	$0.25 \times 0.05 \times 0.40 \times 0.85 = 0.0043$
F(0.25)	F(0.95)	T(0.40)	T(0.10)	$0.25 \times 0.95 \times 0.40 \times 0.10 = 0.0095$
				$\sum = 0.4103$

$Pr(P=T, N=F) = \sum_{e,i,n} Pr(E=e, I=i, N=F, P=T)$

E	I	N	P	Pr
T(0.75)	T(0.65)	F(0.10)	T(0.25)	$0.75 \times 0.65 \times 0.10 \times 0.25 = 0.0122$
T(0.75)	F(0.35)	F(0.10)	T(0.01)	$0.75 \times 0.35 \times 0.10 \times 0.01 = 0.0003$
F(0.25)	T(0.05)	F(0.60)	T(0.25)	$0.25 \times 0.05 \times 0.60 \times 0.25 = 0.0019$
F(0.25)	F(0.95)	F(0.60)	T(0.01)	$0.25 \times 0.95 \times 0.60 \times 0.01 = 0.0014$
				$\sum = 0.0158$

$Pr(P=F, E=T) = \sum_{i,n} Pr(E=T, I=i, N=n, P=F)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	F(0.15)	$0.75 \times 0.65 \times 0.95 \times 0.15 = 0.0658$
T(0.75)	T(0.65)	F(0.10)	F(0.75)	$0.75 \times 0.65 \times 0.10 \times 0.75 = 0.0366$
T(0.75)	F(0.35)	T(0.90)	F(0.90)	$0.75 \times 0.35 \times 0.90 \times 0.90 = 0.2126$
T(0.75)	F(0.35)	F(0.10)	F(0.99)	$0.75 \times 0.35 \times 0.10 \times 0.99 = 0.0260$
				$\sum = 0.3410$

$Pr(P = F, E = F) = \sum_{n,p} Pr(E = e, I = i, N = T, P = F)$

E	I	N	P	Pr
F(0.25)	T(0.05)	T(0.40)	F(0.15)	$0.25 \times 0.05 \times 0.40 \times 0.15 = 0.0008$
F(0.25)	T(0.05)	F(0.60)	F(0.75)	$0.25 \times 0.05 \times 0.60 \times 0.75 = 0.0056$
F(0.25)	F(0.95)	T(0.40)	F(0.90)	$0.25 \times 0.95 \times 0.40 \times 0.90 = 0.0855$
F(0.25)	F(0.95)	F(0.60)	F(0.99)	$0.25 \times 0.95 \times 0.60 \times 0.99 = 0.1411$
				$\sum = 0.2330$

$Pr(P = F, I = T) = \sum_{e,i,n} Pr(E = e, I = F, N = n, P = F)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	F(0.15)	$0.75 \times 0.65 \times 0.90 \times 0.15 = 0.0658$
T(0.75)	T(0.65)	F(0.10)	F(0.75)	$0.75 \times 0.65 \times 0.10 \times 0.75 = 0.0366$
F(0.25)	T(0.05)	T(0.40)	F(0.15)	$0.25 \times 0.05 \times 0.40 \times 0.15 = 0.0008$
F(0.25)	T(0.05)	F(0.60)	F(0.75)	$0.25 \times 0.05 \times 0.60 \times 0.75 = 0.0056$
				$\sum = 0.1088$

$Pr(P = F, I = F) = \sum_{e,i,n} Pr(E = e, I = F, N = n, P = F)$

E	I	N	P	Pr
T(0.75)	F(0.35)	T(0.90)	F(0.90)	$0.75 \times 0.35 \times 0.90 \times 0.90 = 0.2126$
T(0.75)	F(0.35)	F(0.10)	F(0.99)	$0.75 \times 0.35 \times 0.10 \times 0.99 = 0.0260$
F(0.25)	F(0.95)	T(0.40)	F(0.90)	$0.25 \times 0.95 \times 0.40 \times 0.90 = 0.0855$
F(0.25)	F(0.95)	F(0.60)	F(0.99)	$0.25 \times 0.95 \times 0.60 \times 0.99 = 0.1411$
				$\sum = 0.4652$

$Pr(P = F, N = T) = \sum_{e,i,n} Pr(E = e, I = i, N = T, P = F)$

E	I	N	P	Pr
T(0.75)	T(0.65)	T(0.90)	F(0.15)	$0.75 \times 0.65 \times 0.90 \times 0.15 = 0.0658$
T(0.75)	F(0.35)	T(0.90)	F(0.90)	$0.75 \times 0.35 \times 0.90 \times 0.90 = 0.2126$
F(0.25)	T(0.05)	T(0.40)	F(0.15)	$0.25 \times 0.40 \times 0.40 \times 0.15 = 0.0008$
F(0.25)	F(0.95)	T(0.40)	F(0.90)	$0.25 \times 0.40 \times 0.40 \times 0.90 = 0.0855$
				$\sum = 0.3649$

$Pr(P = F, N = F) = \sum_{e,i,n} Pr(E = e, I = i, N = F, P = F)$

E	I	N	P	Pr
T(0.75)	T(0.65)	F(0.10)	F(0.75)	$0.75 \times 0.65 \times 0.10 \times 0.75 = 0.0366$
T(0.75)	F(0.35)	F(0.10)	F(0.99)	$0.75 \times 0.35 \times 0.10 \times 0.99 = 0.0260$
F(0.25)	T(0.05)	F(0.60)	F(0.75)	$0.25 \times 0.05 \times 0.60 \times 0.75 = 0.0056$
F(0.25)	F(0.95)	F(0.60)	F(0.99)	$0.25 \times 0.95 \times 0.60 \times 0.99 = 0.1411$
				$\sum = 0.2093$

Conditional Probabilities

$$Pr(P = T|I = T) = \frac{Pr(P = T, I = T)}{Pr(I = T)} = \frac{0.3913}{0.50} = 0.7826$$

$$Pr(P = F|I = T) = 0.2174$$

$$Pr(P = F|I = F) = \frac{Pr(P = F, I = F)}{Pr(I = F)} = \frac{0.4652}{0.50} = 0.9304$$

$$Pr(P = T|I = F) = 0.0696$$

$$Pr(P = T|N = T) = \frac{Pr(P = T, N = T)}{Pr(N = T)} = \frac{0.4103}{0.775} = 0.5294$$

$$Pr(P = F|N = T) = 0.4706$$

$$Pr(P = T|N = F) = \frac{Pr(P = T, N = F)}{Pr(N = F)} = \frac{0.0158}{0.225} = 0.0702$$

$$Pr(P = F|N = F) = 0.9298$$

$$Pr(P = T|E = T) = \frac{Pr(P = T, E = T)}{Pr(E = T)} = \frac{0.4090}{0.75} = 0.5453$$

$$Pr(P = F|E = T) = 0.4547$$

$$Pr(P = T|E = F) = \frac{Pr(P = T, E = F)}{Pr(E = F)} = \frac{0.0171}{0.25} = 0.0684$$

$$Pr(P = F|E = F) = 0.9316$$

Vita

Yanzhen Li was born in Taiyuan, Shanxi, China, on April 8th, 1977, the son of Yinghua Li and Xiangliu Li. After receiving a Bachelor of Science degree in 2001 from College of Management, Tianjin Univeristy, China, he attended University of Tennessee at Knoxville where he received Master of Science degrees in Industrial and Information Engineering.