5-2010

A Modified FMEA Approach to Enhance Reliability of Lean Systems

Karthik Subburaman

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To the Graduate Council:

I am submitting herewith a thesis written by Karthik Subburaman entitled "A Modified FMEA Approach to Enhance Reliability of Lean Systems." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Dr.Rupy Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

Dr. Xueping Li, Dr. Joe Wilck

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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A Modified FMEA Approach to Enhance Reliability of Lean Systems

A Thesis
Presented for the
Masters of Science
Degree
The University of Tennessee, Knoxville

Karthik Subburaman
May 2010

ACKNOWLEDGEMENTS

I express my sincere gratitude to my research advisor, Dr. Rapinder Sawhney who has guided me with his knowledge and support throughout my thesis. He has been truly inspirational in motivating me to achieve my ambition. I would like to thank my thesis committee members Dr. Xueping Li and Dr. Joseph Wilck for examining my thesis to provide their reviews, recommendations and suggestions.

I would like to thank all the professors who taught me graduate courses for their assistance with their expertise and time. I am grateful to the staff, Diana Bishop, Jeanette Myers and Sharon Sparks for their respective and administrative supports during the program.

I thank all my lab mates Sashi, Gagan, Christian, Joseph, Ashutosh, Prasanna, Tachapon, Amoldeep, Bharadwaj, Eric, Yahia, Ernest, Kaveri, Lavanya, Girish, Gautham who had been like a family instrumental in making the working environment a pleasant one. I would also like to thank Jaya Prakash, Satish, and Dilip who were supportive throughout my course of study in the U.S.

I am very thankful to my parents and dear friends Balu and Saravana Kumar for their valuable support and constant encouragement that were significant throughout my time at The University of Tennessee. Finally, I thank my brother Venkatesh for his special support during my course of study.

I thank god for his constant blessings and providing me everything that I wished to succeed in life.

Abstract

Purpose - The purpose of this thesis is to encourage the integration of Lean principles with reliability models to sustain Lean efforts on long term basis. This thesis presents a modified FMEA that will allow Lean practitioners to understand and improve the reliability of Lean systems. The modified FMEA approach is developed based on the four critical resources required to sustain Lean systems: personnel, equipment, material and schedule.

Design/methodology/approach – A three phased methodology approach is presented to enhance the reliability of Lean systems. The first phase compares actual business and operational conditions with conditions assumed in Lean implementation. The second phase maps potential deviations of business and operational conditions to their root cause. The third phase utilizes a modified Failure Mode and Effects Analysis (FMEA) to prioritize issues that the organization must address.

Findings – A literature search shows that practical methodologies to improve the reliability of Lean systems are non existent.

Research Limitations/Implications –The knowledge database involves tedious calculations and hence it needs to be automated.

Originality/Value

- Defined Lean system reliability
- Developed conceptual model to enhance the Lean system reliability
- Developed knowledge base in the form of detailed hierarchical root trees for the four critical resources that support our Lean system reliability
- Developed Risk Assessment Value (RAV) based on the concept of effectiveness of detection using Lean controls when Lean designer implements Lean change.
- Developed modified FMEA for the four critical resources
- Developed RPLS tool to prioritize Lean failures
- Developed case study to analyze RPN and RAV approach

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVATIONS

Symbols

H_o Null Hypothesis
H_a Alternative Hypothesis
O Probability of occurrence for actual business conditions
S Severity of potential effects
D Effectiveness of detection of root causes using Lean controls
μ_1 Mean of RPN numbers calculated by the traditional approach
μ_2 Mean of RPN numbers calculated by approach
α Significance level

Abbreviations

FMEA Failure Modes and Effects Analysis
VB Visual Basic
HRO High Reliability Organizations
LEI Lean Enterprise Institute
JIT Just In Time
RPN Risk Priority Number
RAV Risk Assessment Value
RPLS Risk Prioritization of Lean System
HTD Hierarchical Tree Diagrams
AHP Analytic Hierarchy Process
A-1 Appendix 1
A-2 Appendix 2

The Use of Journal Articles in Thesis

Disclosure

This thesis was revised based on a journal paper submitted to International Journal of Quality and Reliability Management (2009). Rapinder Sawhney, Karthik Subburaman, Chrsitian Sonntag, Clayton Capizzi, Prasanna V.Rao, A Modified FMEA approach to Enhance Reliability of Lean Systems accepted to International Journal of Quality and Reliability Management, 2009. My primary contributions to this paper include: (i) development of problem statement (ii) literature review (iii) development of conceptual model to enhance the Lean system reliability (iv) development of knowledge base in the form of detailed hierarchical root trees for the four critical resources: personnel, equipment, material and schedules (v) development of Risk Assessment Value (RAV) based on the concept of effectiveness of detection using Lean controls (vi) development of modified FMEA for the four critical resources (vii) development of Risk Prioritization of Lean System (RPLS) tool to prioritize Lean failures (viii) development of case study using Analytic Hierarchy Process (AHP) to compare RAV with RPN to prioritize Lean failures.

Chapter 1: Introduction

This introductory chapter provides a basis for addressing the Lean sustainability issues in industry. Lean has been treated by most manufacturers as a short term cost reduction strategy by achieving efficiency gains. This approach resulted in fragile processes under dynamic business conditions. This is one root cause in manufacturers "back sliding" into their original paradigms. This research effort introduces the concept of reliable Lean systems by developing a methodology that integrates Lean principles with reliability principles. This methodology is intended to allow Lean designers a practical way to consider reliability issues when designing Lean systems. This chapter details the relevance of the problem within the current difficult economic times. In addition, this chapter outlines the methodology that leads to the modified Failure Mode Effects Analysis (FMEA). Finally, this chapter outlines the organization of this thesis.

1.1 Introduction

Manufacturers have invested billions of dollars implementing Lean principles as a way to maintain and enhance their competitiveness. Even though there are manufacturers that have become industry powerhouses by implementing Lean, there are more examples of those who have not been as successful in achieving the anticipated results. Lean systems are intended to attain long term strategic gains as exemplified by Toyota's meteoric rise in the automotive industry (Smart et al., 2003). However, most organizations utilize Lean as a way to attain short term cost reductions and adopt a mentality towards short and intermediate term efficiency gains (Smart et al., 2003). These approaches have raised questions about sustainability within organizations which implement Lean to reduce costs (Smart et al, 2003). Rubrich (2004) concluded in his study that Lean improvement efforts performed at participating companies have not produced the anticipated results. Ransom (2007), chairman of the advisory board of Lean Horizons Consulting LLC., further concluded that 95% of the Lean implementation efforts have failed, while only 5% have succeeded because of how the organization practiced Lean. Wooley (2008), a strategic program manager of Intel Corp has a more optimistic view of the success of

Lean when he states that on an average 60% of Lean transformation efforts fail. These high failure rates according to the Lean Enterprise Institute (2008) are a result of the following top five factors:

- Backsliding – The continuous improvement efforts are reverting back old ways of working after initial progress.
- Middle management resistance – Resistance among middle management employees such as line supervisors and managers to adapt to Lean changes.
- Lack of implementation know how- Lack of clear knowledge about the implementation of various Lean tools.
- Lack of crisis – Lack of urgent situation to start the Lean implementation process.
- Employee resistance – Resistance among the shop floor employees to adapt to new ways of working.

The concept of integrating Lean thinking with high reliability design principles is used in Highly Reliability Organizations (HRO). Organizations that view safety as a primary objective and provide incentives for failure detection are considered highly reliable (Wieck, 1987). Managers working in organizations that require high reliability must combine reliability models with Lean thinking principles in order to achieve intermediate and long term goals (Smart et al., 2003). One solution to sustain Lean on long term basis is to integrate reliability with Lean implementation (Smart et al., 2003). Lean systems are prone to failure therefore increasing the reliability of Lean system components would enhance the system ability to sustain improvements. However, practical models that combine Lean principles with reliability are non existent. This thesis addresses this need by integrating Lean and reliability in a practical manner through the development of modified FMEA approach to enhance the reliability of Lean systems.

1.2 Problem Statement

Lean systems are designed based on optimal conditions. One of the main reasons regarding the inability to sustain Lean is that organizations design Lean systems based on optimal business environment rather than designing Lean systems based on actual business environment (Sawhney et al., 2009). Lean system design would be enhanced if it utilized the fundamental definition of reliability. IEEE[1] defines reliability as “the ability of a system or component to perform its required functions under stated conditions for a specified period of time”[1] [IEEE: STD 610.12 1990]. The key components of designing reliable system in this definition are:

- Intended function – optimal conditions that personnel, material, equipment and schedule must attain in Lean environment. For example, material delivered on time in the right quantity at the right location.
- Stated condition – variation in optimal conditions that personnel, material, equipment and schedule attain in Lean environment. For example, materials not delivered on time due to volatile market behavior.
- Specified period of time – the minimum cycle time that is associated with personnel, material, equipment and schedule adherence.

However, the Lean designers and strategies have ignored the second and third component above in designing Lean systems. Lean designers do not typically consider the stated conditions. For example, Lean systems are designed based on assumptions such as timely arrival of parts, correct quantity of arrivals, equipment working without failure, all personnel being present, and compliance with established schedules. Therefore, Lean is unable to meet the compliances of volatile business environment such as demand fluctuation. This inability to meet real customer demands can lead an organization backsliding to its old methods.

The foremost problem in our case is the inability of manufacturing firms to consider actual business conditions when designing Lean systems. In most manufacturing firms, assumed or ideal business Lean conditions such as punctual replenishments, steady demands for products and constant customer requirements are taken into account to design Lean systems. Due to unexpected circumstances such as economic downturn these business conditions are characterized by volatility. As a result, Lean systems are unable to function under these hostile or unexpected circumstances over a specified period of time when the system is not designed to deal with these events.

In addition the designs of Lean have never been established based on specified time period, a condition after which the design needs to be evaluated. The inherent assumption is that once Lean system is designed, it is designed for eternity. Some may argue that systems must go through a continuous improvement. However, continuous improvement does not have an explicit guideline and generally it is left to the organization for follow through. This leads to a great level of variation on how organizations implement continuous improvement.

1.3 General Approach

The five phases for selecting a better method to prioritize potential Lean failures is shown in Figure 1. The first phase involves defining the Lean system reliability by expressing the four critical resources: personnel, equipment, material and schedule required in Lean in terms of the three basic requirements of reliability. The second phase presents a conceptual framework to allow the Lean system to become operational. The third phase involves developing a three step methodology. The first step in this phase enables the organization to compare the actual business conditions that deviate from the ideal conditions within four critical resources. A knowledge base is developed in the second step that enables one to evaluate the checklist of actual business and ideal conditions. This knowledge base categorizes the conditions based on four categories: personnel, equipment, material, and schedule. This third phase proposes a modified FMEA to enhance the reliability of Lean systems. The modified FMEA considers the actual business conditions that deviate from the ideal business conditions and ranks them based on the three risk factors: probability of occurrence, severity and effectiveness of detection using Lean controls. The fourth phase involves the development of Risk Prioritization of Lean System (RPLS) tool based on modified FMEA approach that enables one to automatically prioritize Lean risks. This RPLS tool would allow the Lean practitioners to automatically assess the probability of occurrence of the actual business conditions, severity of potential effects and effectiveness of detection of root causes for all the Lean failures within four critical resources: personnel, equipment, material and schedule. This tool will rank the top five Lean failures based on Lean risk defined by three factors probability of occurrence, severity and effectiveness of detection. The fifth phase involves performing a case study in order to study the comparison between Risk Assessment Value (RAV) and Risk Priority Number (RPN). This phase determines whether the order in which RAV and RPN ranks for the same Lean failure is statistically different. If found true, then the sixth phase is performed using Analytic Hierarchy Process (AHP) to select appropriate method (RAV or RPN) to prioritize Lean failures.

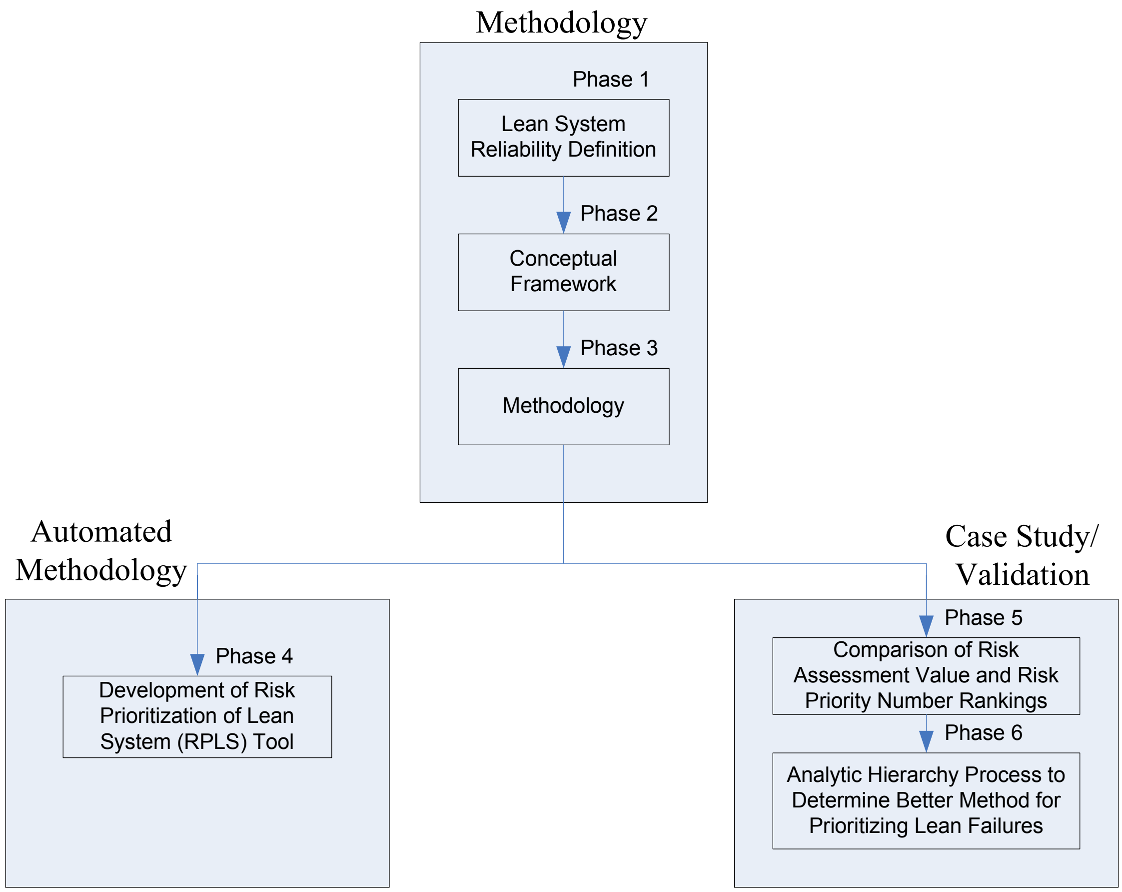

Figure 1 General Approach

1.4 Research Contribution

The contribution of this research is as follows:

- Defines Lean system reliability.
- Develops a conceptual model to enhance the Lean system reliability.
- Develops knowledge base in the form of detailed hierarchical root trees for the four critical resources that support our Lean system reliability.
- Develops RAV based on the concept of effectiveness of detection using Lean controls when Lean designer implements Lean change.
- Develops modified FMEA for the four critical resources.

- Develops a RPLS tool to prioritize Lean failures.
- Develops a case study to select better method between RAV and RPN to prioritize Lean failures.

1.5 Organization of the Thesis

This thesis is organized into six chapters including the introductory chapter. Chapter 2, "Literature Review", provides a comprehensive review to Lean system reliability and modified FMEA approach. This chapter also describes the need for proposed modified FMEA approach to enhance the Reliability of Lean systems. Chapter 3, "Conceptual Framework" provides a general description of the operational framework proposed in this thesis. Chapter 4, "Methodology" provides a general description of the methodology proposed in this thesis. This chapter also describes the development of RAV and RPLS tool to prioritize Lean failures. Chapter 5, "Case Study and Results", utilizes case study to apply the proposed methodology and analyzes the results to demonstrate its practicability. Chapter 6, "Conclusion", summarizes the major conclusion of this thesis. It discusses the major implications of model and scope for further research in this area.

Chapter 2: Literature Review

This chapter is divided into two separate literature searches. The first literature search focuses on defining research efforts associated with measuring, modeling and enhancing Lean system reliability. The second literature search focuses on providing the drawbacks of traditional RPN and the need for modified FMEA approach to address reliability of Lean systems.

2.1 Lean System Reliability

2.1.1 Lean System Reliability Definition

The reliability definition according to IEEE is defined in section 1.2. As per this definition, the three basic requirements in reliability are required function, stated conditions, and specified period of time. This basic definition of reliability is adapted to Lean systems by expressing the four critical resources required in Lean in terms of the three basic requirements of reliability (Sawhney et al., 2009)

1. " The required functions of reliable Lean systems are:
    - Materials in the right quantity delivered at the right time at the right location.
    - Schedule attained without variance, rescheduling and expediting.
    - Equipment should not unexpectedly fail and, if it fails, the repair time should be minimized.
    - Personnel must be available and qualified to perform standard operating procedures so that product quality and delivery requirements can be met.

2. The stated conditions of reliable Lean systems are :
    - Material availability and quality will vary due to volatile market behavior.
    - Schedule must adapt to meet a customer-oriented market with short term fluctuations in demand.
    - Equipment will incur unplanned events, such as extended downtime or performance below the given specification.

- Personnel will incur fluctuations in availability and performance.

3. The specified period of time for a reliable Lean system is defined as the cycle of a system, which depends on the minimum time span associated with material, scheduling, equipment and personnel adherence"**.**

2.1.2 Review of Lean system Reliability categories

As stated in section 2.1.1 Lean requires four critical resources: personnel, material, equipment and schedule to function. What typically fails during unexpected business conditions is one or more of these four critical resources. Each critical component is discussed below.

Personnel

Personnel include the workforce and their capabilities and skills required to implement Lean. Dependability and reliability of the workforce becomes extremely significant because Lean introduces fragility into the system by stretching it and removing contingencies (Womack et.al, 1990; Forrester, 1995). This demands the involvement of the workforce (Biazzo and Panizzolo, 2000) which is assumed by Lean to "naturally want to work" (Forza, 1996).

The role of humans in Lean is a paradox. On one hand, the Lean production system assures that the workforce is the most important link of the entire system. Therefore, the workstation designs are improved according to ergonomic standards, employee morale is increased by a variety of measures, and employees are involved in decision- making (Scherrer-Rathje et al., 2009). On the other hand employees complain that Lean implementation causes a decline in their working conditions. This is verified by several studies. Forrester (1995) recognizes that Lean stresses employees. Meier concludes that Lean creates stress and discomfort among the workforce (Meier, 2001). Hossian demonstrates the correlation between Lean implementation and personal stress (Hossian, 2004). In particular, the workforce reduction results in work that becomes harder, concentrated, monotonous, and standardized (Hawranek, 2008). Older employees are especially strained by these new conditions. The stress factor is often so high that it affects both the morale of the employees and reliability of the system. This is not only an American phenomenon. Even the Japanese workforce resented the loss of individual freedom and suffered stress due to Lean (Green, 1998) to achieve success in the 1970s (Kamata, 1982).

Equipment

Equipment includes primary and auxiliary equipment utilized in Lean systems. Manufacturers typically focus Lean efforts on equipment maintenance which enhances the reliability of the equipment (Smith, 2004). In Lean systems, production equipment capacity is correlated to the forecasted demand of end products. This is essential when one designs a production system around the concept of cellular manufacturing. In fact, cellular manufacturing places a premium on equipment capacity and capability. Furthermore, the effort to achieve system effectiveness by increasing the equipment usage close to its capacity results in a higher risk of failure caused by high load. In addition, this no longer allows for variability in production (Ballard, 1999). This increased equipment failure results in delayed deliveries and eventually the loss of customers and revenues. A typical cellular design does not estimate production capacity based on unplanned events, which truly should be planned for. An unplanned event like machine downtime or incapability of equipment negatively impacts the existing capacity's ability to meet customer expectations (Melnyk, 2007).

Material

Materials include raw materials, works-in-process (WIP), and finished goods. The availability of an inventory system at workstations ensures effective use of the workstation resources. Lean interprets such buffers as a sign of mismanagement or misalignment. High inventories cover the risk of events such as unscheduled downtime and failures (Jeziorek, 1994). Buffers only cover problems – they do not solve them. Therefore, the elimination of these buffers forces the management to face these problems (Jeziorek, 1994). Lean suggests the utilization of minimal buffer stocks must be located in between the operations which require high levels of predictability. As a result, the process is expected to perform within those predictable levels of variations to meet quality and delivery targets. However, failure to predict minimal buffer stocks between operations can hamper quality and delivery targets. A well implemented Lean system does not need a high WIP inventory level except in some cases in ‘supermarkets’ due to Just-in-Time (JIT) concept. A supermarket is a tightly managed amount of inventory within the value stream to allow for a pull system. However this concept assumes conditions which have to be established such as reliable and stable processes, minimal quality based disruptions, punctual and correct replenishments, reliable forecasts, and balanced production lines. Following Japanese methodologies, JIT proponents advocate the development of "symbiotic" relationships with suppliers through long-term agreements (Bennett, 2009). Such agreements are intended to produce the assumed business conditions which are paramount as JIT is based on strict requirements that can easily fail if these conditions are violated. The reduced inventory levels were originally established to compensate for these very issues. This lack of reliability to deal with unplanned circumstances makes the production systems fragile, which affects the entire supply chain. “Such supply chain lacks the extra resources needed to cope with unplanned events” (Melnyk, 2007).

Schedule

Scheduling includes the ability to forecast, plan and schedule a production system. One of the major reasons for failure in transitions to Lean is that production schedule overrides improvement efforts (Choi, 1997; Rother, 1997). Pull systems are a primary mechanism in reducing overproduction in a Lean system. This concept ensures higher customization and a reduction of inventory by setting the production up according to the ‘made per order’ principle. Hence, the production starts only when an order is received. The effectiveness of this principle is undisputable as long as the conditions are normal and predictable. If unpredictable events occur, the production becomes highly inefficient. This volatility is a part of today’s business environment caused in part by customers, who want to avoid long term commitments (Arnold, Chapman, and Clive, 2008). The difficulty occurs for production managers who have to correctly allocate resources and production schedules based on these short term and uncertain orders

(Stein, 1997). In many cases, the manner in which these critical resources are allocated in Lean implementation restricts the breadth of conditions under which the system can work effectively and efficiently. Lean designers must understand this and design systems that can sustain under more robust business conditions. One approach to sustain Lean is to integrate reliability concepts into Lean system design.

2.2 FMEA to Enhance Reliability

2.2.1 Drawbacks of FMEA

FMEA considers only the failure modes that an analyst considers. In many cases, few or many failure modes may be omitted or over emphasized. In most cases, FMEA considers failure modes that affect the higher level of system for a part or product. As a result, FMEA is not the tool to analyze product reliability from a detailed component level. More specifically, FMEA does not measure the reliability of the product, given that this is a requirement. The following are deficiencies of FMEA as a reliability tool (Krasich, 2007):

- FMEA considers each failure mode as independent and does not consider their interaction. Therefore when component failure is considered, FMEA cannot realistically analyze reliability. As a result, the analyst must model the reliability of part or product with another reliability method such as Markov Analysis, Event Tree Analysis, or Fault Tree Analysis with the dynamic event modeling (Krasich, 2007).

- When FMEA addresses only a few component failure of a product, the quantification of product failure is not feasible (Krasich, 2007).

- When FMEA follows the methodology of numerical rating from 1 to 10 for probability of occurrence, severity and detection, it cannot provide information on overall product reliability. As a result, FMEA is fit for the comparison of potential improvements, but not for overall estimation of the product reliability (Krasich, 2007).

- The determination of RPN makes the FMEA a tedious process which provides subjective estimation (Krasich, 2007).

- A variety of different risk scenarios represented by various values of S, O and D generate identical RPN values. FMEA does not allow one to differentiate between different risk implications (Sankar and Prabhu, 2007).

- The FMEA team may average the values of S, O, and D when there is a difference of opinion. This may generate an RPN identical to others without the ability to articulate the risk implications (Sankar and Prabhu, 2007).

2.2.2 Literature Review of Modified FMEA Approaches

Modified versions of FMEA are developed by various researchers. The following is a representative list of research efforts that have attempted to develop the FMEA alternatives (Narayanagounder and Gurusami, 2009):

- John B. Bowles and C Enrique Peláez (1995) proposed a new technique based on fuzzy logic for prioritization of failures for corrective actions in a Failure Mode Effects and Criticality Analysis (FMECA). They represented S, O and D as members of fuzzy sets to assess the failure risk in a FMECA. The relationships between the risks and S, O, D were described by fuzzy if-then rules extracted from expert knowledge and expertise rule base. The ratings for S, O and D were then combined to match the premise of each possible if-then rule and evaluated with min-max inference. The fuzzy conclusion was finally defuzzified by the weighted mean of maximum method to assess the riskiness of the failure.

- Teng, S.H et al (1996) propose that the issues regarding reliability of a product must be included before the completion of design stage and one has to confirm that design requirements are met. To implement FMEA, one has to create FMEA report in the overall quality system. However it is not only difficult to create FMEA report but also to use that information in the overall quality system to improve product and process design.

- Franceschini and Galeto (2001) developed a unique methodology to determine the risk priority level for the failure mode in FMEA. This FMEA was able to deal with situations having different importance levels for the three failure mode component indexes: severity, occurrence, and detection.

- Sankar and Prabhu (2001) proposed modified FMEA approach to prioritize failures in a system FMEA to carry out corrective actions. They introduced a new Risk Priority Rank (RPR) technique that utilizes a ranking scale of 1 to 1000 to represent the increasing risk of S, O and D combinations. This 1000 possible combinations of S,O and D were tabulated by an expert in the order of increasing risk and can be interpreted as ‘ if –then’ rules. Failures having higher rank are given high priority. FMEA identifies the risk associated with a product failure through assignment of a standard RPN. A fundamental problem with FMEA is that it attempts to quantify risk without adequately quantifying the factors that contribute to risk. In particular cases, RPNs can be misleading. A methodology combining the benefits of matrix FMEA and the new RPR technique is used to overcome the deficiency of traditional RPN.

- Devadasan et al., (2003) argue that most organizations have not fully attained the integration of FMEA into their process improvement team. Therefore those organizations did not achieve the maximum quality of FMEA application. FMEA principles are effective and helpful to achieve continuous quality improvement, but it is not practically possible to implement them into real time improvements. Devadasan et al. (2003)., proposed modified version of FMEA known as Total Failure Mode Effects Analysis (TFMEA) to carry out holistic failure prevention to attain continuous quality improvements.

- Pillay and Wang (2003) proposed Evidential Reasoning (ER) using fuzzy rules base and grey relation theory to rank the risks of different failure modes in order to overcome the drawbacks of the traditional FMEA approach. Initially, the relationship between three risk factors S, O and D was established. Every failure mode was then assigned a specific term for each of the risk factors. The three specific terms were combined using the fuzzy rule base generated to produce a term that represents higher risk priority of the failure mode. Once a ranking has been established, the process then followed the traditional method of determining the corrective actions and generating the FMEA report.

- Rhee and Ishii (2003) presented the life-cost based FMEA that measures risk in terms of cost over the life cycle. Life cost based FMEA was used to compare and select design alternatives that can reduce the overall life cycle cost of a particular system. Monte Carlo simulation is utilized to perform sensitivity analysis on variables impacting the life cycle costs. A case study was performed on a large scale particle accelerator to forecast life cycle failure cost, to quantify risks, to plan preventive and scheduled maintenance and finally to improve uptime.

- Seyed-Hosseini et al. (2006) introduced the Decision Making Trial and Evaluation Laboratory (DEMATEL) for reprioritization of failure modes based on severity of effect or influence, and the direct and indirect relationships between them. The benefits of DEMATEL involve analyzing indirect relations, assigning as many ranks to all alternatives and clustering alternatives in large systems. A case study was performed and it was found that DEMATEL method can be an efficient, complementary and confident approach for reprioritization of failure modes in a FMEA.

- Arunachalam and Jegadheesan (2006) proposed a modified FMEA with reliability and cost based approach to overcome the drawbacks of traditional FMEA. A case study was performed with reliability and cost based approach for the cooling system of passenger transport vehicles using data collected from state transport corporation depot.

- Dong (2007) utilized fuzzy based utility theory and fuzzy membership functions to assess severity, occurrence and detection. The utility theory accounts for the nonlinear relationship between failure costs and ordinal ranking costs. The Risk Priority Index (RPI) is developed for the prioritization of failure modes. A case study was performed and it was found that failure costs were taken into account when prioritizing failure modes.

- Chen (2007) evaluated the structure of hierarchy and interdependence of corrective action by Interpretive Structural Model (ISM). He then calculated the weight of a corrective action through the analytic network process (ANP). Finally he combined the utility of corrective actions to make a decision on improvement priority order of FMEA using Utility Priority Number (UPN).

- Wang et al. (2008) used Fuzzy Risk Priority Numbers (FRPNs) to prioritize failure modes and used fuzzy geometric means to weigh the fuzzy ratings for Occurrence (O), Severity (S) and Detection (D), computed using alpha-level-sets and linear programming models. In order to rank the failures, the FRPNs are defuzzified using centroid defuzzification method, in which a new centroid defuzzification formula based on alpha-level sets was derived.

An exhaustive literature search has not identified models explicitly developed to enhance the reliability of Lean systems. Smart and his colleagues from the Cranfield School of Management and Cranfield University are the only group identified in the literature search that explicitly promotes the integration of Lean and reliability (Smart et al, 2003). Based on the above literature search, presently there is no FMEA that is uniquely designed to address the reliability of Lean systems. The traditional FMEA prioritizes risk based on the RPN, which emphasizes the likelihood of occurrence of the failure mode and severity of its effects. The traditional FMEA however has its own drawbacks as defined earlier.

Chapter 3: Conceptual Framework

3.1 Conceptual Framework

The conceptual framework shown in Figure 2 is utilized to further articulate Lean system reliability. In this framework an enterprise is represented by six hierarchical levels: Strategic level, System level, Process level, Workstation level, Resource level and Issue level. Each of these levels is described below:

Strategic Level: This level involves understanding the ability of an enterprise to meet stakeholder's expectations. As a result, this level focuses on efficient, effective and reliable core competencies related to stakeholder's expectations that truly impact the key enterprise level performance metrics. Some of the performance metrics include market share, customer loyalty, brand recognition, profitability and others.

System level: This level allows one to articulate the systems that allow an enterprise to meet stakeholder's expectations and therefore impact the key competencies and enterprise metrics. Examples of systems within an organization include research & development, procurement, environmental health, safety and others. Some of the performance metrics of these systems include number of requirement change requests, number of design changes, failure costs due to research & development as a percentage of sales value, and ratio of research & development expenditure to turnover.

Process level: Each system can be further delineated into a set of complex interrelated processes. One has the ability to map these processes utilizing process mapping and project management techniques. The utilization of process management techniques can lead one to articulate the critical processes that impact the critical systems of an enterprise. Some examples of process level based metrics are lead time, yield, and inventory turnover.

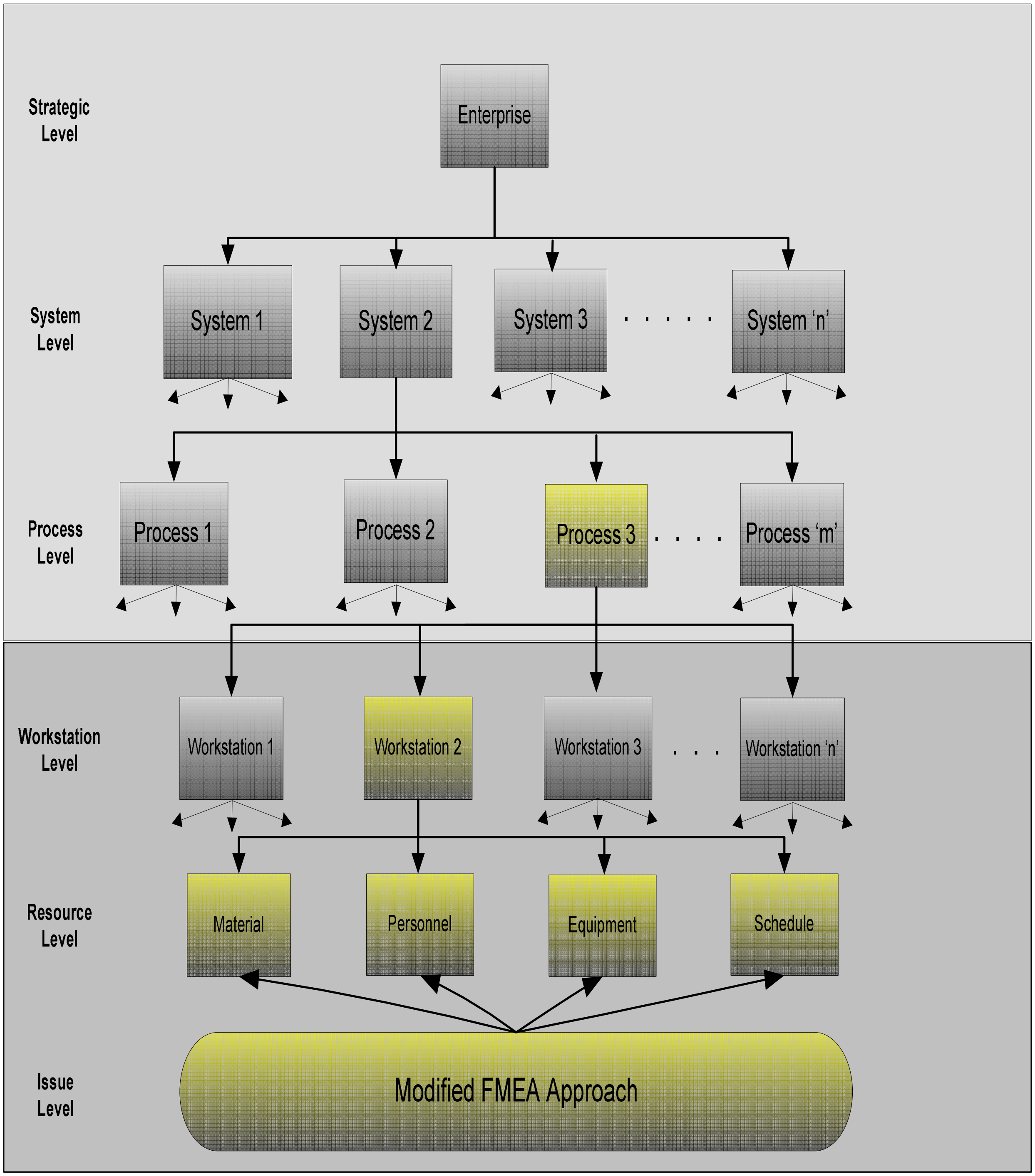

Figure 2 Conceptual Framework

Workstation level: Every process consists of one or more workstations. Each of these processes has a bottleneck workstation. However, to improve the overall system performance, one should focus on the critical process in the system. The workstation that is the bottleneck of the critical process is identified as the leverage point of these systems. Some examples of workstation performance metrics are cycle time, scrap, rework and number of parts produced.

Resource level: The performance of each workstation is based on its ability to deal with the four critical resources as identified in Chapter 2 that defined Lean system reliability. In particular, if one can address the four critical resources within the leverage point of the critical process of a key system within an organization, the probability of achieving the expectations of the stakeholders will be enhanced.

Issue level: This level focuses on identifying the key issues within the four critical resource categories identified in the Lean system definition. A knowledge database that allows one to systematically evaluate all the issues in each category is required. Detailed tree diagrams for each category have been developed in this effort and presented in Section 4.3. In addition; a modified FMEA based approach is presented in Section 4.3 to allow one to prioritize these issues.

The operation of the overall system depends on its processes and, subsequently, the workstations. Hence, each workstation is represented by a series configuration of the four critical resources required for reliable Lean systems. A series configuration implies that all categories must function for the workstation to operate. The emphasis of this conceptual framework is to identify and address the issues that truly impact the enterprise. Specifically, this conceptual framework allows to one evaluate the discrepancy between actual business conditions and the assumptions of normalcy under optimal business Lean conditions. Lean systems are usually implemented based on the expectations of a continued current business environment. Most Lean practitioners assume business conditions, such as punctual replenishments, steady demands for products, and constant customer requirements. In reality business conditions are characterized by volatility as evidenced by current global financial crisis. Lean systems are unable to function under hostile or unexpected circumstances over a specified period of time. Violation of normalcy assumptions when designing Lean systems can create failures within the four critical resources: personnel, materials, equipment and schedules. Greater reliability can be attained by systematically and consistently addressing possible failure within these four critical resources in Lean design.

Chapter 4: Methodology

4.1 Introduction

This chapter describes a practical methodology based on a modified FMEA hereafter referred to as Risk Prioritization of Lean System (RPLS). The objective of RPLS is to allow a user to evaluate the actual operational conditions based on the required conditions for Lean systems. This analysis will be the initial component of the RPLS to prioritize risks to achieve Lean system success and sustainability. The focus of the RPLS is to reduce risk with emphasis on implementation of more effective Lean based controls.

4.2 Methodology

The methodology consists of four phases as shown in Figure 3. The first phase utilizes Hierarchical Tree Diagrams (HTD) to derive a list of necessary operational conditions for Lean success. The output of HTD provides risk factors to determine operational risks in a system. The second phase takes these risk factors and compares with required operational conditions for success. The third phase utilizes modified FMEA to prioritize these risks. The fourth phase uses visual basic application and automates modified FMEA methodology to prioritize Lean risks based on RAV.

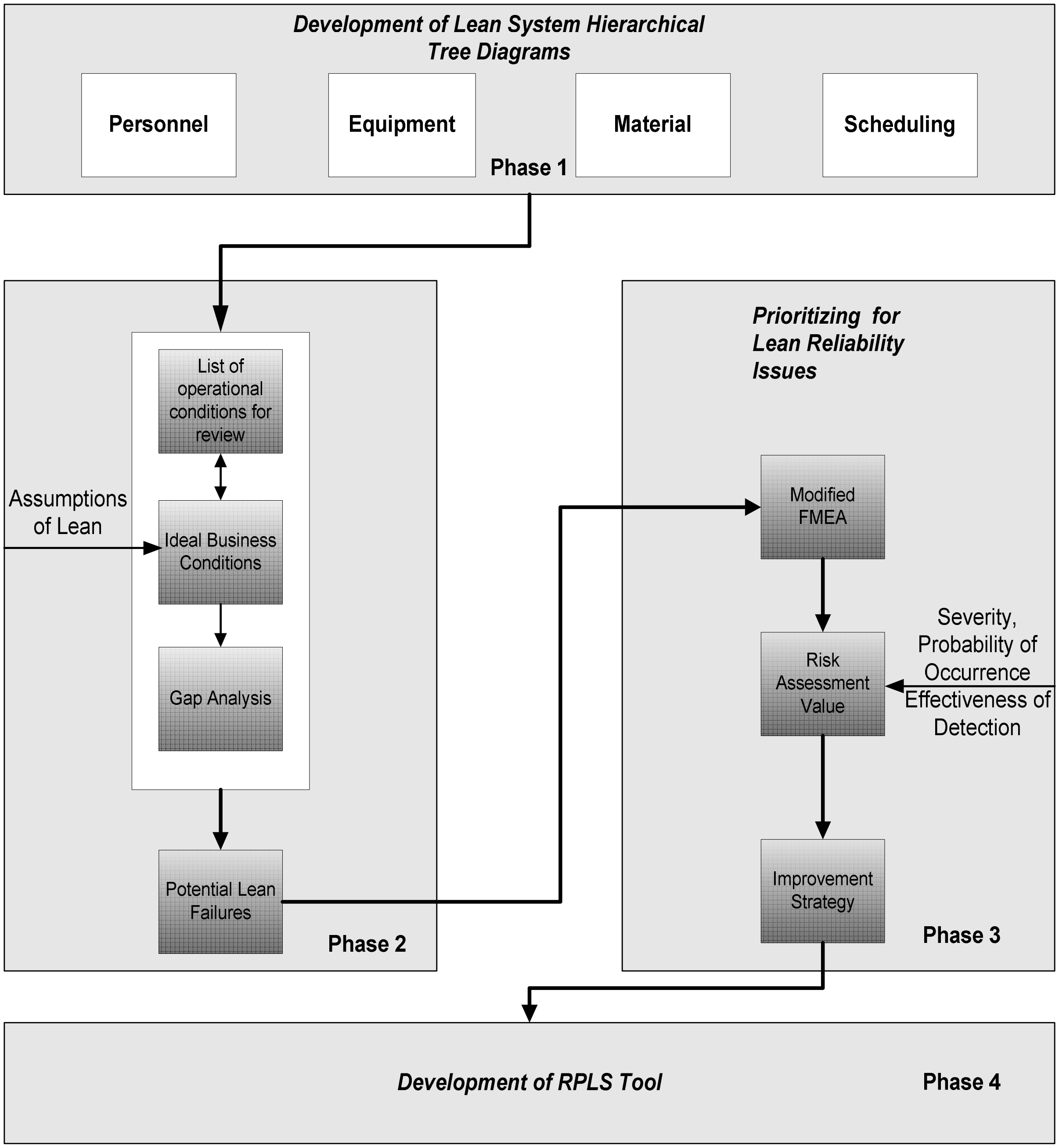

Figure 3 RPLS Methodology Roadmap

Phase 1: Development of Hierarchical Tree Diagrams

In this phase the detailed HTD are developed for personnel, equipment, material and schedule. Figures 4, 5, 6 and 7 illustrate the detailed hierarchical trees developed for the resources: personnel, equipment, material and schedule. The HTD allows one to systematically identify the potential failures and their root causes. The HTD is structured as follows:

- System Components: These are the four critical resources that forms the basis for Lean production: personnel, material, equipment and schedule.

- System Symptoms: These are the potential effects to the overall system reliability. For example in Figure 4, non availability of personnel leads to product defects, customer complaints, ineffective teamwork, incomplete maintenance, reduced employee morale, reduced participation and involvement.

- Direct Causes: These are the potential direct causes of each system symptom. For example in Figure 4, the incomplete maintenance arises due to failure in following standard operating procedures, lack of standard operating procedures, lack of training, training exceeding human capabilities , insufficient tools and equipment failure.

- Root Causes: These are the potential root causes for each direct cause of system symptom. For example in Figure 4, the root causes for training exceeding human capabilities are lack of effective communication, work overload, work underload, poor training, lack of motivation and lack of physical and mental capability.

The HTD were developed by interacting with manufacturing industries in Tennessee. These manufacturing industries in Tennessee were accessed through Dr.Sawhney's Lean fellowship over the past decade. However these HTD's are not completely exhaustive. Due to space constraints, HTD's are developed only for a single operational condition for all the four system components.

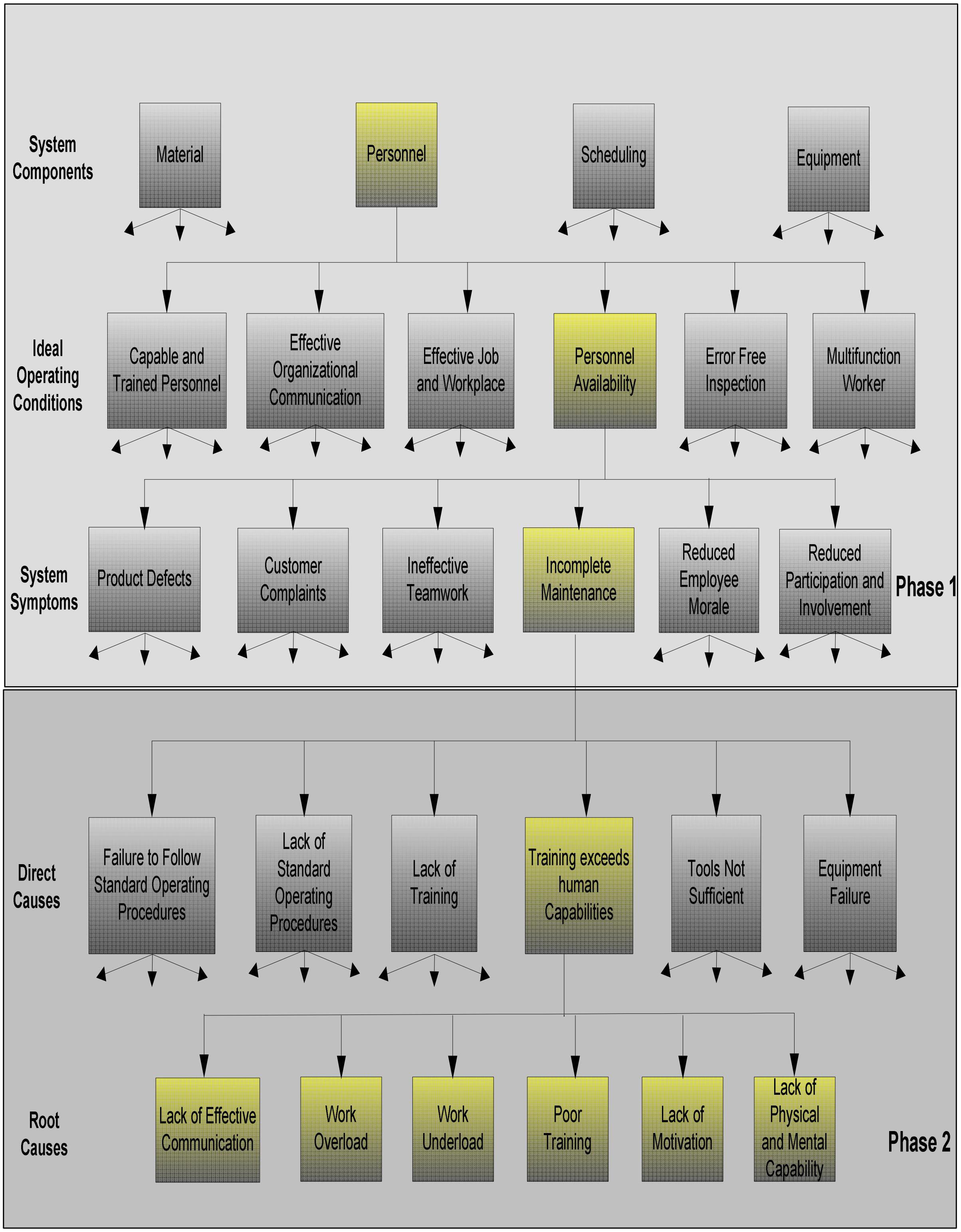

Figure 4 Sample of Detailed Hierarchical for Personnel

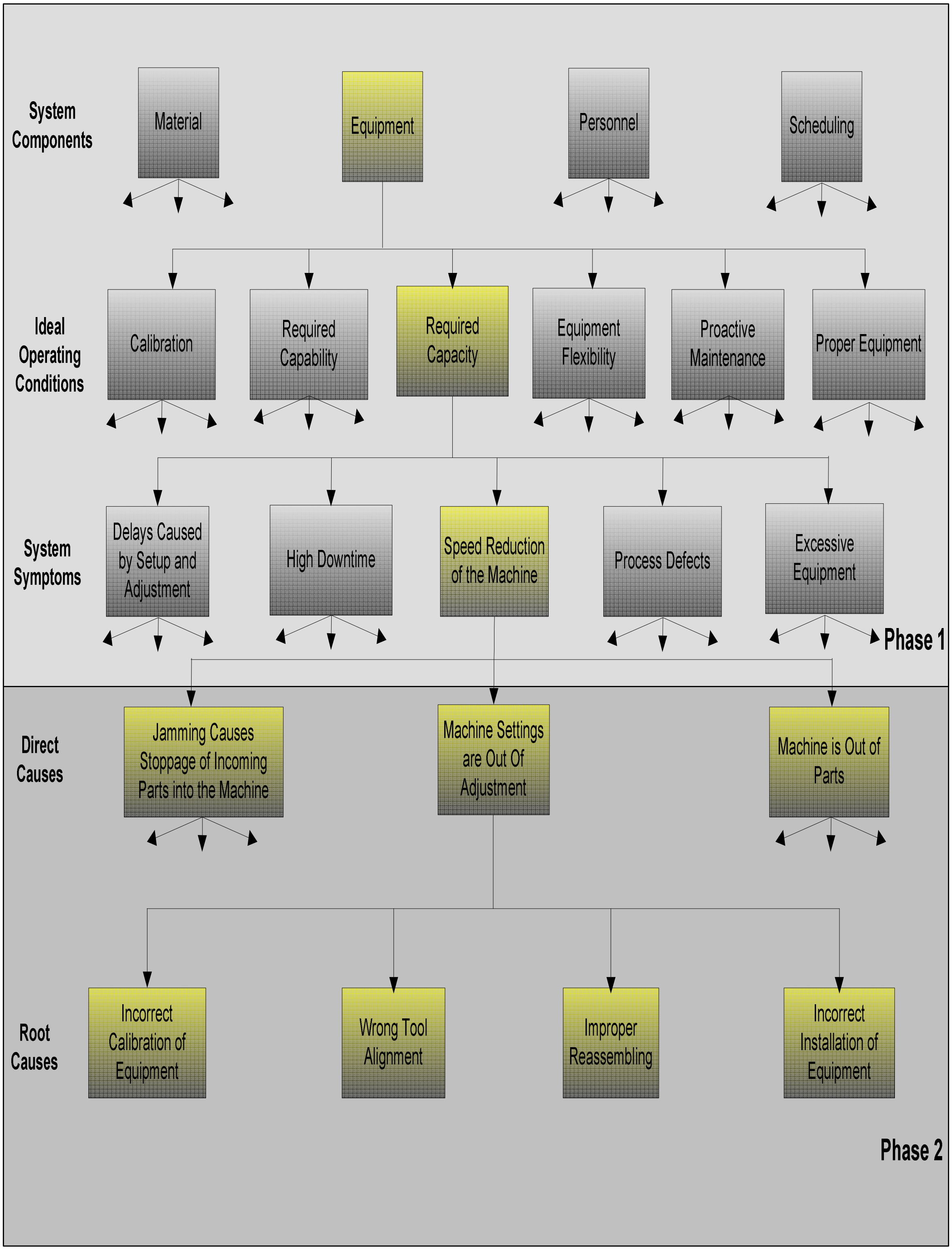

Figure 5 Sample of Detailed Hierarchical Tree for Equipment

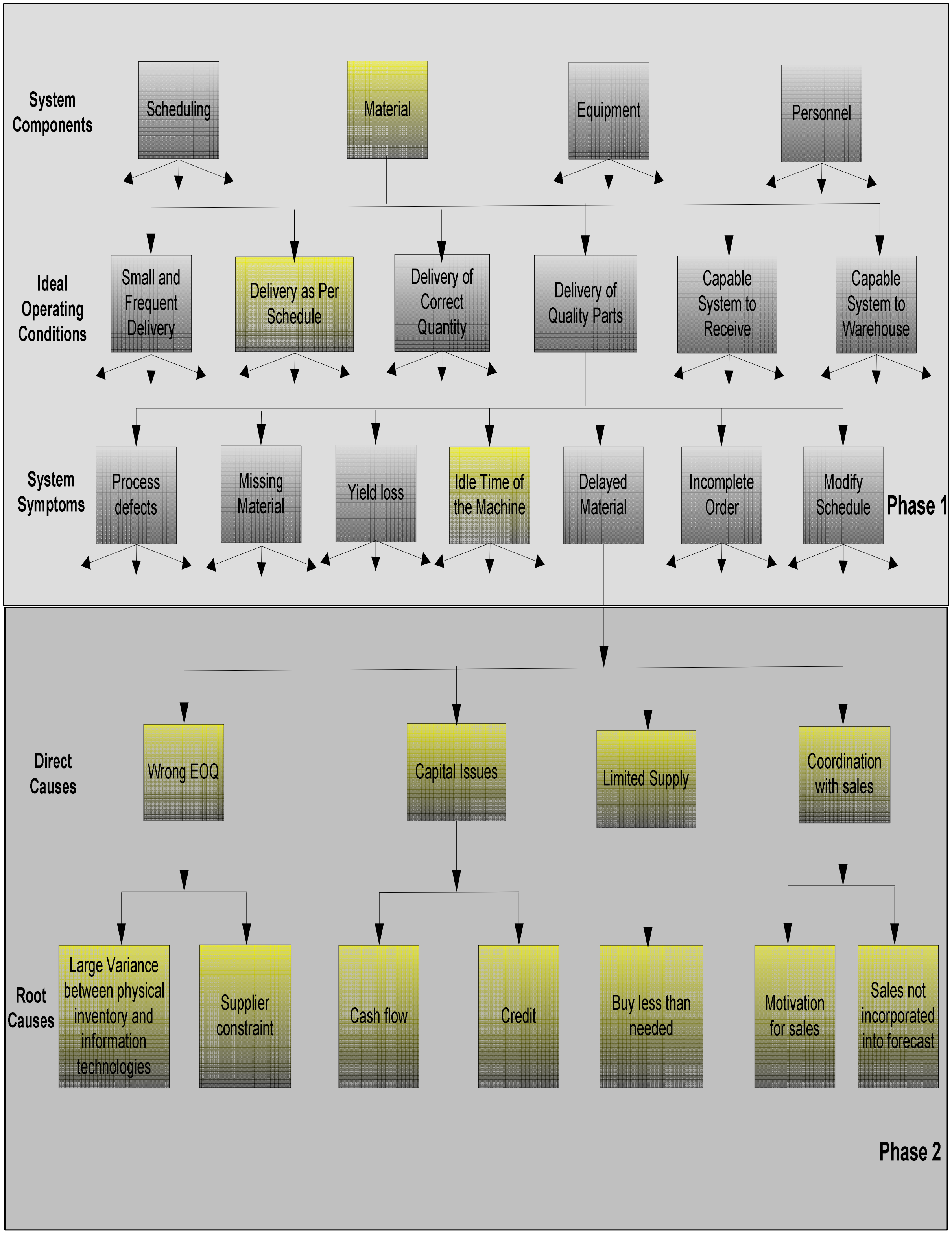

Figure 6 Sample of Detailed Hierarchical Tree for Material

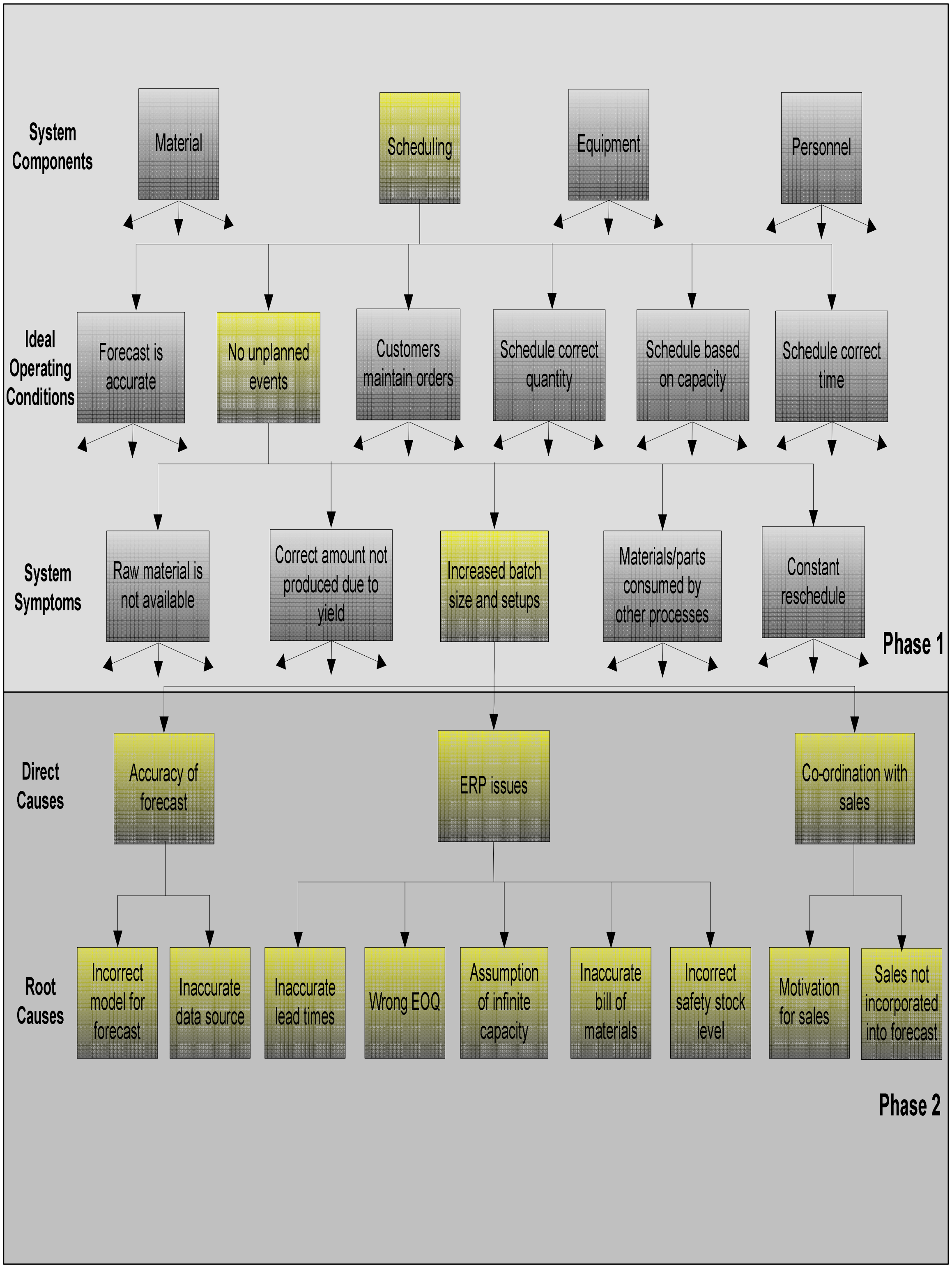

Figure 7 Sample of Detailed Hierarchical Tree for Schedule

Phase 2: Gap Analysis

The inputs for the gap analysis are required conditions of Lean that were obtained from the HTDs. Lean designers do not consider actual business conditions when designing Lean systems. There is no explicit method to determine the extent to which the actual business conditions deviate from the required business conditions. As a result, there is a need to compare actual business conditions with required business conditions. This would allow Lean designers to compare actual business conditions against required business conditions that Lean requires within the four critical subsystems: personnel, equipment, materials, and schedules. Therefore reliability of Lean systems can be increased through its elimination of gaps in the system design. Table 1, 2, 3 and 4 illustrate the gap analysis developed for the resources: personnel, equipment, material and schedule. The components of gap analysis for each of the four critical resources are as follows:

- Assumed Conditions: These are required operational conditions for successful Lean implementation within each of the critical resources. For example, Lean implementation within personnel assumes capable and trained personnel, effective organizational communication, effective job and workplace, personnel availability, error free inspection, multifunction worker, mutual respect and motivated workforce.

- Actual Business Conditions: The extent to which the actual business conditions vary from assumed business conditions is determined based on numerical rating from 1 to 10. A nine point likert scale was chosen to assign numerical ratings as suggested by most psychometricians (Siegel, 2008). The assigned actual business conditions provide the user to input the numerical ratings based on nine point likert scales.
    - Always true: 1
    - Almost always true: 2
    - Almost usually true: 3
    - Almost often true: 4
    - Almost occasionally true: 5
    - Sometimes but infrequently true: 6
    - Usually not true: 7
    - Almost never true: 8
    - Never true: 9 -10

- Violated References: This column is used to determine the deviation of actual business condition from assumed business condition. When the deviation is large, the factor is marked as a potential risk to successful Lean implementation. For research purpose, this work considered any numerical rating of actual condition greater than or equal to 5 as large deviation. Depending on end users this limit can be varied according to practicality. For example, the actual condition for the multifunction worker to be readily available is usually not true. Therefore an 'X' mark is indicated in corresponding row of personnel availability.

The output of gap analysis provides a comparative list of violated references within each of the four critical resources. The risk factors for each violated references needs to be assessed in order to prioritize potential operational risks in Lean system.

Table 1 Gap Analysis for Personnel

LEAN SUBSYSTEM	GAP ANALYSIS			
	Assumed Conditions	**Actual Conditions**		**Violated References**
P E R S O N N E L	Capable and trained Personnel	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Effective organizational communication	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Effective job and workplace	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Personnel availablity	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Error free inspection	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Multifunction worker	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Mutual respect	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Motivated work force	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	

Table 2 Gap Analysis for Equipment

LEAN RESOURCE	GAP ANALYSIS			
	Assumed Conditions	**Actual Conditions**		**Violated References**
EQUIPMENT	Required capacity	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Required capability	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	calibration	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Equipment flexibilty	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Proactive maintenance	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Proper equipment	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Efficient flow	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Efficient setup	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	

Table 3 Gap Analysis for Material

LEAN RESOURCE	GAP ANALYSIS			
	Assumed Conditions	**Actual Conditions**		**Violated References**
MATERIALS	Small and frequent delivery	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Delivery as per schedule	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Delivery of correct quantity	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Delivery of quality parts	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Capable system to receive	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Capable system to warehouse	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Capable part movement based on requirement	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Part properly identified	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	
	Material delivered to point of use	Always True : 1 Almost Always True : 2	Almost Usually True : 3 Almost Often True : 4	X
		Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Usually Not True : 7 Almost Never True : 8 Never True: 9-10	

Table 4 Gap Analysis for Schedule

<table>
<tr><th>LEAN RESOURCE</th><th colspan="4">GAP ANALYSIS</th></tr>
<tr><td rowspan="19">S
C
H
E
D
U
L
E
S</td><td>Assumed Conditions</td><td colspan="2">Actual Conditions</td><td>Violated References</td></tr>
<tr><td rowspan="2">Forecast is accurate</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">Customers maintain orders</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">ERP system is capable</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">Schedule based on capacity</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">No unplanned events</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">Schedule correct quantity</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">Schedule correct time</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">Schedule to pacemaker process</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
<tr><td rowspan="2">Level schedules: volume and mix</td><td>Always True : 1
Almost Always True : 2</td><td>Almost Usually True : 3
Almost Often True : 4</td><td rowspan="2">X</td></tr>
<tr><td>Almost Occasionally True: 5
Sometimes But Infrequently True: 6</td><td>Usually Not True : 7
Almost Never True : 8
Never True: 9-10</td></tr>
</table>

Phase 3: Prioritizing Lean Reliability Issues

The factors that cause risk to Lean system provide input to develop modified FMEA. This modified FMEA is based on RAV to prioritize risk factor issues. FMEA has been modified to fit the requirements of this analysis. Table 5, 6, 7 and 8 represent the modified FMEA. Each column of the modified FMEA is described below:

- Probability of Occurrence: This column is used to determine the likelihood of occurrence of the actual business condition for the four critical resources. The assigned rating of 1 to 10 is given which is contrary to traditional FMEA to rate the probability of occurrence. A value of 1 represents a highly likely occurrence, and, while a value of 10 means an event is extremely unlikely to occur. For example, in personnel the likelihood of occurrence for an error inspection in an organization is low. As a result, the probability of occurrence for personnel availability is given numerical rating of 7.

- Potential Effects: This refers to the potential outcome of each assumed condition on the overall system. Potential effects refer to impacts on end user of each critical resource: personnel, material, equipment and schedule. Therefore each effect needs to be analyzed to enhance Lean system reliability. For example, in personnel the potential effects of effective organizational communication are reduced employee morale and ineffective team work.

- Severity: This is a user input column to estimate the impact of a potential effect on the workstation. A rating of 1 to 10 is given similar to a normal FMEA to rate the consequences of potential effects. In terms of severity, a value of 1 means that the consequences of this particular root cause is insignificant, while a value of 10 yields more severe repercussions.

- Potential Root Causes: This column provides a list of potential root causes of the assumed condition that indicates weakness in Lean design. These potential root causes were obtained from HTD's developed for four critical resources. For example, in personnel the root cause for not achieving proactive maintenance is due to ineffective maintenance program.

- Controls: This is the column that provides the user a list of recommended Lean tools to control reliability of the Lean system. These controls are the primary mechanisms where potential improvements can be initiated. For example, in personnel improper poka yoke controls leads to inability to achieve error free inspection.

- Effectiveness of Detection: This column provides user's ability to accurately measure root cause based on availability of current Lean controls. A value of 1 refers to a control that is effective in capturing and regulating a system's behavior. On the other hand, a value of 10 represents the inability to accurately measure and manipulate the system's performance.

- Risk Assessment Value: In order to determine the risk associated with Lean systems, a RAV is proposed as defined in equation 1. This is a calculated value based on the inputs of probability of occurrence, severity, and effectiveness of detection. From these three assessments, a RAV value can be calculated expressing the potential risks associated with a particular root cause. The value can range from 1 representing the lowest risk to 100 which represents the highest risk, and the need for improvements.

RAV is defined as the ratio of the risk profile of Lean system failure and the effectiveness of Lean to detect and manage the failure. RAV is proposed in order to emphasis the ability to detect and control the failures. As a result RAV emphasizes on designing systems utilizing continuous improvement tools to detect and manage the potential system failures. RAV places a greater emphasis on the Lean practitioner's competence to increase the system's ability to detect and manage Lean failures.

Risk Assessment Value = (O*S) / D (1)

Where,

O - Probability of occurrence of actual business conditions.

S - Severity of the potential effects.

D- Effectiveness of detection to control the root cause.

- Recommendations of Lean Projects: This column provides a list of suggested improvements that can be carried out in order to minimize the risk of Lean system's failure.

Table 5 Modified FMEA Approach for Personnel

LEAN SUBSYSTEM	ENVIRONMENT							LEAN CONTROLS			IMPROVEMENTS				
	Assumed Conditions	Actual Conditions		Violated References	Probability of Occurrence	Potential Effects	Severity	Potential Root Causes	Controls	Effectiveness of Detection	RAV	RAV Ranking	RPN	RPN Ranking	Recommendations of Lean Projects
PERSONNEL	Capable and trained Personnel	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		SOP not followed Defects		Training Responsibility Accountability	Training matrix Personnel evaluation						Utilize training matrix and personnel evaluation to train personnel
	Effective organizational communication	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Reduced employee morale Ineffective teamwork		Organaizational culture management	No Control						Possess Lean controls to measure organizational culture and management
	Effective job and workplace	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Safety issues Quality issues		Organaizational culture management Space shortage	No SOP No 5S						Implement 5S and SOP to ensure capable workplace and job design
	Personnel availablity	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Rescheduling Wasted time		Organaizational culture management	Policy for missing work Personnel evaluation						Requires planning to ensure that personnel is available
	Error free inspection	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Ship defects Customer complaints		Human capability Lean awareness	No poka yoke						Implement Poka Yoke
	Multifunction worker	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Lack of ability to meet dynamic demand		Cross functional training	Training matrix						Implement training matrix
	Mutual respect	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Reduced employee morale Ineffective teamwork		Organaizational culture management	No Control						Possess Lean controls to measure organizational culture and management
	Motivated work force	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Reduced employee morale Participation and involvement		Organaizational culture management	No Control						Possess Lean controls to measure organizational culture and management

Table 6 Modified FMEA Approach for Equipment

LEAN RESOURCE	ENVIRONMENT								LEAN CONTROLS			IMPROVEMENTS				
	Assumed Conditions	Actual Conditions		Violated References	Probability of Occurrence	Potential Effects	Severity	Potential Root Causes	Controls	Effectiveness of Detection	RAV	RAV Ranking	RPN	RPN Ranking	Recommendations of Lean Projects
E Q U I P M E N T	Required capacity	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Inability to deliver overtime Rescheduling		Number of machines Machine downtime Machine yield	Proactive maintenance SMED						Carry out proactive maintenance activities and implement SMED
	Required capability	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Defective product Inability to deliver overtime		Expertise in capabiliy Old equipment maintenance	C_p C_{pk}… maintenance						Process capability studies and maintenance activities must be proficient
	calibration	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Defects Shipped good parts scrapped		No Gauge R&R	Gauge R&R						Implement gauge R&R
	Equipment flexibilty	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Excessive equipment Large setup times Large batch size		Product mix change Old equipment Setup procedure	Cp Cpk… Maintenance						Process capability studies and maintenance activities must be proficient
	Proactive maintenance	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		High downtime Unplanned events Inability to deliver		Ineffective maintenance	No total preventive maintenance						Implement total preventive maintenance
	Proper equipment	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Capacity and capability issues of the equipment		Equipment degradation	No total productive maintenance						Implement total productive maintenance
	Efficient flow	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		High lead time High inventory High material handling		Line balance Pull system Material handling SOP	No kanban No supermarkets						Implement kanban and supermarkets
	Efficient setup	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Large batch size High lead times Inability to deliver		No SMED	SMED						Implement SMED

Table 7 Modified FMEA Approach for Material

LEAN RESOURCE	ENVIRONMENT							LEAN CONTROLS			IMPROVEMENTS				
	Assumed Conditions	**Actual Conditions**		**Violated References**	**Probability of Occurrence**	**Potential Effects**	**Severity**	**Potential Root Causes**	**Controls**	**Effectiveness of Detection**	**RAV**	**RAV Ranking**	**RPN**	**RPN Ranking**	**Recommendations of Lean Projects**
MATERIALS	Small and frequent delivery	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Excessive inventory		No pull system Supplier issues System part requirement Procurement system	No kanban system Annual supplier evaluation ERP system discrepancy No control						Implement kanban system Conduct annual supplier evaluation Make ERP systems efficient
	Delivery as per schedule	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Production stoppage Modify schedule		Order not placed on time Supplier delay	No control Receiving manager						Solve supplier issues
	Delivery of correct quantity	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Modify schedule Incomplete order		Incorrect order Order change Supplier yield	No control Procurement manager						Possess Lean controls for incorrect order, order change and supplier yield
	Delivery of quality parts	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Modify schedule Incomplete order Quality issues		Part design Design documentation Supplier capability	Internal design process Engineering dept manager No Control						Ensure that internal design process is correct in part design and design documentation
	Capable system to receive	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Missing Material Delayed Material		SOP Training Personnel availability	Receiving SOP - unenforced human Resource training						Enforce receiving SOP Conduct human resource training Allocate plant managers appropriately according to the plan
	Capable system to warehouse	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Missing material Delayed material		SOP Training Personnel availability	Warehouse SOP Human resource training						Enforce warehouse SOP Conduct human resource training Allocate plant managers appropriately according to the plan
	Capable part movement based on requirement	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Parts not available when required		SOP Visual controls	Material handler SOP No visual boards						Follow material handler's SOP Follow visual boards
	Part properly identified	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Missing material Lost material		Labeling system Tracking system	SOP Routing sheets						Implement SOP and Routing sheets
	Material delivered to point of use	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Missing material		Lean awareness Space shortage	No SOP No 5S						Implement SOP and 5S

Table 8 Modified FMEA Approach for Schedule

LEAN RESOURCE	ENVIRONMENT							LEAN CONTROLS			IMPROVEMENTS				
	Assumed Conditions	Actual Conditions		Violated References	Probability of Occurrence	Potential Effects	Severity	Potential Root Causes	Controls	Effectiveness of Detection	RAV	RAV Ranking	RPN	RPN Ranking	Recommendations of Lean Projects
SCHEDULES	Forecast is accurate	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Excessive inventory Customer delivery not met		Forecast model Volatile conditions	Forecast accuracy reports						Ensure that forecast data reports are accurate
	Customers maintain orders	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Product not shipped Complete reschedule		Volatile conditions Customer communication	Sales force communication with operations						Make sure that sales do not force communication with operations
	ERP system is capable	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Excessive inventory Customer delivery not met		Inaccurate data Infrequent ERP update	Physical cycle count						Ensure that physical cycle count is correct
	Schedule based on capacity	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Constant reschedule Increased batchsize Increased setups Delayed delivery		ERP not based on capacity	No control						Implement pull systems
	No unplanned events	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Constant reschedule Increased batchsize Increased setups Delayed delivery		Scheduling did not consider unplanned events	No control						Scheduling must be planned correctly
	Schedule correct quantity	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Modify schedule		Forecast sales force ERP	Production reports Routing sheets						Utilize production reports and routing sheets
	Schedule correct time	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Constant reschedule Increased batchsize		Forecast sales force ERP	Production reports Shipment reports						Utilize production reports and routing sheets
	Schedule to pacemaker process	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Increased scheduling complexity Not smooth flow		No Lean concepts	Production supervisor						Ensure that scheduling is carried out at only One point to the pace maker process
	Level schedules: volume and mix	Always True : 1 Almost Always True : 2 Almost Occasionally True: 5 Sometimes But Infrequently True: 6	Almost Usually True : 3 Almost Often True : 4 Usually Not True : 7 Almost Never True : 8 Never True: 9-10	X		Constant reschedule Increased batchsize Increased setups Delayed delivery		No Lean concepts	Heijunka						Implement Heijunka to achieve production levelling for both volume and product mix

Phase 4: Development of RPLS Tool

The development of RPLS tool follows the Systems Development Life Cycle approach (Kendall and Kendall, 1999 and Padiyar.A, 2005). The following steps needs to be followed.

Step 1: Establishing Business Rules:

Business rules are considered for smooth operation of RPLS tool, therefore a set of business rules need to be established.

- All possible required conditions of Lean for each of critical resources need to be listed: personnel, equipment, material and schedule.
- For each required conditions, the actual conditions must be listed.
- Lean designers can compare these required conditions against actual conditions of Lean. When the required condition is not satisfied by an actual condition it is treated as an area of potential failure.
- For each potential failure, root causes must be listed.
- The user has to input risk factors such as probability of occurrence for actual business conditions, severity for potential effects and effectiveness of detection for root cause based on availability of current Lean control.
- The RPLS tool prioritizes Lean risks based on RAV formula defined in equation 1.
- The user has to implement control action at their site in the same order as Lean risks are ranked by RPLS tool.
- The effectiveness of detection for Lean control must be improved to eliminate the root cause of each Lean risk.

Step 2: Designing the recommended system

This phase illustrates the algorithm for input and other logical functions performed by RPLS tool in order to meet desired objective. The following list provides step by step instruction on how RPLS tool operates:

- Initially, the user selects possible required conditions of Lean into the RPLS tool.
- For those selected required conditions, all possible actual conditions are listed. The user has to select actual conditions that are non compliant with required conditions.
- For each actual condition, a list of potential root causes is displayed.
- For each root cause the user has to input probability of occurrence for actual condition, severity for potential effect and effectiveness of detection of root cause based on current Lean controls.
- The RPLS tool calculates RAV based on formula defined in equation 1.
- The RPLS tool prioritizes top five root causes based on RAV values. As a result this root causes needs to be eliminated or minimized to enhance the reliability of system.

Step 3: Developing the software

Visual Basic is used as the database management system software for developing RPLS tool. This RPLS tool can be utilized by Lean practitioners. A Visual Basic (VB) tool was preferred for following features:

- The created program is a self-extracting file which allows Lean designers to use the tool without installation of special software packages.
- This program supports development of user-friendly graphical interfaces for inexperienced programmers.
- VB has the ability to integrate mathematical algorithm with knowledgebase information system.
- The only requirement for use of this tool is that the user should be familiar with all technical and organizational processes within the system.

- If not the user's inputs should be based on reliable information gathered from data, process knowledge and interviews with persons involved with respective processes.

Windows NT/XP operating system and MS Visual Basic 6.0 is required for smooth operation of this RPLS tool.

Step 4: Testing and maintaining the system

The initial step of using this RPLS tool is comparison of required conditions with actual conditions illustrated in Figure 8. A check-mark feature allows the user to select the Lean operating conditions which are not satisfied. This ensures that only pertinent information is displayed and the user is not overwhelmed. The associated root cause screen is presented in Figure 9. The potential root causes will become visible only for the "checked" areas, and this requires user input of estimated values for the three categories: probability of occurrence of actual business conditions, potential effects of severity, and effectiveness of detection of current Lean controls of root cause. In order to prevent input errors drop-down menus are implemented. This feature allows only the input of integer values within the defined range (1 to 10). Another benefit of this software is automatic and error-free calculation of RAV values after the input process is completed.

Figure 10 illustrates the final result that shows a listing of five root causes with the highest RAV values. These root causes represent the most promising opportunities for improvements to enhance Lean reliability. The success of an improvement project is ensured if the RAV value of the respective area is significantly reduced.

Step 5: Implementing and evaluating the system

This last phase of System Development Life Cycle involves installing the RPLS tool. A tool demonstration for users is required to evaluate and implement RPLS tool. Clear guidelines for using and maintaining this RPLS tool are formulated and documented as described in previous section.

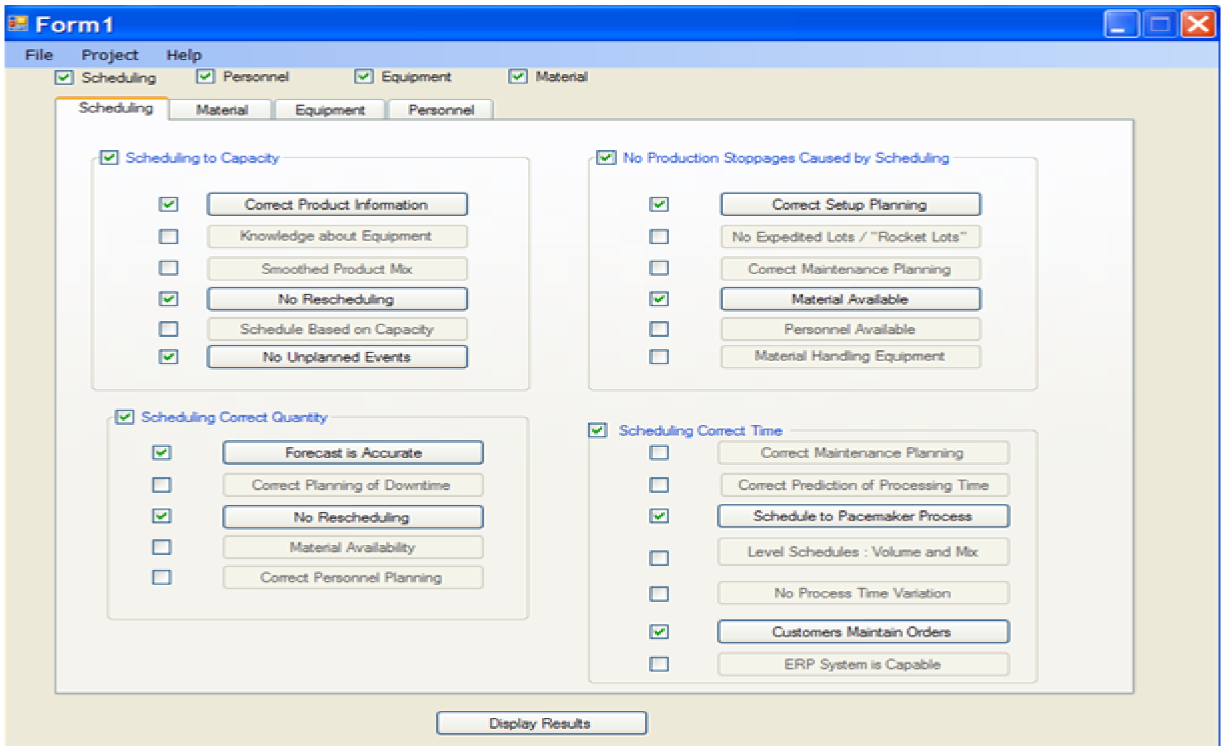

Figure 8 Screen for Operating Conditions for Scheduling

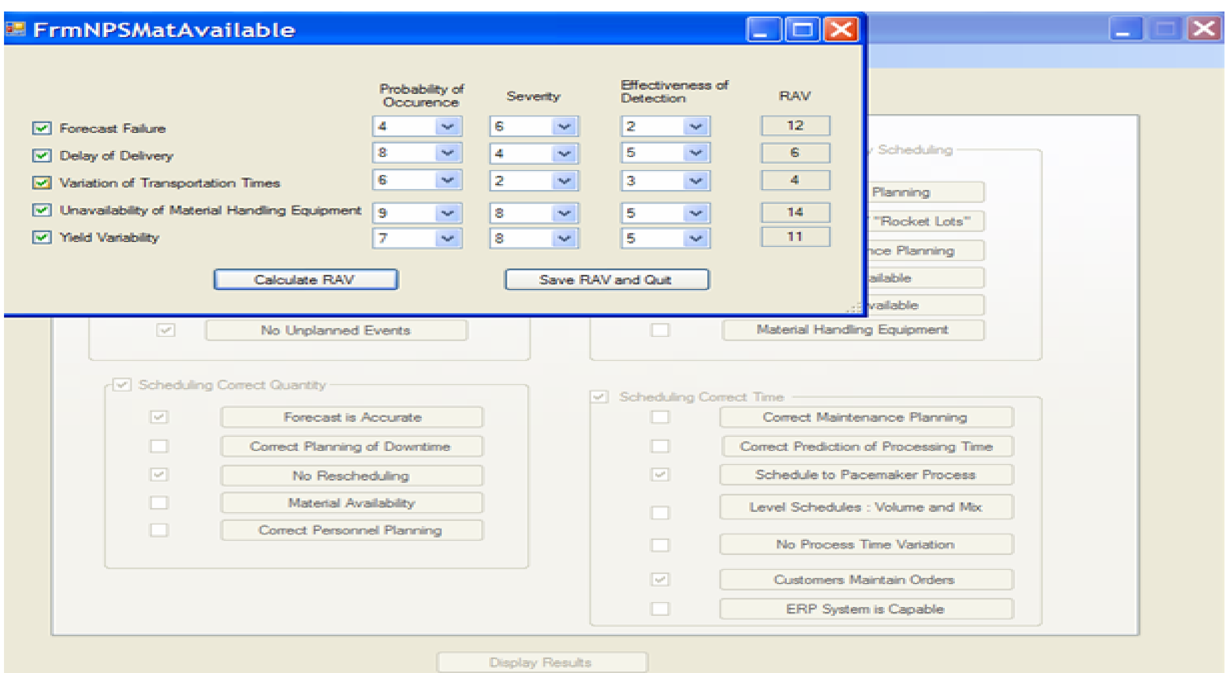

Figure 9 Screen for Assessing Root Causes

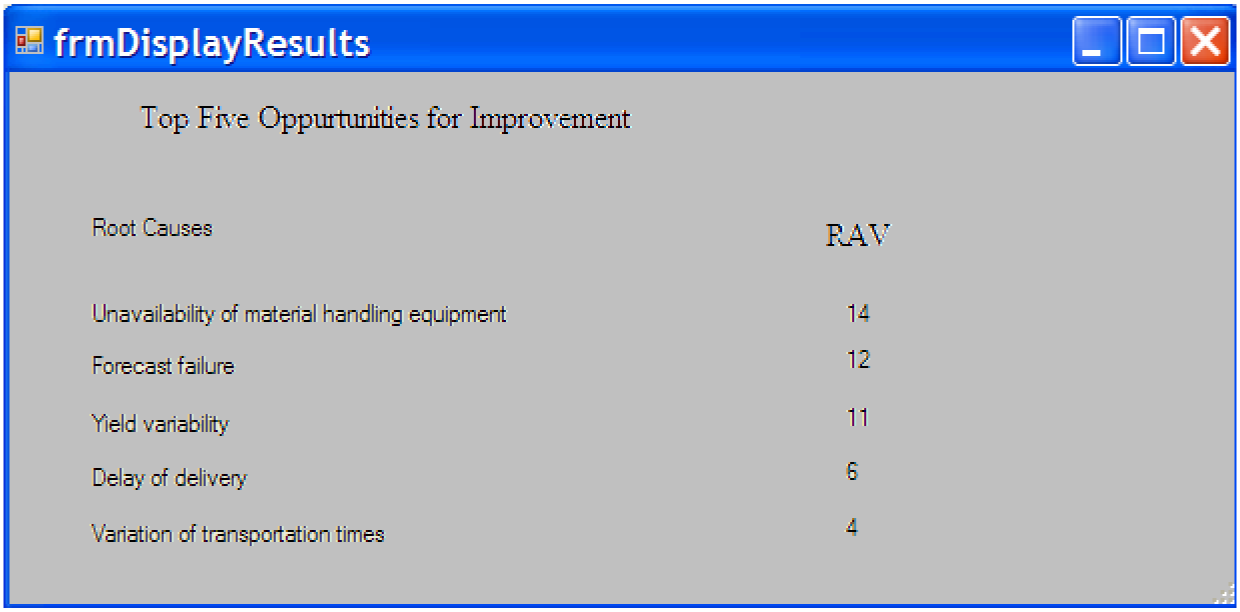

Figure 10 Screen of Final Results

Chapter 5: Case study and Validation

5.1 Introduction

This chapter draws a comparison between RAV and RPN rankings to determine the value of RAV to prioritize risks associated with Lean system. A hypothesis test is used to test for significant difference between RAV and RPN in prioritizing Lean system failures. An actual manufacturing facility was utilized as a test case. A survey was conducted among the shop floor employees to collect the data for the hypothesis test. This analysis was done in two phases. Phase 1 utilized hypothesis testing to determine if the ranking between RAV and RPN is different. Once the results indicated a difference between RAV and RPN, phase 2 utilized an Analytic Hierarchy Process (AHP) to determine which approach better method the Lean failures. A basic comparison between RAV and RPN is presented in Table 9.

RAV is better aligned with addressing Lean. The RAV numerator is the component of the equation that is not easily, directly, consistently or immediately impacted by Lean practitioners. Any improvement of this component is typically a by-product of the system's ability to detect a Lean system failure and subsequently design and apply controls that manage such failures. Effectiveness of detection is the only factor within RAV that have impact by human control. The factors S, O and D for RAV range from 1 to 10. The minimum and maximum value of RPN ranges from 1 to 1000 whereas RAV ranges from 0.1 to 100. Table in Appendix 1 provides a detailed illustration of how the RPN and RAV values were calculated.

Table 9 Difference between RPN and RAV

RPN	RAV
RPN = S*O*D where O - Probability of occurrence that the failure will occur S - Severity of the potential effect of the failure D - Likelihood that the problem will be detected	RAV = (S*O)/D where O - Probability of occurrence of actual conditions of Lean S - Severity of the potential effect of the failure D - Effectiveness of detection of root cause using current Lean controls
$1 \leq S \leq 10$ $1 \leq O \leq 10$ $1 \leq D \leq 10$	$1 \leq S \leq 10$ $1 \leq O \leq 10$ $1 \leq D \leq 10$
Minimum Value - 1 Maximum Value - 1000	Minimum Value - 0.1 Maximum Value - 100

5.2 Hypothesis Testing

Hypothesis testing consists of a pair of statements about the unknown parameter that enables one to make a decision whether to accept or reject a statement (Montgomery C. Douglas et al., 2001). The unknown parameter called Null Hypothesis is the first statement denoted by H_0. The second statement called Alternative Hypothesis is a declaration based on the new information denoted by Ha. The process of rejecting or not rejecting the null hypothesis H_0 is called hypothesis testing. The parameters in this case would be the RPN and RAV numbers that are calculated by the traditional FMEA approach and modified FMEA approach respectively**.** The hypothesis testing procedure outlined by Montgomery is utilized to perform hypothesis testing.

Step 1: Determine the parameter of interest

The critical task in this method is to determine if there is any difference in means of RPN and RAV numbers. Hence, the parameter of interest in this approach will be μ_1 and μ_2, the mean of the RPN numbers and RAV numbers.

$\mu_1 =$ mean of RAV numbers.

$\mu_2 =$ mean of RPN numbers.

Step 2: Define the null hypothesis, H_0

There is no difference in the means of RPN and RAV numbers. For a given Lean failure, RPN and RAV values have same ranking.

H_0: $\mu_1 = \mu_2$.

Step 3: Define the alternative hypothesis, H_a

The means of RPN and RAV numbers are not equal. For a given failure, RPN and RAV values have different ranking.

H_a: $\mu_1 \neq \mu_2$.

Step 4: Specify the significance level, α

The significant level is set at 0.05 for this case study.

Step 5: Test for Normality

Figure 11 and 12 provide a summary of the normal distribution test performed on RAV and RPN numbers respectively. RAV and RPN numbers were tested using JMP (Sall et al., 2005). The p value of normality test is significant to determine whether data fits normal distribution. If p value> 0.05 then RPN numbers and RAV numbers follow normality. From these figures, the p value determined from the Shapiro - Wilk test is <.0001 (Sall et al., 2005). This proves that RAV and RPN numbers do not fit the normal distribution.

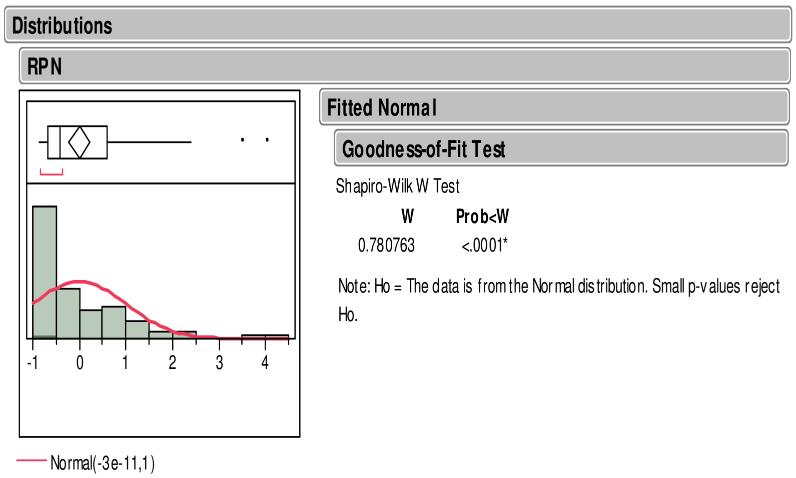

Figure 11 Test for Normality of RPN Numbers

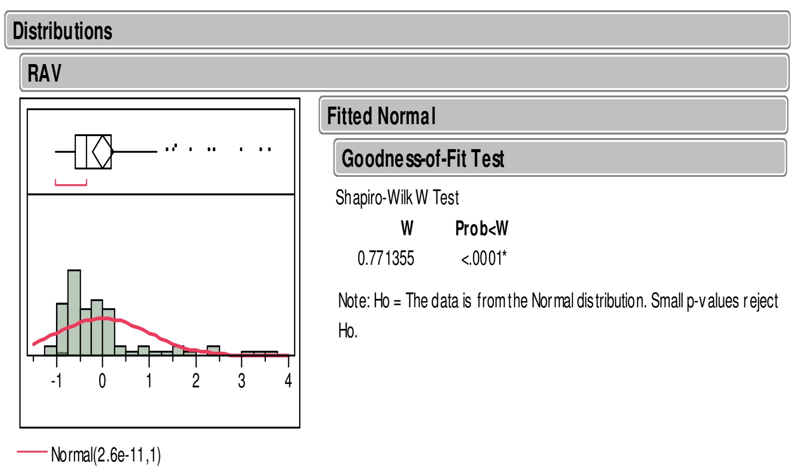

Figure 12 Test for Normality of RAV Numbers

Step 6: Non parametric rank F- test

When the distributions of error terms do not follow normality, a nonparametric test is used to perform hypothesis testing (Kutner et al., 2005). The assumption of continuous distribution is the requirement to perform this test. It was assumed that two samples followed continuous distribution. This test provides the basis for differences in means assuming that the shapes of two samples are identical.

In this step, the F_R* and F test statistic model developed in Microsoft Excel is assessed to accept or reject null hypothesis. As a result F_R* and F test statistic value for RAV and RPN numbers is calculated. If $F_R^* \leq F(1-\alpha; r-1, n_T-r)$ null hypothesis is concluded and if $F_R^* \leq F(1-\alpha; r-1, n_T-r)$ alternate hypothesis is concluded. Table A-2 shows the F_R* and F test statistic calculated for RAV and RPN numbers. The F_R* test statistic value is defined as ratio of MSTR to MSE. Equation 2 show the mathematical formula used for calculating F_R*.

$$F_R^* = MSTR/MSE \quad (2)$$

Where,

$$\text{Treatment Mean Square (MSTR)} = \frac{\sum n_i(\overline{R_i.} - \overline{R..})^2}{r-1} \quad (3)$$

$$\text{Error Mean Square (MSE)} = \frac{\sum\sum(R_{ij} - \overline{R}_{i..})^2}{(n_T - r)} \quad (4)$$

Where,

$$\overline{R}_{i.}. = \frac{\sum_j R_{ij}}{n_i} \quad (5)$$

$$\overline{R}.. = \frac{\sum\sum R_{ij}}{n_i} = \frac{(n_T+1)}{2} \quad (6)$$

Equation 3 and 4 represent the mathematical formula for calculating MSTR and MSE utilizing equation 5 and 6. The F statistic value is calculated using equation 7.

$$F\,(1\text{-}\alpha;\ r\text{-}1,\ n_T\text{-}r) \qquad (7)$$

Where,

α - Significance level
(r-1) - Degree of freedom 1
(n_T -r) - Degree of freedom 2

Step7: Accept or Reject the null hypothesis

This step is used to determine whether the means of RPN and RAV numbers are significantly different from each other. Table A-2 shows the results of non parametric rank F test performed on the means of RAV and RPN numbers at 95% significance level. It can be observed that F_R*> F (1-α; r-1, n_T -r) thereby rejecting the null hypothesis. This implies that the means of RAV and RPN numbers are not equal. Thus it can be concluded that means of RAV and RPN numbers are statistically different. Hence the question arises which of these two approaches will be a better approach to rank Lean failures?

5.3 Decision making with the Analytic Hierarchy Process (AHP)

Many problems in engineering involve decision making when the situation faces multiple objectives. Thomas Saaty's Analytic Hierarchy Process (AHP) is a powerful tool utilized to make such decisions. In this research, the objective of AHP is to determine which of these approaches: traditional RPN or RAV approach is better method to prioritize Lean risks. The approach follows the Saaty's procedure as described by Winston (2004).

Step 1: Construct a hierarchy modeling

The objective of AHP process is to determine the best approach to prioritize Lean failures. The criteria used to choose the objective is based on probability of occurrence; severity and effectiveness of detection. The hierarchy modeling for prioritizing Lean failures is shown in Figure 13.

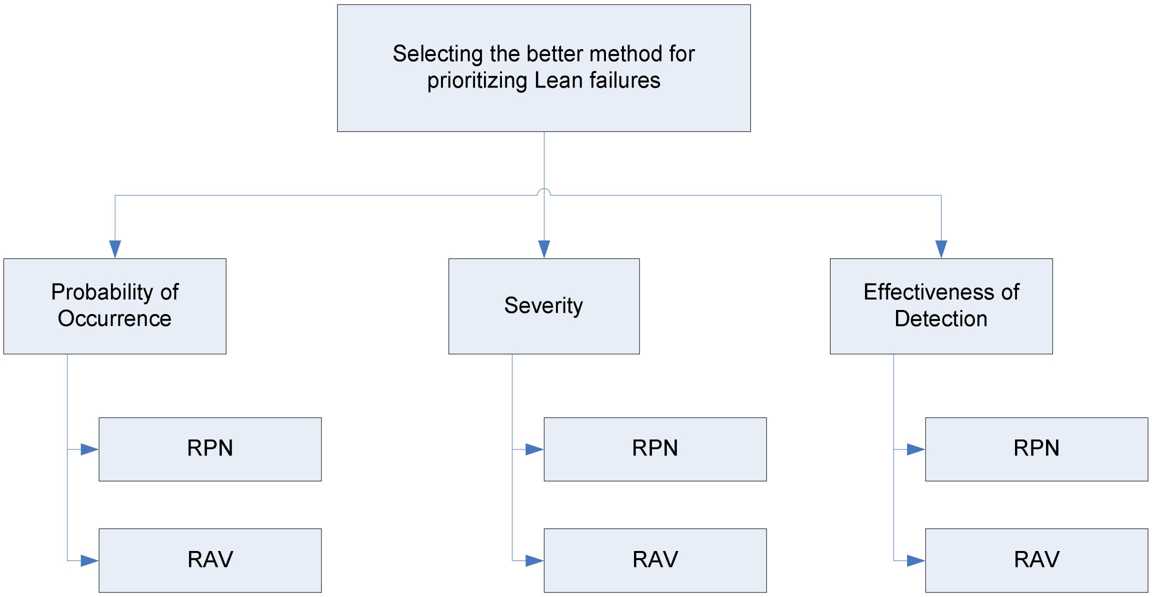

Figure 13 Hierarchy Modeling to Prioritize Lean Failures

Step 2: Determine the weights for each criteria and establishing pair wise comparisons

Pair wise comparison is used to describe the relative importance of one criterion over another. Table 10 shows Saaty's Interpretation of Entries in a Pair Wise Comparison Matrix that is used to establish comparison.

Table 10 Saaty's Interpretation of Entries in a Pair Wise Comparison Matrix

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment slightly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of the above	If activity I has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with I	A reasonable assumption
1.1 - 1.9	If the activities are very close	May be difficult to assign the best value but when compared with another contrasting activity the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

In RAV, the controls S and O do not have the ability to impact the occurrence of a risk event, as it is an external constraint which is outside the immediate control. In other cases, these controls may address the root cause of the failure and therefore reduce the occurrence of the risk event. Even in this case, the ability to impact the probability of occurrence may be medium to long term. The controls have lesser ability to impact the severity of a failure, as severity is an independent issue from either detection or occurrence. In essence, the numerator of RAV represents the risk profile of a Lean system failure. This profile is defined by the probability of Lean system failure to occur weighted by its consequence.

RAV better aligns with reducing Lean system risk as the RAV denominator, D is the only variable within RAV that Lean practitioners can directly and immediately impact by implementing Lean. A majority of the Lean tools are explicitly designed to detect/control and manage various system conditions. Examples of some common Lean tools that detect/control system status are 5S, production boards, supermarkets, proactive maintenance and moving lines. 5S organizes and standardizes the work area including tools, supplies and materials and has the ability to immediately detect missing/displaced tools, supplies and materials. Production boards detect if the system is producing based on specified schedules and within the given timetables. A supermarket detects the amount of inventories in the system and manages production based on these inventories. Proactive maintenance detects the condition of the equipment and maintains equipment to reduce unplanned events. Moving lines detect stoppages in production lines and manage the system to minimize line stoppages. The denominator of RAV represents the effectiveness of Lean tools to detect and manage failures. As a result, the pair wise comparison is established based on following assumptions.

- Effectiveness of detection is more important than probability of occurrence.
- Probability of occurrence is more important than severity.
- Effectiveness of detection is very strong than severity.

Step 3: Finding the score of alternative for an objective using Excel

It is important to conduct criterion analysis in order to determine the weighing values for the three criteria: effectiveness of detection, probability of occurrence and severity. Table 11 shows the results of weighing analysis obtained for each of three criteria.

Table 11 Pair Wise Comparison Matrix and Synthesis of Results for Overall Weighing Analysis

<table>
<tr><th colspan="4">Weighing Analysis for Overall Criteria</th></tr>
<tr><td>Weighing Analysis</td><td>Effectiveness of Detection</td><td>Probability of Occurrence</td><td>Severity</td></tr>
<tr><td>Effectiveness of Detection</td><td>1.000</td><td>3.000</td><td>7.000</td></tr>
<tr><td>Probability of Occurrence</td><td>0.333</td><td>1.000</td><td>5.000</td></tr>
<tr><td>Severity</td><td>0.143</td><td>0.200</td><td>1.000</td></tr>
<tr><td>Sum</td><td>1.476</td><td>4.200</td><td>13.000</td></tr>
<tr><td rowspan="3">Pairwise Synthesis</td><td>0.677</td><td>0.714</td><td>0.538</td></tr>
<tr><td>0.226</td><td>0.238</td><td>0.385</td></tr>
<tr><td>0.097</td><td>0.048</td><td>0.077</td></tr>
<tr><td rowspan="3">Row Average</td><td colspan="3">0.643</td></tr>
<tr><td colspan="3">0.283</td></tr>
<tr><td colspan="3">0.074</td></tr>
<tr><td rowspan="7">Aw^T</td><td>1.000</td><td>5.000</td><td>7.000</td></tr>
<tr><td>0.200</td><td>1.000</td><td>2.000</td></tr>
<tr><td>0.143</td><td>0.500</td><td>1.000</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>0.738</td><td colspan="2">2.237</td></tr>
<tr><td>0.168</td><td colspan="2">0.504</td></tr>
<tr><td>0.094</td><td colspan="2">0.284</td></tr>
<tr><td>λ_{max}</td><td colspan="3">3.014</td></tr>
<tr><td>CI</td><td colspan="3">0.007</td></tr>
<tr><td>RI</td><td colspan="3">0.012</td></tr>
<tr><td>CR</td><td colspan="3">0.012</td></tr>
</table>

Step4: Finding the score of an alternative for each criterion

Once the weighing analysis is determined, it is important to establish the alternate analysis for each criteria. Table 12, 13 and 14 shows the scores of RAV and RPN for the probability of occurrence, severity and effectiveness of detection.

Table 12 Determining the Scores of an Alternative for Probability of Occurrence

Probability of Occurrence		
Probability of Occurrence	RAV	RPN
RAV	1.000	0.333
RPN	3.000	1.000
Sum	4.000	1.333
Pairwise Synthesis	0.250	0.250
	0.750	0.750
Row Average	0.250	
	0.750	
Aw^T	0.500	
	1.500	
λ_{max}	2.000	
CI	-0.500	
RI	-0.862	

Table 13 Determining the scores of an Alternative for Severity

Severity		
Severity	RAV	RPN
RAV	1.000	0.333
RPN	3.000	1.000
Sum	4.000	1.333
Pairwise Synthesis	0.250	0.250
	0.750	0.750
Row Average	0.250	
	0.750	
Aw^T	0.500	
	1.500	
λ_{max}	2.000	
CI	-0.500	
RI	-0.862	

Table 14 Determining the Scores of an Alternative for Effectiveness of Detection

Effectiveness of Detection		
Effectiveness of Detection	RAV	RPN
RAV	1.000	5.000
RPN	0.020	1.000
Sum	1.200	6.000
Pairwise Synthesis	0.833	0.833
	0.166	0.166
Row Average	0.833	
	0.166	
Aw^T	1.666	
	0.333	
λ_{max}	2.000	
CI	-0.500	
RI	-0.862	

Step 5: Establishing the overall priorities for objective

Once the weighing values for the three criteria and scores of alternative for each criterion are determined, it is necessary to establish the overall priorities to achieve the objective. Table 15 shows the results of overall priorities of RAV and RPN in order to determine the better approach for prioritizing Lean risks. It can be observed from Table 15 that the overall priority for RAV is greater than RPN. Therefore it may be concluded that RAV is better approach to rank Lean failures.

Table 15 Overall Priorities

Criteria	Effectiveness of Detection		Probability of Occurrence		Severity	
Weighing	0.74		0.17		0.09	
Alternative	RAV	RPN	RAV	RPN	RAV	RPN
Priorities	0.83	0.17	0.25	0.75	0.25	0.75
Overall Priorities						
RAV	0.68					
RPN	0.32					
Conclusion - RAV is better						

Chapter 6: Conclusion

6.1 Introduction

This chapter summarizes the thesis work. It also describes the areas for further improvement.

6.2 Summary of Research

The main purpose of this thesis was to develop a methodology to enhance the reliability of Lean systems. The model developed in this thesis ranks Lean risks based on calculated RAV. It provides a structured approach for calculating RAV to prioritize Lean risks that the company is considering to implement. As a result Lean risks are eliminated or minimized to enhance the reliability of Lean systems. The empirical approach followed in this thesis eliminates the need for Lean practitioners and academicians to be aware of the Lean risks involved within four critical resources. The visual basic based RPLS tool developed for RAV calculation eliminates any additional effort needed by the end user.

The contributions of this research are as follows:

- Defined Lean system reliability in terms of four critical resources of Lean: personnel, equipment, materials and schedules
- Developed conceptual framework to justify the need for using modified FMEA approach
- Performed gap analysis for the four critical resources
- Developed a knowledge base in the form of detailed hierarchical root trees for the four critical resources that support our Lean system reliability
- Developed RAV based on concept of effectiveness of detection using Lean controls when Lean designer implements Lean change
- Developed modified FMEA for the four critical resources to prioritize Lean risks
- Developed RPLS tool to automate modified FMEA
- Developed case study to compare RAV and RPN numbers for the four critical resources of Lean
- Determined RAV as better method to prioritize Lean risks

6.3 Recommendation

Further research could be carried out utilizing neural networks to develop a more robust decision model. This requires that the application of logic be established that defines the relationship within the HTD's. The following are areas for further research

- Validated weighing values for probability of occurrence, severity and effectiveness of detection would enhance the RAV calculations based on Lean experts input.
- All the four resources can be surveyed among more industries to determine its practicality.
- In the automated RPLS tool, Lean controls for all the potential root causes can be determined.

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Appendix

Table A-1 Survey Results of RAV and RPN Numbers

Lean Failure	Probability of Occurrence	Prob of occ in %	Potential Effects	Severity	Controls	Effectiveness of Detection	RPN	Untied Rankings	Tied RPN Rankings	RAV	Untied Rankings	Tied RAV Rankings
Required Capacity	5	0.05	Inability to Deliver Overtime	3	Preventive Maintenance	9	1.350	49	49.000	0.017	15.000	15.000
	5	0.05	Rescheduling	3	SMED	7	1.050	45	45.000	0.021	27.000	27.000
Required Capability	4	0.04	Defective Product	4	Cp and Cpk Maintenance	3	0.480	31	32.500	0.053	61.000	61.000
	4	0.04	Inability to Deliver Overtime	3		3	0.360	23	24.000	0.040	45.000	47.500
Calibration	8	0.08	Defects	4	Gauge R and R	8	2.560	63	63.000	0.040	45.000	47.500
	8	0.08	Shipped Good Parts Scrapped	5		8	3.200	68	68.500	0.050	57.000	57.500
Equipment Flexibility	7	0.07	Excessive Equipment	6	Cp and Cpk Maintenance	3	1.260	47	47.000	0.140	75.000	75.000
	7	0.07	Large Setup Times	7		3	1.470	51	51.000	0.163	76.000	76.000
	7	0.07	Large Batch Size	8		3	1.680	53	53.000	0.187	78.000	78.000
Proactive Maintenance	8	0.08	High Downtime	3	No Total Preventive Maintenance	10	2.400	59	60.500	0.024	28.000	29.500
	8	0.08	Unplanned Events	4		10	3.200	68	68.500	0.032	41.000	41.000
	8	0.08	Inability to Deliver Overtime	5		10	4.000	73	73.000	0.040	45.000	47.500
Proper Equipment	3	0.03	Capability and Capability Issues of the Equipment	8	No Total Productive Maintenance	10	2.400	59	60.500	0.024	28.000	29.500
Efficient Flow	9	0.09	High Lead Time	6	No Kanban	10	5.400	75	75.500	0.054	62.000	62.500
	9	0.09	High Inventory	8	No Kanban	10	7.200	77	77.000	0.072	66.000	66.000
	9	0.09	High Material Handling	9	No Supermarkets	10	8.100	78	78.000	0.081	68.000	68.000
Efficient Setup	6	0.06	Large Batch Size	7	No SMED	10	4.200	74	74.000	0.042	52.000	52.000
	6	0.06	High Lead Time	6		10	3.600	72	72.000	0.036	44.000	44.000
	6	0.06	Inability to Deliver Overtime	9		10	5.400	75	75.500	0.054	62.000	62.500
Small and Frequent Delivery	2	0.02	Excessive Inventory	4	No Kanban System	10	0.800	40	40.500	0.008	3.000	3.500
	2	0.02		4	Annual Supplier Evaluation	3	0.240	16	16.000	0.027	32.000	32.000
	2	0.02		4	ERP System Discrepancy	4	0.320	20	21.000	0.020	17.000	20.500
	2	0.02		4	No Control	10	0.800	40	40.500	0.008	3.000	3.500
Delivery as per Schedule	2	0.02	Production Stoppage	2	No Control	10	0.400	26	27.000	0.004	1.000	1.500
	2	0.02	Modify Schedule	2	Receiving Manager	4	0.160	10	11.000	0.010	5.000	6.500
Delivery of Correct Quantity	2	0.02	Modify Schedule	2	No Control	10	0.400	26	27.000	0.004	1.000	1.500
	3	0.03	Incomplete Order	2	Procurement Manager	5	0.300	19	19.000	0.012	9.000	9.000
Delivery of Quality Parts	3	0.03	Modify Schedule	2	Internal Design Process	2	0.120	5	7.000	0.030	35.000	37.500
	3	0.03	Incomplete Order	2	Engineering Dept Manager	2	0.120	5	7.000	0.030	35.000	37.500
	3	0.03	Quality Issues	7	No Control	10	2.100	57	57.500	0.021	25.000	25.500
Capable System to Receive	2	0.02	Missing Material	2	Receiving SOP - Unenforced	4	0.160	10	11.000	0.010	5.000	6.500
	2	0.02	Delayed Material	2	Human Resource Training	3	0.120	5	7.000	0.013	11.000	12.000
Capable System to Warehouse	1	0.01	Missing Material	2	Ware House SOP	2	0.040	1	1.500	0.010	5.000	6.500
	1	0.01	Delayed Material	2	Human Resource Training	2	0.040	1	1.500	0.010	5.000	6.500
Capable Part Movement Based on Requirement	2	0.02	Parts not Available When Required	2	Material Handler SOP	2	0.080	3	3.500	0.020	17.000	20.500
	2	0.02		2	No Visual Boards	2	0.080	3	3.500	0.020	17.000	20.500
Part properly identified	3	0.03	Missing Material	4	SOP	4	0.480	31	32.500	0.030	35.000	37.500
	2	0.02	Lost Material	4	Routing Sheets	4	0.320	20	21.000	0.020	17.000	20.500

Table A-1 Survey Results of RAV and RPN Numbers

Lean Failure	Probability of Occurrence	Prob of occ in %	Potential Effects	Severity	Controls	Effectiveness of Detection	RPN	Untied Rankings	Tied RPN Rankings	RAV	Untied Rankings	Tied RAV Rankings
Material Delivered to Point of Use	2	0.02	Missing Material	2	No SOP	3	0.120	5	7.000	0.013	11.000	12.000
Forecast is Accurate	2	0.02	Excessive Inventory	5	Forecast Accuracy Reports	2	0.200	15	15.000	0.050	57.000	57.500
	2	0.02	Customer Delivery not Met	4		2	0.160	10	11.000	0.040	45.000	47.500
Customers Maintain Orders	3	0.03	Product not Shipped	2	Sales force communication with operations	3	0.180	13	13.500	0.020	17.000	20.500
	3	0.03	Complete Reschedule	3		3	0.270	17	17.500	0.030	35.000	37.500
ERP System is Capable	4	0.04	Excessive Inventory	5	Physical Cycle Count	2	0.400	26	27.000	0.100	70.000	70.000
	4	0.04	Customer Delivery not Met	4		2	0.320	20	21.000	0.080	67.000	67.000
Schedule Based on Capacity	3	0.03	Constant Reschedule	6	No Control	10	1.800	55	55.000	0.018	16.000	16.000
	3	0.03	Increased Batch Size	7		10	2.100	57	57.500	0.021	25.000	25.500
	3	0.03	Increased Setups	8		10	2.400	59	60.500	0.024	28.000	29.500
	3	0.03	Delayed Delivery	9		10	2.700	64	64.000	0.027	33.000	33.000
No Unplanned Events	4	0.04	Constant Reschedule	6	No Control	10	2.400	59	60.500	0.024	28.000	29.500
	4	0.04	Increased Batch Size	7		10	2.800	65	66.000	0.028	34.000	34.000
	4	0.04	Increased Setups	8		3	0.960	43	43.500	0.107	72.000	72.000
	4	0.04	Delayed Delivery	9		2	0.720	37	38.000	0.180	77.000	77.000
Schedule Correct Quantity	2	0.02	Modify Schedule	3	Production Reports	3	0.180	13	13.500	0.020	17.000	20.500
	2	0.02		3	Routing Sheets	2	0.120	5	7.000	0.030	35.000	37.500
Schedule Correct Time	3	0.03	Constant Reschedule	6	Production Reports	4	0.720	37	38.000	0.045	55.000	55.000
	5	0.05	Increased Batch Size	7	Shipment Reports	10	3.500	71	71.000	0.035	42.000	42.000
Schedule to Pacemaker Process	3	0.03	Increased Scheduling Complexity	7	Production Supervisor	4	0.840	42	42.000	0.053	60.000	60.000
	3	0.03	Not Smooth Flow	8		4	0.960	43	43.500	0.060	65.000	65.000
Level Schedules : Volume and Mix	3	0.03	Constant Reschedule	6	Heijunka	2	0.360	23	24.000	0.090	69.000	69.000
	3	0.03	Increased Batch Size	7		2	0.420	29	29.000	0.105	71.000	71.000
	3	0.03	Increased Setups	8		2	0.480	31	32.500	0.120	73.000	73.000
	3	0.03	Delayed Delivery	9		2	0.540	35	35.500	0.135	74.000	74.000
Capable and Trained Personnel	5	0.05	SOP not followed	5	Training Matrix	7	1.750	54	54.000	0.036	43.000	43.000
	5	0.05	Defects	6	Personnel Evaluation	6	1.800	56	56.000	0.050	59.000	59.000
Effective Organizational Communication	3	0.03	Reduced Employee Morale	4	No Control	6	0.720	37	38.000	0.020	17.000	20.500
	3	0.03	Ineffective Teamwork	3		6	0.540	35	35.500	0.015	14.000	14.000
Effective Job and Workplace	4	0.04	Safety Issues	3	No SOP	3	0.360	23	24.000	0.040	45.000	47.500
	4	0.04	Quality Issues	2	No 5S	6	0.480	31	32.500	0.013	11.000	12.000
Personnel Availability	3	0.03	Rescheduling	3	Policy for missing work	3	0.270	17	17.500	0.030	35.000	37.500
	3	0.03	Wasting Time	5	Personnel Evaluation	3	0.450	30	30.000	0.050	56.000	56.000
Error Free Inspection	5	0.05	Ship Defects	7	No Poka Yoke	8	2.800	65	66.000	0.044	53.000	53.000
	5	0.05	Customer Complaints	8		7	2.800	65	66.000	0.057	64.000	64.000
Multifunction Worker	4	0.04	Lack of ability to meet dynamic demand	9	Training Matrix	9	3.240	70	70.000	0.040	45.000	47.500
Mutual Respect	4	0.04	Reduced Employee Morale	4	Organizational Culture Management	8	1.280	48	48.000	0.020	17.000	20.500
	4	0.04	Ineffective Teamwork	3		9	1.080	46	46.000	0.013	10.000	10.000
Motivated Workforce	2	0.02	Reduced Employee Morale	3	Organizational Culture Management	9	1.442	50	50.000	0.044	54.000	54.000
	2	0.02	Ineffective Teamwork	4		8	1.664	52	52.000	0.040	51.000	51.000

Table A-2 Non Parametric Rank F Test Calculation

RPN	Normalized RPN	RAV	Normalized RAV
1.350	-0.058	0.017	-0.693
1.050	-0.241	0.021	-0.573
0.480	-0.588	0.053	0.231
0.360	-0.661	0.040	-0.105
2.560	0.679	0.040	-0.105
3.200	1.069	0.050	0.147
1.260	-0.113	0.140	2.414
1.470	0.015	0.163	3.002
1.680	0.143	0.187	3.589
2.400	0.582	0.024	-0.508
3.200	1.069	0.032	-0.306
4.000	1.556	0.040	-0.105
2.400	0.582	0.024	-0.508
5.400	2.408	0.054	0.248
7.200	3.505	0.072	0.701
8.100	4.053	0.081	0.928
4.200	1.678	0.042	-0.054
3.600	1.312	0.036	-0.206
5.400	2.408	0.054	0.248
0.800	-0.393	0.008	-0.911
0.240	-0.734	0.027	-0.441
0.320	-0.685	0.020	-0.609
0.800	-0.393	0.008	-0.911
0.400	-0.636	0.004	-1.012
0.160	-0.783	0.010	-0.860
0.400	-0.636	0.004	-1.012
0.300	-0.697	0.012	-0.810
0.120	-0.807	0.030	-0.357
0.120	-0.807	0.030	-0.357
2.100	0.399	0.021	-0.583
0.160	-0.783	0.010	-0.860
0.120	-0.807	0.013	-0.776
0.040	-0.856	0.010	-0.860
0.040	-0.856	0.010	-0.860
0.080	-0.831	0.020	-0.609
0.080	-0.831	0.020	-0.609
0.480	-0.588	0.030	-0.357
0.320	-0.685	0.020	-0.609
0.120	-0.807	0.013	-0.776

Table A-2 Non Parametric Rank F Test Calculation

RPN	Normalized RPN	RAV	Normalized RAV
0.200	-0.758	0.050	0.147
0.160	-0.783	0.040	-0.105
0.180	-0.770	0.020	-0.609
0.270	-0.716	0.030	-0.357
0.400	-0.636	0.100	1.406
0.320	-0.685	0.080	0.903
1.800	0.216	0.018	-0.659
2.100	0.399	0.021	-0.583
2.400	0.582	0.024	-0.508
2.700	0.764	0.027	-0.432
2.400	0.582	0.024	-0.508
2.800	0.825	0.028	-0.407
0.960	-0.295	0.107	1.574
0.720	-0.442	0.180	3.421
0.180	-0.770	0.020	-0.609
0.120	-0.807	0.030	-0.357
0.720	-0.442	0.045	0.021
3.500	1.251	0.035	-0.231
0.840	-0.368	0.053	0.210
0.960	-0.295	0.060	0.399
0.360	-0.661	0.090	1.155
0.420	-0.624	0.105	1.532
0.480	-0.588	0.120	1.910
0.540	-0.551	0.135	2.288
1.750	0.186	0.036	-0.213
1.800	0.216	0.050	0.147
0.720	-0.442	0.020	-0.609
0.540	-0.551	0.015	-0.735
0.360	-0.661	0.040	-0.105
0.480	-0.588	0.013	-0.776
0.270	-0.716	0.030	-0.357
0.450	-0.606	0.050	0.147
2.800	0.825	0.044	-0.010
2.800	0.825	0.057	0.327
3.240	1.093	0.040	-0.105
1.280	-0.101	0.020	-0.609
1.080	-0.222	0.013	-0.776
1.442	-0.002	0.044	0.001
1.664	0.133	0.040	-0.099
1.445		0.044	
Std Dev	1.642	0.040	

Table A-2 Non Parametric Rank F Test Calculation

Normalized RPN and RAV	Untied Ranking	Tied Ranking
-0.058	100.000	100.000
-0.241	86.000	86.000
-0.588	55.000	89.250
-0.661	38.000	100.667
0.679	128.000	128.000
1.069	136.000	136.000
-0.113	91.000	91.000
0.015	105.000	105.000
0.143	108.000	108.000
0.582	124.000	132.500
1.069	137.000	137.000
1.556	144.000	144.000
0.582	125.000	125.500
2.408	149.000	151.500
3.505	154.000	154.000
4.053	156.000	156.000
1.678	146.000	146.000
1.312	141.000	141.000
2.408	150.000	149.500
-0.393	74.000	52.000
-0.734	30.000	30.000
-0.685	35.000	50.667
-0.393	75.000	74.500
-0.636	42.000	34.667
-0.783	19.000	31.667
-0.636	43.000	43.000
-0.697	33.000	33.000
-0.807	14.000	37.200
-0.807	15.000	16.000
0.399	121.000	70.500
-0.783	20.000	20.000
-0.807	16.000	16.000
-0.856	9.000	9.500
-0.856	10.000	9.500
-0.831	11.000	11.500
-0.831	12.000	11.500
-0.588	56.000	56.500
-0.685	36.000	36.000
-0.807	17.000	16.000

Table A-2 Non Parametric Rank F Test Calculation

Normalized RPN and RAV	Untied Ranking	Tied Ranking
-0.758	28.000	28.000
-0.783	21.000	20.000
-0.770	26.000	28.500
-0.716	31.000	37.500
-0.636	44.000	43.000
-0.685	37.000	36.000
0.216	115.000	118.500
0.399	122.000	121.500
0.582	126.000	125.500
0.764	130.000	130.000
0.582	127.000	125.500
0.825	131.000	94.333
-0.295	84.000	76.000
-0.442	68.000	37.667
-0.770	27.000	26.500
-0.807	18.000	16.000
-0.442	69.000	69.000
1.251	140.000	140.000
-0.368	76.000	76.000
-0.295	85.000	84.500
-0.661	39.000	39.000
-0.624	45.000	45.000
-0.588	57.000	56.500
-0.551	62.000	87.500
0.186	113.000	113.000
0.216	116.000	115.500
-0.442	70.000	69.000
-0.551	63.000	62.500
-0.661	40.000	39.000
-0.588	58.000	56.500
-0.716	32.000	31.500
-0.606	54.000	49.500
0.825	132.000	132.000
0.825	133.000	132.000
1.093	138.000	138.000
-0.101	98.000	98.000
-0.222	88.000	88.000
-0.002	103.000	103.000
0.133	107.000	107.000
-0.693	34.000	34.000

Table A-2 Non Parametric Rank F Test Calculation

Normalized RPN and RAV	Untied Ranking	Tied Ranking
-0.573	61.000	61.000
0.231	117.000	117.000
-0.105	92.000	125.333
-0.105	93.000	94.500
0.147	109.000	141.750
2.414	151.000	151.000
3.002	152.000	152.000
3.589	155.000	155.000
-0.508	64.000	76.500
-0.306	83.000	83.000
-0.105	94.000	94.500
-0.508	65.000	65.500
0.248	118.000	123.500
0.701	129.000	129.000
0.928	135.000	135.000
-0.054	101.000	101.000
-0.206	90.000	90.000
0.248	119.000	118.500
-0.911	3.000	37.000
-0.441	71.000	71.000
-0.609	46.000	28.250
-0.911	4.000	3.500
-1.012	1.000	1.500
-0.860	5.000	24.250
-1.012	2.000	1.500
-0.810	13.000	13.000
-0.357	77.000	41.667
-0.357	78.000	79.500
-0.583	59.000	32.500
-0.860	6.000	6.500
-0.776	23.000	23.500
-0.860	7.000	6.500
-0.860	8.000	6.500
-0.609	47.000	49.500
-0.609	48.000	49.500
-0.357	79.000	79.500
-0.609	49.000	49.500
-0.776	24.000	23.500
0.147	110.000	110.500
-0.105	95.000	94.500

Table A-2 Non Parametric Rank F Test Calculation

Normalized RPN and RAV	Untied Ranking	Tied Ranking
-0.609	50.000	49.500
-0.357	80.000	79.500
1.406	142.000	142.000
0.903	134.000	134.000
-0.659	41.000	41.000
-0.583	60.000	59.500
-0.508	66.000	65.500
-0.432	72.000	72.000
-0.508	67.000	65.500
-0.407	73.000	73.000
1.574	145.000	145.000
3.421	153.000	153.000
-0.609	51.000	49.500
-0.357	81.000	79.500
0.021	106.000	106.000
-0.231	87.000	87.000
0.210	114.000	114.000
0.399	123.000	123.000
1.155	139.000	139.000
1.532	143.000	143.000
1.910	147.000	147.000
2.288	148.000	148.000
-0.213	89.000	89.000
0.147	111.000	110.500
-0.609	52.000	49.500
-0.735	29.000	29.000
-0.105	96.000	94.500
-0.776	25.000	23.500
-0.357	82.000	79.500
0.147	112.000	110.500
-0.010	102.000	102.000
0.327	120.000	120.000
-0.105	97.000	94.500
-0.609	53.000	49.500
-0.776	22.000	75.000
0.001	99.000	99.000
-0.099	104.000	104.000

Table A-2 Non Parametric Rank F Test Calculation

RPN Ranking	RAV Ranking	ri.	r (bar) i.	n i							
100.000	34.000	134.000	67.000	2.000	-12.256	150.199	300.397	33.000	-33.000	1089.000	1089.000
86.000	61.000	147.000	73.500	2.000	-5.756	33.126	66.253	12.500	-12.500	156.250	156.250
89.250	117.000	206.250	103.125	2.000	23.869	569.750	1139.501	-13.875	13.875	192.516	192.516
100.667	125.333	226.000	113.000	2.000	33.744	1138.688	2277.375	-12.333	12.333	152.111	152.111
128.000	94.500	222.500	111.250	2.000	31.994	1023.644	2047.289	16.750	-16.750	280.563	280.563
136.000	141.750	277.750	138.875	2.000	59.619	3554.478	7108.956	-2.875	2.875	8.266	8.266
91.000	151.000	242.000	121.000	2.000	41.744	1742.599	3485.197	-30.000	30.000	900.000	900.000
105.000	152.000	257.000	128.500	2.000	49.244	2425.015	4850.031	-23.500	23.500	552.250	552.250
108.000	155.000	263.000	131.500	2.000	52.244	2729.482	5458.964	-23.500	23.500	552.250	552.250
132.500	76.500	209.000	104.500	2.000	25.244	637.282	1274.564	28.000	-28.000	784.000	784.000
137.000	83.000	220.000	110.000	2.000	30.744	945.221	1890.442	27.000	-27.000	729.000	729.000
144.000	94.500	238.500	119.250	2.000	39.994	1599.556	3199.111	24.750	-24.750	612.563	612.563
125.500	65.500	191.000	95.500	2.000	16.244	263.882	527.764	30.000	-30.000	900.000	900.000
151.500	123.500	275.000	137.500	2.000	58.244	3392.415	6784.831	14.000	-14.000	196.000	196.000
154.000	129.000	283.000	141.500	2.000	62.244	3874.371	7748.742	12.500	-12.500	156.250	156.250
156.000	135.000	291.000	145.500	2.000	66.244	4388.326	8776.653	10.500	-10.500	110.250	110.250
146.000	101.000	247.000	123.500	2.000	44.244	1957.571	3915.142	22.500	-22.500	506.250	506.250
141.000	90.000	231.000	115.500	2.000	36.244	1313.660	2627.320	25.500	-25.500	650.250	650.250
149.500	118.500	268.000	134.000	2.000	54.744	2996.954	5993.908	15.500	-15.500	240.250	240.250
52.000	37.000	89.000	44.500	2.000	-34.756	1207.949	2415.897	7.500	-7.500	56.250	56.250
30.000	71.000	101.000	50.500	2.000	-28.756	826.882	1653.764	-20.500	20.500	420.250	420.250
50.667	28.250	78.917	39.458	2.000	-39.797	1583.819	3167.638	11.208	-11.208	125.627	125.627
74.500	3.500	78.000	39.000	2.000	-40.256	1620.510	3241.020	35.500	-35.500	1260.250	1260.250
34.667	1.500	36.167	18.083	2.000	-61.172	3742.041	7484.082	16.583	-16.583	275.007	275.007
31.667	24.250	55.917	27.958	2.000	-51.297	2631.405	5262.810	3.708	-3.708	13.752	13.752
43.000	1.500	44.500	22.250	2.000	-57.006	3249.633	6499.267	20.750	-20.750	430.563	430.563
33.000	13.000	46.000	23.000	2.000	-56.256	3164.688	6329.375	10.000	-10.000	100.000	100.000
37.200	41.667	78.867	39.433	2.000	-39.822	1585.809	3171.619	-2.233	2.233	4.988	4.988
16.000	79.500	95.500	47.750	2.000	-31.506	992.600	1985.200	-31.750	31.750	1008.063	1008.063
70.500	32.500	103.000	51.500	2.000	-27.756	770.371	1540.742	19.000	-19.000	361.000	361.000
20.000	6.500	26.500	13.250	2.000	-66.006	4356.733	8713.467	6.750	-6.750	45.563	45.563
16.000	23.500	39.500	19.750	2.000	-59.506	3540.911	7081.822	-3.750	3.750	14.063	14.063
9.500	6.500	16.000	8.000	2.000	-71.256	5077.354	10154.708	1.500	-1.500	2.250	2.250
9.500	6.500	16.000	8.000	2.000	-71.256	5077.354	10154.708	1.500	-1.500	2.250	2.250
11.500	49.500	61.000	30.500	2.000	-48.756	2377.104	4754.208	-19.000	19.000	361.000	361.000
11.500	49.500	61.000	30.500	2.000	-48.756	2377.104	4754.208	-19.000	19.000	361.000	361.000
56.500	79.500	136.000	68.000	2.000	-11.256	126.688	253.375	-11.500	11.500	132.250	132.250
36.000	49.500	85.500	42.750	2.000	-36.506	1332.656	2665.311	-6.750	6.750	45.563	45.563
16.000	23.500	39.500	19.750	2.000	-59.506	3540.911	7081.822	-3.750	3.750	14.063	14.063

Table A-2 Non Parametric Rank F-Test Calculation

RPN Ranking	RAV Ranking	ri.	r (bar) i.	n i							
28.000	110.500	138.500	69.250	2.000	-10.006	100.111	200.222	-41.250	41.250	1701.563	1701.563
20.000	94.500	114.500	57.250	2.000	-22.006	484.244	968.489	-37.250	37.250	1387.563	1387.563
28.500	49.500	78.000	39.000	2.000	-40.256	1620.510	3241.020	-10.500	10.500	110.250	110.250
37.500	79.500	117.000	58.500	2.000	-20.756	430.793	861.586	-21.000	21.000	441.000	441.000
43.000	142.000	185.000	92.500	2.000	13.244	175.415	350.831	-49.500	49.500	2450.250	2450.250
36.000	134.000	170.000	85.000	2.000	5.744	32.999	65.997	-49.000	49.000	2401.000	2401.000
118.500	41.000	159.500	79.750	2.000	0.494	0.244	0.489	38.750	-38.750	1501.563	1501.563
121.500	59.500	181.000	90.500	2.000	11.244	126.438	252.875	31.000	-31.000	961.000	961.000
125.500	65.500	191.000	95.500	2.000	16.244	263.882	527.764	30.000	-30.000	900.000	900.000
130.000	72.000	202.000	101.000	2.000	21.744	472.821	945.642	29.000	-29.000	841.000	841.000
125.500	65.500	191.000	95.500	2.000	16.244	263.882	527.764	30.000	-30.000	900.000	900.000
94.333	73.000	167.333	83.667	2.000	4.411	19.458	38.916	10.667	-10.667	113.778	113.778
76.000	145.000	221.000	110.500	2.000	31.244	976.215	1952.431	-34.500	34.500	1190.250	1190.250
37.667	153.000	190.667	95.333	2.000	16.078	258.495	516.990	-57.667	57.667	3325.444	3325.444
26.500	49.500	76.000	38.000	2.000	-41.256	1702.021	3404.042	-11.500	11.500	132.250	132.250
16.000	79.500	95.500	47.750	2.000	-31.506	992.600	1985.200	-31.750	31.750	1008.063	1008.063
69.000	106.000	175.000	87.500	2.000	8.244	67.971	135.942	-18.500	18.500	342.250	342.250
140.000	87.000	227.000	113.500	2.000	34.244	1172.682	2345.364	26.500	-26.500	702.250	702.250
76.000	114.000	190.000	95.000	2.000	15.744	247.888	495.775	-19.000	19.000	361.000	361.000
84.500	123.000	207.500	103.750	2.000	24.494	599.978	1199.956	-19.250	19.250	370.563	370.563
39.000	139.000	178.000	89.000	2.000	9.744	94.954	189.908	-50.000	50.000	2500.000	2500.000
45.000	143.000	188.000	94.000	2.000	14.744	217.399	434.797	-49.000	49.000	2401.000	2401.000
56.500	147.000	203.500	101.750	2.000	22.494	506.000	1012.000	-45.250	45.250	2047.563	2047.563
87.500	148.000	235.500	117.750	2.000	38.494	1481.822	2963.645	-30.250	30.250	915.063	915.063
113.000	89.000	202.000	101.000	2.000	21.744	472.821	945.642	12.000	-12.000	144.000	144.000
115.500	110.500	226.000	113.000	2.000	33.744	1138.688	2277.375	2.500	-2.500	6.250	6.250
69.000	49.500	118.500	59.250	2.000	-20.006	400.222	800.445	9.750	-9.750	95.063	95.063
62.500	29.000	91.500	45.750	2.000	-33.506	1122.622	2245.245	16.750	-16.750	280.563	280.563
39.000	94.500	133.500	66.750	2.000	-12.506	156.389	312.778	-27.750	27.750	770.063	770.063
56.500	23.500	80.000	40.000	2.000	-39.256	1540.999	3081.997	16.500	-16.500	272.250	272.250
31.500	79.500	111.000	55.500	2.000	-23.756	564.326	1128.653	-24.000	24.000	576.000	576.000
49.500	110.500	160.000	80.000	2.000	0.744	0.554	1.108	-30.500	30.500	930.250	930.250
132.000	102.000	234.000	117.000	2.000	37.744	1424.643	2849.286	15.000	-15.000	225.000	225.000
132.000	120.000	252.000	126.000	2.000	46.744	2185.043	4370.086	6.000	-6.000	36.000	36.000
138.000	94.500	232.500	116.250	2.000	36.994	1368.589	2737.178	21.750	-21.750	473.063	473.063
98.000	49.500	147.500	73.750	2.000	-5.506	30.311	60.622	24.250	-24.250	588.063	588.063
88.000	75.000	163.000	81.500	2.000	2.244	5.038	10.075	6.500	-6.500	42.250	42.250
103.000	99.000	202.000	101.000	2.000	21.744	472.821	945.642	2.000	-2.000	4.000	4.000
107.000	104.000	211.000	105.500	2.000	26.244	688.771	1377.542	1.500	-1.500	2.250	2.250
			r(bar)..								
	r..	12363.867	79.256	156.000		MSTR	215598.799				
										SSE	94502.976
										MSE	613.656
										F-Value	351.335
										F*	3.840

Vita

Karthik Subburaman was born in Chennai, India. He graduated in 2006 with a Bachelor's degree in Mechanical Engineering. He came to The University of Tennessee, Knoxville in 2007 to pursue his Master's degree in the Industrial Engineering. He joined Dr.Rupy Sawhney as a Graduate Research Assistant and worked on industrial projects over the course of two years. Karthik is currently completing his master's degree in Industrial Engineering.