A SYSTEMATIC CONSIDERATION OF THE HUMAN AND TECHNICAL ELEMENTS IN THE IMPLEMENTATION OF LEAN MANUFACTURING CELLS

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Some manufacturing companies are successful, while many others fail in their efforts to implement lean philosophies and practices into their manufacturing operations. Although the technical process flows and cell designs meet the standards and criteria specified in the literature, these companies most often do not fully consider the impact of the human element in the management of change.

It is hypothesized that an approach that combines the implementation of lean manufacturing cells with technical, human and lean practices considerations will result in improved cell performance. This research investigates how to create and implement such a system and evaluate its impact on a manufacturer's cell performance.

A questionnaire is developed, based on literature and industry research, to collect employee perceptions regarding the importance rating and implementation levels of the technical, human and lean practices within a manufacturing cell. Manufacturing cell performance data is collected and analyzed in concert with the questionnaire to prove the hypothesis. The approach is piloted at an aero engine manufacturer and the results are provided.

The findings indicate that as a foundation, manufacturing cells must achieve a certain level of implementation in the technical areas of machines, methods, and materials. With all else equal, manufacturing cells that achieve higher implementation levels of the human and lean practices, also achieve higher cell performance.

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PREFACE

I would like to thank Dr. Bopaya Bidanda, Dr. Kim LaScola Needy, Dr. Larry Shuman, Dr. Bryan Norman, Dr. Jayant Rajgopal, Dr. David Cleland and Dr. Harvey Wolfe for their support through my graduate school experience. I greatly appreciated the financial assistance provided through the Industrial Engineering Department, Manufacturing Assistance Center, and research projects which enabled me to pursue both my Masters and Ph.D. degrees. In addition, I would like to thank the Swanson School of Engineering, the Society of Manufacturing Engineers, and the National Science Foundation for fellowship and grant support.

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1.0 INTRODUCTION

In order to satisfy their customers and remain globally competitive, many companies have made major investments of time, resources, and capital in implementing lean philosophies into their manufacturing operations. While some succeed, a much higher proportion fail to achieve the full benefits of lean manufacturing (Dale 1999, Wemmerlov and Hyer 1989). The 2007 Industry Week / Manufacturing Performance Institute Census of Manufacturers polled 433 companies and reported that nearly 70% of the manufacturing plants in the United States are currently employing lean as an improvement methodology (Blanchard 2007, Pay 2008). Further, only 2% of the responding companies have fully achieved their performance objectives, while 24% have reported significant improvements. The balance of the companies, or 74% percent, state that they have not made the progress with lean that was anticipated (Blanchard 2007, Pay 2008).

1.1 BACKGROUND

Lean manufacturing can be described as a production system and management philosophy that employs a systematic approach to eliminating waste while creating value for the customer (Womack and Jones 1996). When analyzing the root cause of failure of advanced manufacturing technologies such as lean manufacturing, one of the most common failure modes cited is insufficient consideration of the human element (Chung 1996, Mital 1995, Sawhney and Chason

2005). A listing of key enablers for successful implementation of lean manufacturing are as follows (Bidanda *et al.* 2005, Chung 1996, Needy *et al.* 2002): clear objectives, human-centered approach, up-front involvement of workers in planning stages, use of pilot projects to illustrate success, appointment of a senior change champion, a structured approach to employee selection and training, use of techniques to overcome resistance, development of fit-for-purpose reward systems, organizational re-design alignment, and worker empowerment. The majority of these factors have the human element in common which supports the need for further research on the topic of the human element in lean manufacturing.

1.2 PROBLEM STATEMENT

While companies may achieve robust technical process flows and manufacturing cell designs, many do not fully consider the human element and its importance in achieving the full benefits of lean manufacturing in terms of performance measures such as delivery, quality and cost. There exists a need for a simple and systematic approach that fully considers both the technical and human issues in the implementation of lean manufacturing cells. Additionally, organizations require structured guidance on which areas to focus in a prioritized manner to most expeditiously achieve the anticipated benefits of lean.

1.3 PURPOSE OF THE STUDY

The approach proposed in this work has the potential to assist manufacturing companies that are just beginning the lean journey or are currently experiencing issues with implementing and sustaining lean within their operations. The purpose of the research is to investigate how to design and implement a model than enables an organization to achieve manufacturing system performance improvements by focusing both on the technical and human aspects of lean manufacturing and its successful implementation.

An assessment questionnaire is developed to gather data on the manufacturing cell specific variables and the lean practices that are required for successful implementation. A field study is conducted in four manufacturing cells over a 56 month period at an aero engine manufacturer. Performance data and questionnaire data regarding the cell and business unit are collected, analyzed and the results reported. Finally, the research investigates the importance and implementation levels of technical and human aspects within lean manufacturing cells and evaluates the relationship between these aspects and the performance of the cells.

2.0 LITERATURE REVIEW

2.1 CELLULAR MANUFACTURING

Group technology (GT) is a management philosophy that was originally proposed by Mitrofanov in 1966 and extended by Burbidge in 1971. GT attempts to identify parts with similar design and/or manufacturing characteristics so that they may be produced together. This results in reductions in setup time, work-in-process inventory, cycle time, tooling requirements and material handling (Heragu 1994, Huq 1992).

Cellular manufacturing (CM) is an application of GT in a manufacturing system. CM is based on operators processing part families, or collections of similar parts, in cells, or clusters of dedicated machines which are dissimilar in function (Wemmerlov and Hyer 1987). The justification for cell formation includes those associated with GT plus the ability to realize significant improvements in product quality, scheduling, space utilization, control of operations and employee morale (Heragu 1994, Singh 1993, Wemmerlov and Hyer 1987, Wemmerlov and Hyer 1989).

The cell formation problem involves the decomposition of a manufacturing system into cells (Singh 1993). Numerous techniques have been developed for solving this complex problem (Heragu 1994, Singh 1993). Each of these techniques can be placed into one or more of the following broad categories: classification and coding, production flow analysis, similarity coefficients, mathematical programming, fuzzy clustering, artificial intelligence (e.g. neural networks, genetic algorithms, tabu search, simulated annealing), knowledge-based, cost-based and heuristics (Heragu 1994, Singh 1993, Vakharia and Selim 1994).

Over the past 35 years numerous techniques have been developed for solving the cell formation problem (Heragu 1994, Joines *et al*. 1995, Singh 1993). However, users of these techniques often obtain varying levels of success within their cellular systems (Wemmerlov and Hyer 1989).

2.2 LEAN MANUFACTURING

In 1950, a Japanese engineer named Eiji Toyoda visited the Ford Motor Company River Rouge plant in Detroit Michigan (Dennis 2007, Toyoda 1987). At the time, his home country and the Toyota Motor Company, which was founded in 1937 by his family, were in chaos. After 13 years of production operations, Toyota had only produced 2,685 automobiles, while Ford's River Rouge plant was producing 7,000 per day (Dennis 2007, Toyoda 1987, Womack 2000). Upon his return to Japan, Eiji Toyoda teamed with his engineering genius, Taiichi Ohno, and determined that they must develop an alternative to mass production due to the severe restrictions that existed including: depression, lack of capital, and restricted credit which almost forced the small company into bankruptcy (Dennis 2007, Womack 2000).

After extensive negotiation, the family owners of Toyota Motor Company and the union crafted an agreement with three key points: 1) twenty-five percent of the workforce was terminated, 2) Kiirchiro Toyoda resigned as president and claimed responsibility for the failure, 3) the remaining workers were guaranteed lifetime employment and pay related to seniority with bonus tied to company profitability (Dennis 2007, Toyoda 1987, Womack 2000). An employment contract built upon cooperation, flexibility and mutual benefits had been instituted as a partnership. Toyota managed to achieve the most important condition for lean production – through consideration of the human element – and the Toyota Production grew out of pure necessity and as a mechanism for survival (Dennis 2007).

The Toyota Motor Company is widely credited with conceiving, developing, and implementing many of the fundamental tenants that form the foundation of lean manufacturing (Calarge *et al.* 2011, Genaidy and Karwowski 2003, Nightingale and Mize 2002, Womack *et al*. 1990). The Toyota Production System focused primarily on the manufacturing level of an organization (Monden 1998, Ohno 1988) with a philosophy of identification and progressive reduction of waste. Traditionally, seven wastes were recognized: transportation, inventory, movement, waiting, over-processing, over-production, and defects (Ohno 1988). An eighth waste was recognized as "people", or more clearly, the waste of human talents and creativity (Dennis 2007, Womack *et al.* 1990).

The term "lean production system" was first introduced by John Krafcik, a graduate student at Massachusetts Institute of Technology (MIT) and a research assistant in their International Motor Vehicle Program (IMVP) (Krafcik 1988, Murman *et al.* 2002). The term was chosen because lean does more and more with less and less while moving closer and closer to providing customers with exactly what they want (Krafcik 1988, Murman *et al.* 2002, Nightingale 1998, Womack *et al.* 1990).

The results of the first five years of the IMPV research at MIT were published in The Machine that Changed the World (Womack *et al.* 1990). The research was based upon a benchmarking study of more than 90 automobile assembly plants in 17 countries which represented approximately half of the worldwide capacity. Womack *et al.* (1990) reported that Japanese-owned plants, regardless of location, were more productive than American-owned plants in the United States. In addition, European-owned plants in Europe performed even more poorly. From a product quality standpoint, Japanese plants performed an average of 50 percent better than the US plants and 47 percent better than the European plants. In addition, Japanese-owned plants achieved higher productivity and quality when compared with the domestically owned plants in Europe and the US, where either one or the other attribute could be found, but not both. The researchers attributed the differences to the lean production systems within the Japanese manufacturing facilities. It was clearly time for lean production systems to be adopted into American automobile manufacturing and assembly plants.

In the early 1990s, shortly after the end of the Cold War, new pressures began to be exerted on aerospace manufacturers. The industry faced massive reductions in defense budgets and increased competition in commercial and military markets. The aerospace mantra of "Higher, Faster, Farther" changed in an instant when Dan Goldin, the Administrator of NASA set the challenge of "Better, Faster, Cheaper" (Murman *et al.* 2000a, Murman *et al.* 2000b, Murman *et al.* 2002). In 1992, the Aeronautical Systems Center of the US Air Force contacted the IMVP at MIT to launch an exploratory effort to determine if lean principles could be applied to the defense aerospace industry (Murman *et al.* 2000a, Murman *et al.* 2000b, Murman *et al.* 2002, Nightingale 1998).

The Lean Aircraft Initiative (LAI) was born out of practicality and was formally launched in 1993 when leaders from the US Air Force, MIT, labor unions, and defense aerospace businesses forged a partnership to revolutionize the industry using a philosophy called lean (Murman *et al.* 2000a, Murman *et al.* 2000b, Murman *et al.* 2002, Nightingale 1998, Nightingale and Mize 2002). In 1998, the name was changed to the Lean Aerospace Initiative with the addition of the space sector to the consortium (Murman *et al.* 2002). Then, in 1999, when Boeing Commercial Airplane Group joined, the program's scope was complete, covering all areas of the aerospace industry. This also raised awareness that the scope would have to address the wider domain of defense and commercial aerospace (Murman *et al.* 2002). Currently, the scope has broadened once more to include automotive, electronics and healthcare. The consortium is now titled the Lean Advancement Initiative, with strong ties to the United Kingdom LAI, and continues to work to expand the concept of the "lean enterprise" (Nightingale and Mize 2002).

Womack and Jones (1996), from MIT, employ benchmarking data in their book *Lean Thinking* to illustrate that there is a better way to organize and manage customer relations, the supply chain, product development, and production operations. Their framework includes two key tenants that must be accomplished in parallel: eliminating waste while creating value for the customer. They introduce the five accepted principles of lean production: 1) identify value in the eyes of the customer, 2) map the value stream, 3) make the value stream flow, 4) plan for the customer to pull the product, and 5) strive for perfection. The researchers present various case studies, but one of the largest contributions is that they provide insight into the application of lean in the aerospace industry via a case study at Pratt and Whitney, as well as an evolution of the world aerospace history. Pratt was the world's largest producer of military jet engines and held the world's largest market share in commercial engines at that time (Womack and Jones 1996). Additionally, Murman *et al.* (2002) provide a comprehensive timeline of intellectual history of lean in their book, *Lean Enterprise Value*.

2.3 INDUSTRY GUIDELINES ON LEAN PRACTICES

As previously noted, lean manufacturing had its roots in Japanese auto manufacturing due to devastating economic pressures, and then migrated into the United States automotive industry and eventually into the aerospace industry (Kessler 1999, Murman *et al.* 2002). Standardization is a key component to the implementation of advanced manufacturing technologies (Mital 1995, SAE 1999b, Vasilash 2000). In almost parallel timelines, two major industries were developing lean operations standards for companies to use which provided common definitions and an approach to measure the implementation level of lean practices within their organizations.

2.3.1 Society of Automotive Engineers J4000 Specification

As part of their ongoing Best Manufacturing Practices survey program, the Society of Automotive Engineers (SAE) conducted a survey in 1998 and determined that the vice presidents of six major auto manufacturers ranked lean manufacturing as the most important success factor in the competitiveness of the industry looking forward (SAE 1999a). In response, SAE began the development of their lean operation standard.

The standard was based upon evaluating companies including the Donnelly Corporation, Freudenberg-NOK, Johnson Controls Inc., Lockheed Martin Corporation, Raytheon Corporation, and The Timken Company – all recognized as lean models. SAE J4000: Identification and Measurement of Best Practice in Lean Operation was first published in August 1999 and can be used to identify and measure implementation of lean systems and management practices in automotive manufacturing companies (Calarge *et al.* 2008, Calarge *et al.* 2011, SAE 1999a). It was later supplemented by the SAE J4001: Implementation of Lean Operation User Manual in November 1999 (SAE 1999b) as a detailed guide for users.

SAE J4000 covers six lean elements: 1) management/trust, 2) people, 3) information, 4) supplier/organization/customer chain, 5) product, and 6) process / flow. There are 52 items within the six elements that provide measurable points of reference for successful lean implementation (SAE 1999a). Each individual item is measured on a four point scale from zero to three and is summarized in Table 2.1 below (SAE 1999a, SAE 1999b).

Table 2.1 SAE J4000 Scoring Legend

Score	Meaning
0	The component (item) is not implemented or there are fundamental inconsistencies in its implementation
1	The component (item) is implemented but there are still less significant inconsistencies in its implementation
2	The component (item) is satisfactorily implemented
3	The component (item) is satisfactorily implemented and has shown a continuous improvement for the last 12 months

The characteristic that differentiates the SAE J4000 standard from its counterparts is the scoring description for level 3. The nature of requiring continuous improvement within the last 12 months makes the standard dynamic in nature. Further, an organization may score a 3 on an element at a specific point in time, but then decline to a score of 2 if they do not meet the improvement requirement. This suggest that lean is not a destination, but a continuing journey for an organization (Degirmenci 2008, Vasilash 2000).

Although SAE J4000 has been developed after extensive research and industry benchmarking, it has not received the attention from industry that had been hoped, nor achieved the ultimate goal of becoming the common standard for lean implementation (Degirmenci 2008).

Of the 244 companies responding to Degirmenci's (2008) 13 question survey regarding lean, 85% of the companies responded that they were not at all aware of the SAE J4000 standard. In an attempt to diagnose root cause for the poor deployment of the standard, Degirmenci (2008) contacted SAE and interviewed their Director of SAE Automotive Headquarter Operations, who was a member of the team that developed the SAE J4000 standard. The director provided three reasons as to why he believed the standard was not successful in being adopted by companies and lean practitioners: lack of advertising and promotion, SAE's strong sector affiliation, companies adopted lean principles from other resources and were hesitant to change course to utilize the new standard (Degirmenci 2008).

2.3.2 Lean Aerospace Initiative Lean Enterprise Model

The Lean Enterprise Model (LEM) is a systematic framework for organizing and disseminating research results of the Lean Aerospace Initiative (LAI) (Ramirez-de-Arellano *et al.* 2000). It is comprised of lean enterprise principles and practices and is populated by research-based benchmarking data derived from surveys, case studies, and other research activities (Nightingale 1998, Nightingale and Mize 2002, Ramirez-de-Arellano *et al.* 2000). The LEM is designed to help practitioners and management assess the leanness of their own organizations and processes, and is intended to help leverage opportunities for future lean efforts (Murman *et al.* 2000a, Nightingale 1998, Ramirez-de-Arellano *et al.* 2000). There a realization that lean is not unique to aerospace, and therefore, the principles of the LEM are quite generic for application across a range of industries (Nightingale 1998).

The LAI LEM covers twelve overarching lean practices (elements): 1) identify and optimize enterprise flow, 2) assure seamless information flow, 3) optimize capability and utilization of people, 4) make decisions at lowest possible level, 5) implement integrated product and process development, 6) develop relationships based on mutual trust and commitment, 7) continuously focus on the customer, 8) promote lean leadership at all levels, 9) maintain challenge of existing processes, 10) nurture a learning environment, 11) ensure process capability and maturation, 12) maximize stability in a changing environment (MIT 1996). Each individual item is measured on a three point scale, from zero to two, and is summarized in Table 2.2 below (MIT 1996, Ramirez-de-Arellano *et al.* 2000).

Table 2.2 LAI LEM Scoring Legend

Score	**Meaning**
0	Lack of implementation of an enabling practice (item)
1	Partial implementation of an enabling practice (item)
2	Full implementation of an enabling practice (item)

Many of the 12 overarching practices (elements) and 61 enabling practices (items) of the LEM are directly related to the consideration of the human element in the implementation of lean.

As part of LAI's aircraft engine sector research, Ramirez-de-Arellano *et al.* (2000) completed a study of final assembly operations at three different aero engine manufacturers from 1995 to 1997. They spent on average three to six months at each site. The study focused on capturing the manufacturing system performance measures and comparing those to attributes of the manufacturing system to understand what attributes enabled better performance. Data was gathered at each site on one type of military and one type of commercial engine models. The smallest sample sizes, of only ten engines for each type, occurred at the poorest performing site and ranged to a maximum 77 engines at the most successful site. The researchers utilized six of the overarching practices: 1, 2, 3, 4, 8, and 10 as listed above to evaluate the three sites. They revisited one of the sites that have made marked improvements during the course of the study, so four sites are reported in the results. When the total LEM score was summed for the six overarching practices for each site, it became quite apparent that the sites which achieved the best delivery performance tended to have higher LEM scores, indicating they had implemented more of the lean practices from the LEM (Ramirez-de-Arellano *et al.* 2000). The study considered system performance measures of product throughput time, on-time delivery, and disruptions to the final assembly process.

2.3.3 Lean Aerospace Initiative Lean Enterprise Self Assessment Tool

As an extension to the development of the LAI LEM, the broader Lean Enterprise Self Assessment Tool (LESAT) was developed by a team of industry, government and academicians under the auspices of the LAI at MIT (Nightingale and Mize 2002). The tool was concurrently developed between the United States LAI and the United Kingdom LAI and was field tested on 20 companies before the team arrived at a common set of LESAT Maturity Matrices (Nightingale and Mize 2002).

The LESAT is organized into three assessment sections: 1) Lean Transformation / Leadership, 2) Life Cycle Processes, and 3) Enabling Infrastructure. Nightingale and Mize (2002) provide a comprehensive overview of the LESAT development, deployment, and future plans for maturity.

2.4 THE NEED TO CONSIDER THE HUMAN ELEMENT

Competitive advantage can result when the human element is considered in the cellular manufacturing environment (Bidanda *et al*. 2005, Jordan 1997, Norman *et al*. 2002). Additionally, a marked number of researchers have cited the absence of, and clear need for, consideration of the human element in lean manufacturing (Askin and Huang 1997, Askin and Huang 2001, Bidanda *et al.* 2000, Bidanda *et al.* 2005, Huq 1992, Min and Shin 1993, Needy *et al*. 2001, Needy *et al*. 2002, Norman *et al*. 2000, Norman *et al*. 2002, Russell *et al.* 1991, Warner *et al*. 1997, Wemmerlov and Hyer 1987).

In general, winning efforts in lean manufacturing result from understanding the four basic components of manufacturing cells: 1) *people* who utilize 2) *equipment* under 3) *operating rules* to transform 4) *material* into a saleable product (Bidanda *et al*. 1999, Vakharia and Selim, 1994). Successful companies do not ignore the first component - people. They include members from all areas of their organizations in every step of the transition. The employees who will eventually operate, manage, support, and maintain the cells are the people who design, develop, and build them (Bidanda *et al*. 1999).

Overall, misconceptions exist concerning the implementation of advanced manufacturing technologies such as lean manufacturing cells into an organization. The literature provides abundant examples of difficulties that may result when a company adopts an advanced manufacturing technology assuming that it is simply a matter of good technical design, some basic training, and perhaps rewriting a few job descriptions (Liker and Majchrzak 1994).

A study of users of cellular manufacturing in U.S. industry indicates that 25 of the 32 companies surveyed, or 78%, implemented only “manned” cells (low degree of automation, high labor intensity) in their facilities. Also, 6 more of the 32 companies implemented both “manned” and “unmanned” cells (high degree of automation, low labor intensity) (Wemmerlov and Hyer 1989). Therefore, 98% of the companies were required to make decisions regarding the placement of workers and the related human issues in their manufacturing cells.

The issues associated with a group of people working closely together in the same manufacturing cell are crucial to the success of the cellular implementation and need to be considered and integrated along with the technical requirements of the cellular manufacturing system (Huber and Hyer 1985, Huq 1992, Min and Shin 1993).

Therefore, to be both useful and applicable in most industrial implementations, research efforts should be focused towards developing new cell formation methods that consider multiple objectives along with human issues, such as the assignment of workers to cells (Frazier *et al.* 1990, Ham and Han 1986, Min and Shin 1993, Venugopal and Narendran 1992, Wemmerlov and Hyer 1987). Bidanda *et al*. (2005) provide a comprehensive review of the literature in regard to the human related issues in lean manufacturing design, implementation and operation. Their review is quite complete as they considered lean and cellular manufacturing sources as well as sources in regard to the general area of technology implementation.

2.5 PREVIOUS CONSIDERATION OF THE HUMAN ELEMENT

The complete implementation of lean manufacturing into an organization typically requires major modifications of the production system, which can result in significant changes in worker roles (Johnson and Manoochehri 1990). An important requirement for lean manufacturing is an increased level of technical skills and flexibility for workers. In lean manufacturing, workers can be assigned to different machines within a cell or to a different cell depending on production requirements for the system (Hedge *et al.* 1994, Johnson and Manoochehri 1990). Johnson and Manoochehri (1990) summarize the employee requirements for success in lean manufacturing: dedicated workers who have multiple skills (including technical as well as communication and interpersonal skills); who have the discipline to follow strict methods and procedures; who are willing to make decisions and accept responsibility; and who are committed to efficient and effective production operations.

For the implementation of lean manufacturing, the type and extent of training required often depends on the nature of the production process, the size of the plant, and the previous methods of production (Huq 1992). However, in introducing lean manufacturing, another handicap for successful implementation has been the general inability of the personnel and training functions of companies to make an accurate assessment of the skills and knowledge requirements of a particular job. Without this information, the required education and training inputs cannot be accurately deduced (Huq 1992). This further supports the development of worker assignment models and consideration of the human element in lean manufacturing.

2.5.1 Cell Formation and Worker Assignment Models

A 1989 study of U.S. users of lean manufacturing shows that in 75% of the companies surveyed, the cell operators were either directly selected by management, or volunteered for the job and were later approved by management (Wemmerlov and Hyer 1989). Workers are primarily assigned to a cell based on their experience and knowledge of how to run the required machines or perform the required operations. These decisions are usually based on the judgment of a supervisor or manager and not on scientific methods (Wemmerlov and Hyer 1989).

The vast majority of cell formation literature considers manufacturing cells in terms of their respective parts and machines, and regards the machines' capacities as the factors that limit production (Russell *et al*. 1991). In a lean manufacturing environment, however, it is most common to find workers operating two or more machines at the same time, or completing multiple assembly tasks within a cell. This has led to the limited study of labor allocation approaches in lean manufacturing. Unfortunately, these methods only consider humans and their assignment to cells in terms of their labor capacity (Russell *et al*. 1991), or rate at which they can produce a part, and not in terms of the skills they possess.

Due to the nature of manufacturing cells, single worker assignments cannot be independently considered. The worker assignments need to be made on a team basis within a cell, because the collective skills of the team members and their interactions with one another will be directly correlated to the output of the cell (Min and Shin 1993, Vakharia and Selim 1994). Consideration of individual workers or individual cells will likely lead to sub-optimization within the cellular system.

In an attempt to rectify the lack of consideration of worker skills, Min and Shin (1993) have proposed the simultaneous development of machine and human manufacturing cells. Simultaneous is defined as forming cells and assigning workers to those cells in the same solution step. The problem is formulated as a multi-objective mathematical program with numerous constraints, but must be decomposed into two smaller sub-problems to be efficiently solved (Min and Shin 1993).

In the first sub-problem, cell formation occurs, whereby parts and machines are grouped together using a traditional grouping method (Min and Shin 1993). In the second sub-problem, workers are assigned to the resulting cells based on their skill match. Skill match is defined as a worker's ability to produce the required parts within their respective cells.

The primary limitation of this model is the development of the skill matching factors which are specified in scales ranging from 0 (no match) to 5 (perfect match). The drawback to this work is that hypothetical data is utilized. Also, the model only considers the conflicting objectives of maximizing the skill match while minimizing the labor costs. This provides no prediction of the cellular system's outcome in terms of its production performance measures, such as throughput, performance to schedule, and product quality. Finally, the model considers the worker skills to be static with no provision for training.

Askin and Huang (1997) develop and compare two integer programming models for minimizing the total training cost when transitioning a facility from a functional to cellular layout. A sample list of technical and human skills is provided under the headings of equipment operation, administration, maintenance, and quality assurance (Askin and Huang 1997). The model considers cross-training, but does not include a job rotation plan for the tasks for which the workers were cross-trained. In addition, the skills are only examined in a binary manner, rather than multiple possible levels. The work is extended by Askin and Huang (2001) to examine the formation of worker teams and the specification of worker cross-training plans in manufacturing cell design. A number of heuristic algorithms are applied to solve the team formation and worker assignment problem. A full factorial designed experiment is employed to evaluate the heuristics. The low and high levels for the number of workers per cell are 2 and 8. These same values are used for the low and high number of cells. The number of skills evolves in this model from the binary consideration (Askin and Huang 1997) to two levels (one for a low level of skill and two for a high level of skill). The multi-objective model assigns workers to cells to minimize the costs of worker training, loss due to mismatch between an individual's physical or cognitive abilities and the requirements of the tasks they are assigned, and team synergy.

Warner (1996) and Warner *et al.* (1997) investigate the relevant technical and human elements that need to be considered when assigning workers to cells. Technical skills are described as mechanical, mathematic and measurement ability, while human skills are comprised of communication, leadership, teamwork and decision-making ability (Capelli and Rogovsky 1994). Hierarchical matrices are utilized to map which workers have the required skills to perform the tasks within a defined manufacturing cell (Warner 1996, Warner *et al.* 1997).

Needy *et al.* (2000) directly extend the research of Warner (1996) and Warner *et al.* (1997) with the objective of developing a systematic approach and an output predictive performance model for implementing manufacturing cells with both technical and human skills considerations. The formulation explicitly considers the human element both in the objective function and in the model constraints. In addition to technical and human skills, this source also introduces a new category of "lean" skills (Needy *et al.* 2000).

Needy *et al.* (2001) and Needy *et al.* (2002) propose a model for assessing human capital in a lean manufacturing environment. The primary steps to their research methodology are as follows: building a skills database, identifying critical skills, and assessing those skills. The critical skills are populated into a Skills Inventory Form (SIF) which is then used to assess the skill levels of each worker. The researchers recommend choosing three to five skills in each of the three skill categories of technical, human and lean for a total of nine to fifteen skills.

The model is then applied to a case study at a unionized Fortune 100 manufacturing company that employs about 700 workers. From their specific skills database, eight technical, four human and three lean skills were selected to populate the SIF. The sample included 45 employees across two shifts.

After analyzing the results, both shifts selected four technical and two lean skills for their training program focus. None of the human skills were chosen as a training focus. As a result, three training courses were initiated: 5S / workplace organization (Hirano 1993, Hirano 1995), an explanation of how their product works, and troubleshooting / problem-solving. A detailed discussion is provided in regard to training, selection, worker assignment, employee compensation and reward systems (Needy *et al.* 2002).

Norman *et al*. (2000) and Norman *et al*. (2002) develop a worker assignment model which extends the previous work (Askin and Huang 1997, Askin and Huang 2001, Bhaskar *et al.* 1997, Bokhorst and Slomp 2000, Campbell 1999, Caron *et al.* 1999, Cessani and Steudel 2000a, Cessani and Steudel 2000b, Kher 2000, Min and Shin 1993, Needy *et al.* 2002, Warner 1996, Warner *et al.* 1997) with the aim of addressing a number of their shortcomings. The model includes both technical and human skills considerations and is formulated as a mixed integer programming problem. The objective is to maximize the effectiveness of the organization which is defined as a function of the productivity, output quality, and training costs associated with a particular worker assignment solution.

The model provides flexibility in that the skill level of the workers may be increased through additional training. Testing was performed on 32 problems with varying levels of total training time, available training time for each worker, training costs, productivity coefficients and quality coefficients. The formulation considers six workers, six tasks, six skills (four technical and two human) and four levels of skills. In summary, the researchers illustrate that the model provides better worker assignments when both human and technical skills are considered (Norman *et al.* 2002).

Similar to Norman *et al*. (2002), McDonald *et al.* (2009) propose a worker assignment model in a lean manufacturing environment that extends the various models from the current literature via a mixed integer programming problem. The overall objective of the model is to minimize the net present cost of production. Net present cost is comprised of four components: initial training costs, additional training costs, inventory costs and the cost of poor quality. The model also considers job rotation and determines the level of skills and training necessary to deliver the required customer demand.

For demonstration purposes, the model is used to generate a worker assignment schedule for workers in a lean manufacturing cell at an electronics assembly plant where 13 workers perform 25 tasks. The resulting worker assignment schedules are evaluated using cost results from the optimization model in tandem with a cell simulation model to assess net present costs and the worker assignment schedules based on flow time, inventory and shipments (McDonald *et al.* 2009). This work provides management with a tool to evaluate the financial impact of increased cross-training within a lean manufacturing cell. In addition, the topic of job-rotation for skills retention across multiple tasks is considered as a key outcome.

2.5.2 Surveys and Frameworks

In addition to cell formation and worker assignment research, there have been a marked number of surveys developed and used to explore various elements of lean manufacturing. Fazakerley (1976) employed questionnaires, open-ended interviews and participant observations in her research. She concluded that the implementation of lean manufacturing cells does not create increased job flexibility. Fazakerley (1976) reported that within the newly created work teams, task interdependence and cohesiveness were greater. In addition, she noted that significant social benefits are realized upon the transition from a functional to cellular layout.

Huber and Hyer (1985) examined Fazakerley's work and noted a number of criticisms on the lack of detail of the methodologies employed. Details regarding the number, size and type of plants and the number of workers and managers interviewed were not provided. There also appears to be no clear discussion of the analysis approach and tools employed for data analysis which brings the results into question.

Huber and Hyer (1985) purported that their research was the first attempt to scientifically consider the human impact of lean manufacturing cell implementation. The researchers developed a questionnaire to examine their six hypotheses focused on employee perceptions of their jobs, their job satisfaction, and employee performance. The one research site was chosen because, at that time, it was the only one of the 30 known U.S. users of cellular manufacturing where both functional and cellular layouts were being utilized. Although two physically separate plants would have been preferred, the situation did not exist and the authors consciously chose not to confound the treatments with differences in equipment, operations, organizational procedures and job responsibilities.

The functional unit consisted of four types of machines, milling, drilling, cutting and special processes. Five cells were considered which included three to five dissimilar machines. Work teams consisted of two to three workers and they operated more than one machine at a time. The study was completed six months after the cells were implemented and there were 42 respondents with 19 working in the cellular layout (Huber and Hyer 1985). They found that cellular manufacturing neither increases, nor decreases, employee performance or satisfaction in comparison with a functional manufacturing layout. The employees that worked in the new cellular system did not perceive greater autonomy, significance, identity, or cohesiveness in their jobs than their counterparts. The cell workers were as satisfied with their jobs, supervision and advancement options as the functional workers, but were more satisfied with their pay. The supervisory ratings of employee performance did not differ between groups.

Shaffer *et al.* (1995) seek to extend the research of Huber and Hyer (1985) by examining the effects of cellular and functional layouts on employee perceptions and attitudes. The research considers a larger sample size (n=153) from two sister clothing manufacturing plants, where functional and cellular employees from the first plants are compared with cellular employees from the second plant. In addition, the cells considered in the study were operational for two years.

Little information is provided on the development of the survey. However, the researchers measured the employee perceptions of five job characteristics (skill variety, task identity, task significance, autonomy, and feedback from the job) which were developed as part of Hackman and Oldham's (1975) Job Diagnostic Survey. Shaffer *et al.* (1995) used five additional commonly used instruments to gain further insight into the effects of cellular manufacturing on employee perceptions and attitudes. In addition, they measured the individual's intention to stay with the job and growth need strength (Hackman and Oldham 1975).

The results indicate that cellular manufacturing has both positive and negative effects on employees' attitudes, which is in conflict with the Huber and Hyer (1985) conclusions. The two groups of cellular workers expressed less job satisfaction, weaker organization commitment, weaker intentions to remain working in the organization, greater role conflict, and greater role ambiguity than their functional counterparts.

Genaidy and Karwowski (2003) investigate human performance in a lean production environment with a focus on work demand and work energizer profiles along with worker health. They provide an overview and appraisal of four existing human performance theories and models on work demand and energizers.

In their framework, factors impacting human factors are classified in two ways: those acting on the individual and those experienced by the individual. In both situations, demands and energizers are considered. The acting demands and energizers consist of the following variables: physical, cognitive, social, organizational, technological, economic growth and individual growth (Genaidy and Karwowski 2003). The experienced demands include work effort, work performance, work satisfaction, and risk or benefit from work tasks and environment. (Genaidy and Karwowski 2003). The researches assert that the work demands and energizers should be studied from both white-collar and blue-collar standpoints. They hypothesize that the higher the work compatibility, the better the work outcomes and related human performance practices in lean manufacturing. However, they do not establish this concept mathematically or in relation to output measures of the lean system.

Seppala and Klemola (2004) examine how employees perceive their organization and job when lean manufacturing is implemented within their operations. The study considers four Finnish manufacturing companies and considers 1) the extent that lean principles and related technologies were implemented, 2) the way different occupational groups experienced their organization and work upon implementation, and 3) which factors in the change process were associated with the employees' negative or positive perceptions of production, job satisfaction and stress. The firms employed between 90 and 260 workers.

The research methods included interviews, observations, and questionnaires. The questionnaire used was based the Healthy Organization Questionnaire (Lindstrom 1997) and was amended with questions relevant to the topic including 1) job content, development opportunities, work control, 2) interaction, communication and collaboration, 3) group work, 4) supervisory work, 5) change implementation, 6) health and wellness, 7) change history, and 8) information technology use (Seppala and Klemola 2004). The response rates ranged from 60 to 90 percent, with the exception of one firm which was only 30%. In total, 525 employees participated out of the population of 702.

The findings suggest that the implementation of lean principles has primarily positive consequences from the viewpoint of production and job content. A marked number of respondents agreed that the fluency of work processes and collaboration within work unit had improved over time. The greatest difference in job perception appeared between white and blue-collar workers. Although everyone's job responsibilities had grown, the increase of supervisor to employee ratios and new tasks related to operating in the new system resulted in more time pressure, mental load and stress among the white-collar employees than their counterparts (Seppala and Klemola 2004).

Sawhney and Chason (2005) develop an exploratory model called the Personnel Behavior Based Lean Model (PBBLM) which attempts to integrate the human perspective into the lean design. The model is based on an evaluation of the elements required for human behavior changes across the identified phases of lean implementation. The PBBLM is comprised of a 6x6 matrix that includes six categories of human behavior and six categories of lean implementation.

The human behavior elements of the PBBLM were first presented by Gilbert's (1996) Behavior Engineering Model and are as follows: data, instruments, incentives, knowledge, capacity and motives. The lean elements proposed by the researchers are: planning, workplace, flow, support, consistency, and sustaining.

A survey is developed as a data collection tool to populate the cells of the matrix in the model. The researchers stated that it is imperative that the survey be administered to a cross section of employees, to include a sample of workers, team leaders, and management to ensure a holistic view. A five point rating scale (0 to 4) is employed to rate the level of availability required for implementation. The matrix cells are then color coded using red, orange, yellow and green to visually display where to focus improvement efforts.

A case study is provided that pilots the PBBLM at two facilities that have gathered data over a three year period. Historical information was available in the form of value stream maps, operational metrics, and a lean survey based on observations and interviews. The previous survey provided valuable information to populate a baseline level of achievement for the lean elements. These initial surveys were very similar in nature, indicating both facilities had some awareness of lean, but had not made any signification lean implementation progress. At the end of the three year period, both facilities were reassessed. The results indicated a marked improvement in facility 1 and almost no change in facility 2. Facility 1 scored higher on each of the six human behavior elements and on each of the six lean elements. In addition, the overall PBBLM index for facility 1 was significantly higher (2.12 vs. 1.01) in comparison with facility 2. Ultimately there exists a greater difference in the human behavior element between the two facilities than in the lean element.

In addition to providing quite a complete review of the literature relating to human related issues in manufacturing cell design, implementation, and operation, Bidanda *et al.* (2005) conducts survey research in regard to the importance of eight human issues in cellular manufacturing. The survey categories were as follows: worker assignment strategies, skill identification, training, communication, autonomy, reward / compensation systems, teamwork and conflict management. The survey was administered to about 40 participants that were equally divided into three subgroups of academics, managers and workers. The response rate was 82.5% due to the diligence of the research team. Across all subgroups, the top three issues were communication, teamwork and training, with communication being the most important to the managers and workers. The survey results provide a foundation for additional interaction and collaboration between academicians and industry, especially from a standpoint of worker assignment strategies.

Calarge *et al.* (2011) extend the research from Calarge *et al* (2008) as they present a field study that evaluates and compares the level of implementation of lean best practices at nine Brazilian and seven Spanish automotive companies. The researchers utilize the Society of Automotive Engineers J4000 Specification as the primary data collection instrument (SAE 1999a). The SAE J4000 Specification was previously described in this document. The standard prescribes that the implementation degree of an element can be calculated by dividing the sum of grades obtained in the evaluation of the element's individual items by the maximum possible score for the items within the element. In addition, the lean degree is calculated by dividing the sum of the grades of the elements by the number of elements considered in the comparison (Calarge *et al.* 2011). The research sites ranged from 100 to 4000 employees, but no details are provided in regard to data collection timing.

Statistically, there is no significant variance between the results from the Brazilian and Spanish companies in regard to lean implementation level (Calarge *et al.* 2011). A similar pattern of behavior also resulted as the companies scored similarly low on Ethics and Organization (Element 1) and Client / Supplier Relation and Organization (Element 4). From a practical standpoint, the Spanish companies score higher that the Brazilian companies on People and Human Resource Management (Element 2), Information Systems (Element 3), Product and Process Management (Element 5), and on Product and Process Flow (Element 6).

Glover *et al.* (2011) completed an empirical study on the critical success factors for the sustainability of kaizen event human resource outcomes. The researchers identify the factors that most strongly influence the sustainment of employee attitudes and commitment to kaizen events via a field study of 65 events in eight manufacturing organizations. The study utilized four questionnaires as follows: event kick-off questionnaire (19 items), report out questionnaire (39 items), event information questionnaire (15 items), and post-event information questionnaire (67 items). The kick-off questionnaire measured goal clarity and goal difficulty. The report out questionnaire measured management support. Additionally, the event information questionnaire measured team functional heterogeneity and work area routineness. Finally, the post-event questionnaire measured work area attitude and commitment, improvement culture, institutionalizing change, performance, accepting changes, learning and stewardship, experimentation and continuous improvement, management participation, management changes, employee changes, and production system changes.

The kaizen event team members completed the kick-off questionnaire and the report out questionnaire and the event facilitators completed the event information questionnaire. A lag in time of nine to eighteen months occurred between completion of the first three questionnaires and the post-event information questionnaire which was then completed by the event facilitator or the work area manager. The researchers employed exploratory multiple regression and ultimately develop a three predictor model that included performance review, experimentation and continuous improvement, and accepting changes as direct predictors of work area attitude and commitment (Glover *et al.* 2011).

2.5.3 Performance Measurement

A primary shortcoming of many cell formation techniques is that they focus only on the single objective of developing cells by identifying similar parts and their corresponding machines. However, there are other important performance objectives that include maximizing total productivity, and minimizing throughput times, setup times and job tardiness (Heragu 1994, Min and Shin 1993). Additionally, most of the common performance improvements realized through implementation of cellular manufacturing with lean manufacturing principles are as follows: on-time delivery, throughput, inventory, lead-time, productivity, floor space, travel distance, quality and cost (Askin and Estrada 1999, Dale 1999, Irani *et al.* 1999, Murman *et al.* 2000a, Nightingale 1998, Wemmerlov and Hyer 1989).

Dale (1999) provides an approach to predict the performance benefits of implementing cellular manufacturing. The research is based on a survey of 35 companies that have introduced lean manufacturing into the operations. Before and after data was collected for 42 different elements (Burgess *et al.* 1993, Dale 1999). Examples of performance measures such as lead-time and on-time delivery are provided, with the raw data and the percentage improved used as a normalizing approach to make comparisons possible. Linear regression and correlation analysis were used to examine relationships and it was found that17 out of the 42 elements were significantly correlated at a 95% confidence level (Dale 1999). The researchers then proceed to develop predictions for 12 additional companies to determine if cellular manufacturing could be beneficial to them. Overall, the average error of prediction in the model is 13.7% underestimated in comparison with the achieved performance results (Dale 1999).

2.6 FINDINGS FROM THE LITERATURE

A large volume of information has been written on the required content of the human infrastructure design, but little has been written on the process by which a human infrastructure compatible to technical needs is designed for lean to be successfully implemented (Liker and Majchrzak, 1994). Many of the sources reviewed use illustrative data rather than actual manufacturing cell implementation data. Additionally, a number of researchers cite the need for longer term studies to understand the evolution of lean manufacturing within companies over time.

Much of the survey research only considers employee job perceptions of differences between functional and cellular manufacturing environments, which comprise a very small subset of the range of human issues that should be considered. The majority of the cell formation and worker assignment models tend to focus on worker skills and matching to the system requirements with some inclusion of performance objectives.

Lean standards have been developed for two major industries – automotive and aerospace, yet no assessment has been made to their commonality. In addition, there is little awareness of the standards outside either industry, with some exception as LAI is working to disseminate to a broader audience. There is an absence of a simple approach to consider the technical, human and lean practices required for organizations to achieve the expected performance gains evidenced through the literature. A deeper understanding must be established regarding the relationships between cell performance measures and the identified technical, human and lean practices. Another challenge for researchers is studying the relationship between perceived importance of the technical, human and lean practices and perceived implementation level to arm organizations with a sound prioritization approach to guide their lean efforts.

3.0 RESEARCH HYPOTHESIS

Based on findings from the literature, there is a clear need to consider the technical and human elements along with supporting lean practices in the transition of organizations from functional to cellular layouts using lean manufacturing philosophies.

3.1 OBJECTIVE

The primary objective of this research is to provide an approach to measure, evaluate and improve the performance of manufacturing cells considering technical and human elements, including the supporting lean practices.

3.2 HYPOTHESIS STATEMENT

The major hypothesis is in a manufacturing cell, there exists a relationship between the human and technical elements and the cell performance measures.

3.3 RESEARCH AIM

The research aim is to 1) explore and examine differences in performance measures during the three discrete phases of cell implementation and maturity, 2) examine relationships between the cell specific system variables and performance measures, 3) examine relationships between supporting lean practices and performance measures, and 4) evaluate factors that relate to differences between cells in regard to importance and implementation levels of cell specific system variable and supporting lean practices.

3.4 CONTRIBUTION

This research contributes to the current body of knowledge in the following manner:

- Is one of the few studies that uses real manufacturing cells rather than hypothetical data
- Increases the understanding of cell performance over time through consideration of three discrete phases of cell maturity
- Establishes a consolidated view of the cell specific variables that need to be addressed when implementing manufacturing cells
- Incorporates a cross-reference of the two major sources of lean best practices in the automotive and aerospace industries
- Develops an assessment questionnaire that can be used by companies to measure both importance and implementation of the system variables and lean practices
- Examines whether employees respond differently to the assessment questionnaire based on demographic factors

- Demonstrates whether cells that exhibit better performance have achieved higher levels of implementation of the cell specific system variables and lean practices
- Determines which cell specific variables and lean practices are most and least important to the questionnaire respondents

4.0 RESEARCH METHODOLOGY

The research methodology was comprised of the following steps:

1) Identified the Cell Specific System Variables
2) Identified the Cell Performance Measures
3) Developed an Assessment Questionnaire based on Cell Specific System Variables and Lean Practices
4) Collected data through a field study
5) Analyzed data and summarized the results
    a. Cell performance measures
    b. Assessment questionnaire responses
    c. Integration of cell performance measures and questionnaire responses
6) Developed conclusions with broad implications

4.1 IDENTIFYING THE CELL SPECIFIC SYSTEM VARIABLES

A focus group was conducted at the research site to consider the potential cell specific system variables. The group was comprised of Operations Directors, Capacity Owners, Team Leaders, and Manufacturing Engineers that were chosen based on their level of experience with both functional and cellular manufacturing. Eight people participated in the brainstorming event.

The first question for the session was: What are the key variables to consider to achieve successful implementation of lean manufacturing cells? The team chose to use an affinity diagram to capture and organize their ideas. The participants listed their ideas on Post-It notes and silently placed them on a white board. They then worked to organize them under logical headings. The results of the session are provided in Figure 4.1. Note that one category of the figure is related to the human element and is titled "People". It covers the basic requirements of staffing the cell with salaried and hourly personnel, specific training, communication between shifts, teamwork, and celebrating success. After discussion with the focus group, they felt that they covered part measurement aspects under both the machine and methods headings, but that cell performance measurement and improvement was missing. Therefore, an additional category called Cell Measurement and Improvement was added, resulting in a total of six elements. Five elements are considered to be technical in nature. The Cell Specific System Variables were also validated through various sources in the literature (Bidanda *et al.* 1999, Burgess *et al.* 1993, Dale 1999, Irani *et al*. 1999). As a result, Machines (Element 1) was comprised of eight items, Materials (Element 2) was comprised of four items, Environment (Element 3) was comprised of seven items, Methods (Element 4) was comprised of nine items, People (Element 5) was comprised of 17 items, and Cell Measurement and Improvement (Element 6) was comprised of six items. There were 51 total items under the six elements of the Cell Specific System Variables, with 33% of the items related to the human element.

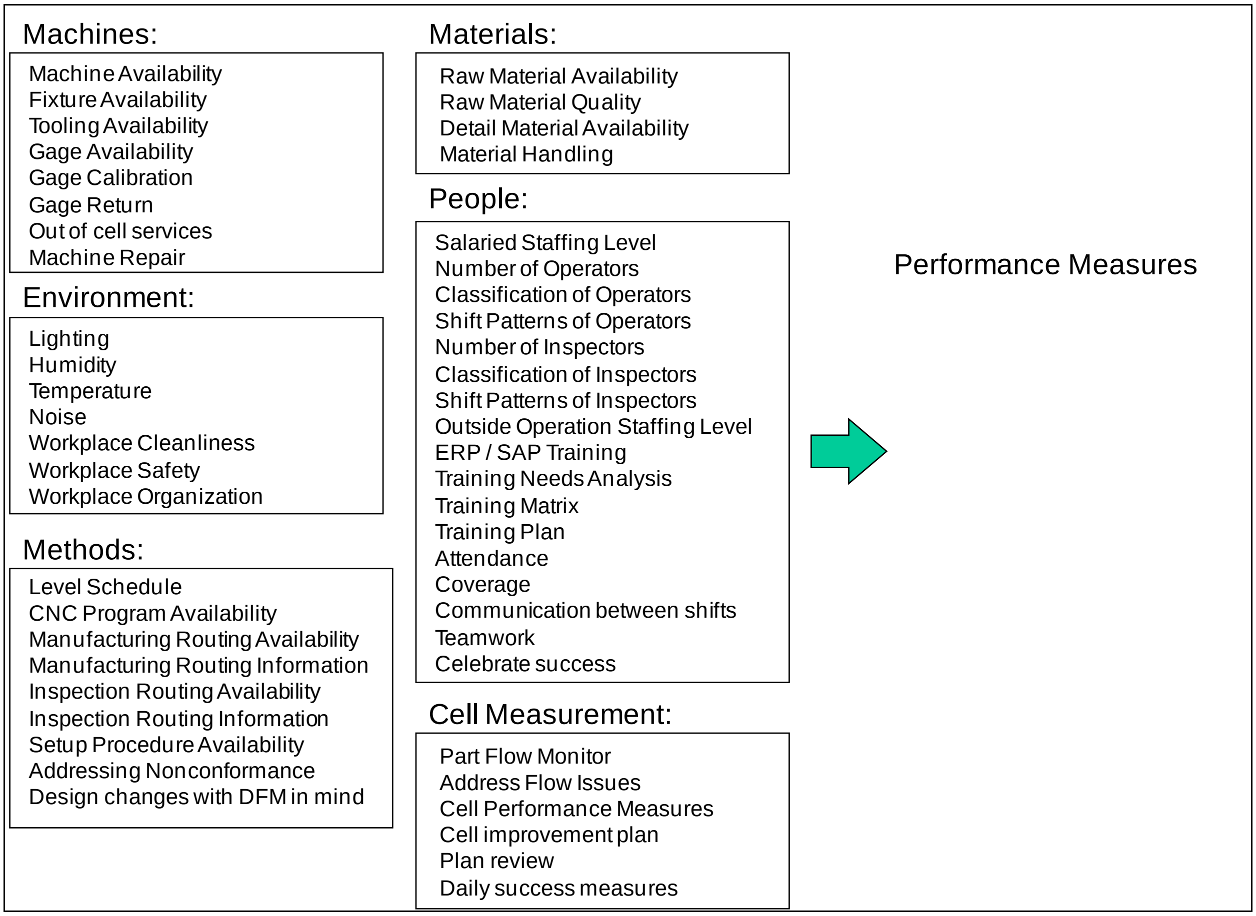

Figure 4.1 Cell Specific System Variables

4.2 IDENTIFYING THE CELL PERFORMANCE MEASURES

During the same brainstorming event, the team was asked a second question: What are the key performance measures that can be improved through implementation of lean manufacturing cells? In general the team decided that the main objective of the lean manufacturing cells were to deliver the products on time at the right quality and cost to satisfy their customers. Together they developed the following operational definitions for the performance measures:

- Delivery Performance

    - Throughput = number of good parts produced over a period of time
    - Lead-time = number of days elapsed from first operation to completion of last operation
- Quality Performance
    - Cost of non-quality = dollar value of the scrap, rework and concessions
- Cost Performance
    - Product cost = dollar amount of labor + material + burden + overhead
    - Inventory = dollar value of the number of pieces of raw, work-in-progress and stored parts

These performance measures are consistent with sources from the literature (Askin and Estrada 1999, Dale 1999, Irani *et al.* 1999, Murman *et al.* 2000a, Nightingale 1998, Wemmerlov and Hyer 1989). In many cases the cells that were designed and implemented to support this unforseen increase in customer demand had to increase their output by 50% to 85%. Failure to meet the customer demand could also have negative results on the ongoing bid for replacement of the largest customer's fleet. Since the primary objective of the lean manufacturing cell strategy was to increase output to meet the sudden sharp upturn in the market demand, the focus group settled on throughput as the primary performance measure. The focus group felt strongly that every person that worked in or supported the cells needed to align with the customer requirements via a simple and straightforward measure such as throughput. The focus group members also determined that the throughput measure could be obtained in the most accurate manner via the cell inspection logs which serve as the sales records for the Federal Aviation Authority. There are numerous definitions of throughput and throughput time in the literature, but the focus group agreed to define throughput as "the number of good parts produced over a period of time" (American Heritage Dictionary 2000). Additionally, there have been a number of varying definitions of lead-time identified, depending on how much of the value stream or supply chain in considered. The focus group felt strongly that the lead-time measure be within their control, from part launch to part delivery, rather than from part order to part delivery due to the extended raw material lead-times and expanded planning horizons that exist in aero engine manufacturing.

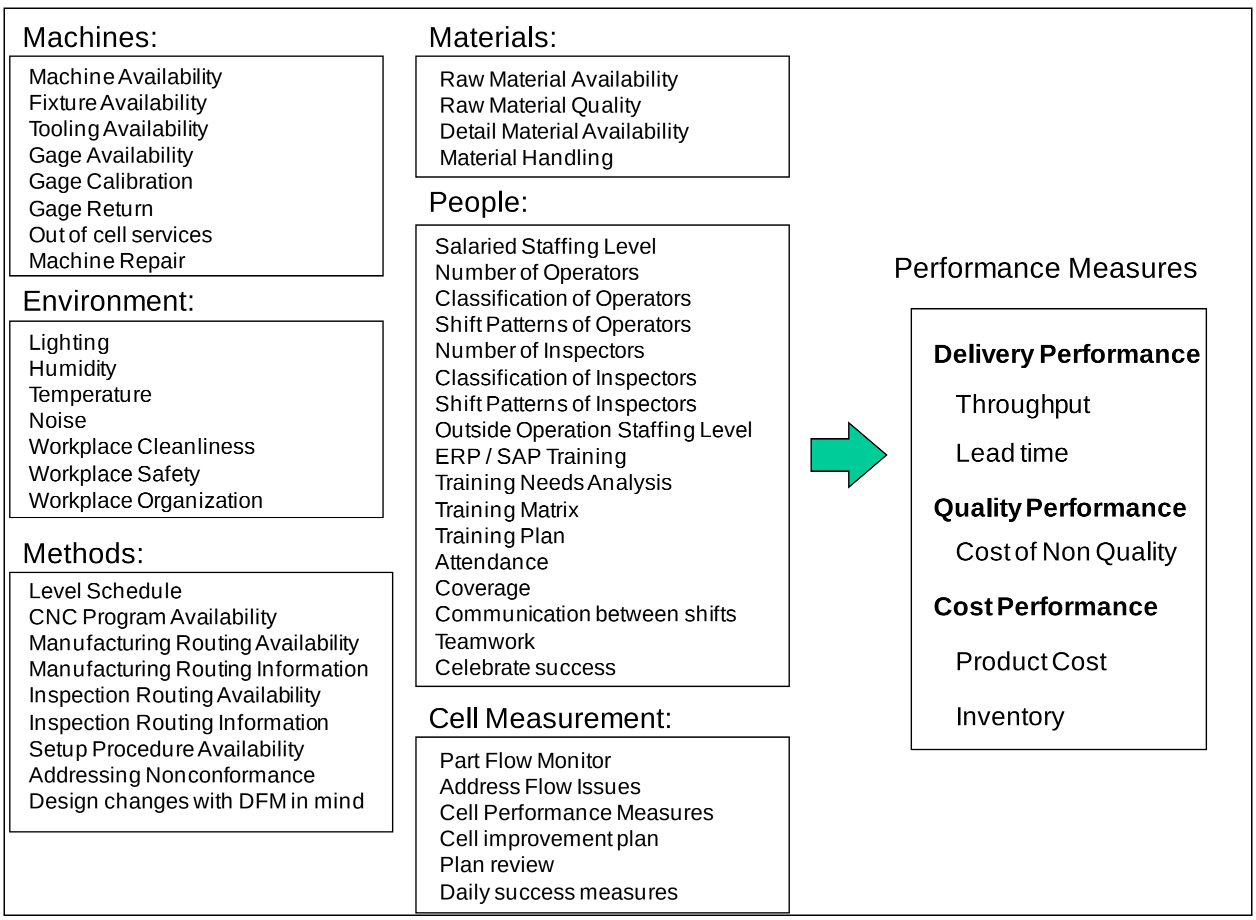

Figure 4.2 Cell Performance Measures

4.3 DEVELOPING THE ASSESSMENT QUESTIONNAIRE

In order to gather data for the research effort, a data collection method had to be developed. The research team was challenged to find a way to collect information in regard to the Cell Specific System Variables and the supporting Lean Practices.

4.3.1 Purpose

The assessment questionnaire was developed as the primary method for gathering employee perceptions from the workers, supervisors, technical staff and managers that manage and operate the lean manufacturing cells. The assessment questionnaire responses would be used to increase the understanding of:

- Relationships between cell specific system variables and cell performance measures
- Relationships between lean practices and cell performance measures
- Differences between cells
- Which elements of the cell specific system variables and lean practices were most and least important to the respondents

4.3.2 Development and Format

The assessment questionnaire developed as part of the research is comprised of three sections. The first section collects demographic information regarding the respondents. The second section collects information regarding the importance level and the implementation level for each of the Cell Specific System Variables (Section 2) that are illustrated in Figure 4.1.

The third section of the questionnaire is based on a cross-reference of the two major sources of lean best practices in industry, the automotive SAE J400 Lean Operation Standard Specification (SAE 1999a) and the aerospace LAI Lean Enterprise Model (MIT 1996).

A cross-reference was created that considered every item in both sources. The complete comparison is provided in Appendix A. As a result, the Lean Practices (Section 3) of the assessment questionnaire was developed from this cross-reference. Recall that there were 52 items in the SAE J4000 standard and 61 items in the LAI LEM. When the automotive and aerospace standards were compared, 43 items, or 54%, were similar. Note that some items mapped from one item in a standard to two or more items in the other standard. Lean Practices (Section 3) of the assessment questionnaire uses the six element headings from the SAE J4000 standard and consists of 79 total items. As a result, Management / Trust (Element 1) was comprised of 15 items, People (Element 2) was comprised of 19 items, Information (Element 3) was comprised of six items, Supplier (Element 4) was comprised of ten items, Product (Element 5) was comprised of 11 items, and Cell Process / Flow (Element 6) was comprised of 18 items. The focus group categorized Management / Trust (Element 1) and People (Element 2) as human centered. There were 79 total items under the six elements of Lean Practices (Section 3), with 43% of the items considered to be human variables.

Table 4.1 provides an overview of the assessment questionnaire Sections 2 and 3, their elements, and the relevant coding. The complete questionnaire is provided in Appendix B. Note that the People (S2E5) element from the Cell Specific System Variables (Section 2) portion of the questionnaire covers human issues, while the other five elements are more technical in nature. Also, the Management / Trust (S3E1) and People (S3E2) elements from the Lean

Practices (Section 3) portion of the questionnaire cover human issues, while the other four elements are more technical in nature.

Table 4.1 Questionnaire Section and Element Coding

Section and Element Coding	Section 2: Cell Specific System Variables
S2E1	Machines, Equipment, and Outside Services
S2E2	Materials
S2E3	Environment
S2E4	Methods
S2E5	People
S2E6	Cell Measurement and Improvement
	Section 3: Lean Practices
S3E1	Management / Trust
S3E2	People
S3E3	Information
S3E4	Supplier / Organization / Customer Chain
S3E5	Product
S3E6	Process / Flow

The respondents were asked to rate each item listed in the Cell Specific System Variables (Section 2) and Lean Practices (Section 3) portions of the assessment questionnaire in two ways. First, the respondents were asked to rate the importance of the item in achieving the business goals on a scale from 1 (not important) to 5 (most important) as illustrated in Table 4.2.

Table 4.2 Questionnaire Importance Scoring Legend

Score	Meaning
1	not important
2	somewhat important
3	important
4	very important
5	most important

Second, the respondents were asked to rate the implementation level of each item within their respective cell in Section 2 and business unit in Section 3. More specifically, the Cell Specific System Variables (Section 2) and Lean Practices (Section 3) portions of the assessment questionnaire use a slight modification of the implementation scale (0, 1, 2, 3) from the SAE J4000 specification, as illustrated in Table 4.3, rather than the LAI LEM implementation scale (0, 1, 2). The decisions was taken as the (0, 1, 2, 3) scale was preferred by the industry reviewers due to its requirement for continuous improvement within the last twelve months at level three.

Table 4.3 Questionnaire Implementation Scoring Legend

Score	Meaning
0	not in place or major inconsistencies in implementation
1	in place with minor inconsistencies
2	fully in place and effectively implemented
3	fully in place with improvement over past 12 months

4.3.3 Institutional Review Board

The University of Pittsburgh follows strict guidelines when human subjects are used in any type of research. These guidelines are established and governed by the Institutional Review Board (IRB). The researchers met the stringent requirements of the IRB through submission of the following:

- Proof of successful completion of online training for all researchers
- Research abstract
- Complete research protocol per the IRB specifications
- Researcher qualifications to conduct the research
- Confidentiality statements
- Company approval letter
- Questionnaire and cover letter

After multiple iterations, the research study was granted "exempt" status and subsequently all data was collected in accordance with IRB guidelines and approvals.

4.3.4 Piloting and Modification

With any data collection instrument, piloting and modification are key activities to ensure that the data collected can be used to appropriate and thoroughly test the theories put forward by the researchers. Once the first draft of the assessment questionnaire was completed, an initial review was conducted separately with the dissertation director and three individuals from industry. This was done to assure that all of the identified cell specific system variables were addressed through an element in the questionnaire. Additionally, an attempt was made to reduce any redundancy between the Cell Specific System Variable elements in Section 2 and the Lean Practices elements in Section 3. The recommendations were incorporated into a first revision of the questionnaire.

Next, a verbal protocol was conducted with two different individuals from industry to review the directions and the questionnaire in general. As a result, revisions were made to the directions and some individual elements were reworded for clarity and readability. Finally, the second revision of the questionnaire was piloted with six process improvement personnel from the field study site to determine how much time should be allotted for employees to complete the questionnaire. Section 1 and 2 took from ten to 18 minutes to complete and Section 3 took from 15 to 26 minutes to complete. It was recommended that 45 minutes be allotted for respondents to complete the questionnaire and that only salaried employees complete Section 3 of the questionnaire.

4.3.5 Population Characteristics and Administration

For each of the four cells, the aim was to solicit input from the four key salaried employees to include the Capacity Owner, Cell Team Leader, Manufacturing Engineer and MRP Controller. In addition, five hourly operators and one hourly inspector were randomly chosen and invited to participate in the questionnaire. The total planned responses for the questionnaire was ten responses per cell for a total of 40 responses. The questionnaire was administered and completed in one session for each cell. A cover letter accompanied the questionnaire and is provided in Appendix C. Areas of the letter are blacked out to maintain the anonymity of the field study site.

4.4 ANALYSIS APPROACH

A structured approach was taken in developing the analysis plan to test the theories that underpin the research. The analysis was considered from three standpoints as follows: cell performance measures, assessment questionnaire responses, and integration of the cell performance measures with the questionnaire responses. All analysis is completed using the Minitab v15 statistical software package or Microsoft Excel.

4.4.1 Cell Performance Measures Analysis

4.4.1.1 Examining the Relationships: Throughput, Lead-time and Inventory

A matrix plot and a correlation study are used to develop an understanding of the relationships between the cell performance measures of throughput, lead-time and inventory. A matrix plot is commonly used to assess the relationship among several pairs of variables at once and is actually an array of individual scatter plots. Scatter plots are simply a type of graphical analysis using Cartesian coordinates to display values for two variables in regard to a set of data. The data is displayed with each point having the value of one variable determine the position on the vertical axis and the other variable determining the locations on the horizontal axis (Groebner *et al.* 2011). Scatter plots were first introduced by Francis Galton in the 1880s (Galton 1888).

Scatter and matrix plots provide a graphical view of the relationships between two variables, however, a mathematic view can be established through the use of the Pearson product moment correlation coefficient which was developed by Karl Pearson and extended the research of his mentor Francis Galton (Galton 1890, Pearson 1900, Stigler 1989). The correlation coefficient (usually denoted as *r)*, is a measure of the strength of the linear relationship between two variables (Groebner *et al.* 2011). The correlation coefficient is often referred to as Pearson's *r* and can range from a perfect positive correlation, +1, to a perfect negative correlation, -1. Additionally, a correlation close to 0 indicates no liner relationship. A Pearson correlation coefficient above 0.7 is generally accepted as a strong relationship, but a formal hypothesis test should be conducted to assess statistical significance (Groebner *et al.* 2011).

On a cautionary note, correlation does not necessarily imply causation. Only controlled experiments allow a researcher to truly determine causality. In some cases, a confounding variable can be at work giving the illusion of causation. Additionally, a single extreme value can greatly affect the coefficient. Therefore, one should always consider outliers and their potential effect on analysis of the data set (Groebner *et al.* 2011).

4.4.1.2 Examining the Secondary Cell Performance Measures

The secondary cell performance measures are lead-time, cost of non-quality, product cost, and inventory. These measures will be examined in a simple manner due to limitations in data availability. For the secondary performance measures, the value of the measure before Phase 1 implementation and the value of the measure at the end of Phase 3 are collected and the resulting percentage improvement is calculated.

4.4.1.3 Examining the Primary Cell Performance Measure

The primary cell performance measure is throughput and data is collected on a monthly basis during the entire course of the research for all cells in the field study. An initial graphical analysis is conducted to begin to develop an understanding of this performance measure over time via use of box plots and control charts.

The box plot is a simple approach toward examining one or more sets of data graphically and depicts groups of numerical data through their five-number summaries: the lower limit, first quartile (Q1), median (Q2), third quartile (Q3), and largest upper limit (Groebner *et al.* 2011, McGill *et al.* 1978). A box plot may also indicate which observations might be considered outliers, which is signified through the use of an asterisk for any values beyond Q1 minus 1.5 times the interquartile range (Q3-Q1) or Q3 plus 1.5 times the interquartile range (Q3-Q1) in the Minitab software.

The control chart was invented by Walter Shewhart while working for Bell Labs in the 1920s as he had realized the importance of reducing variation in manufacturing processes (Shewhart 1931). He introduced the concepts of common cause and special cause variation and developed a set of rules to be used with the control chart to distinguish between the two types of variation. Shewhart (1931) stated that bringing a production process into a state of statistical control, or stability, where only common cause variation exists is necessary to predict future output and manage a process economically.

For the purpose of the research, a staged Individual and Moving Range control chart is used with the stages defined by the three discrete cell phases to gain insight and assist with theories in regard to the implementation phases. The combined Individual and Moving Range (I&MR) Control Chart plots individual observations (I chart) and moving ranges (MR chart) over time for continuous data. Sometimes this chart is referred to as an X-bar and R chart (Groebner *et al.* 2011). This type of combination chart is employed to monitor process center and variation when it is difficult or impossible to group measurements into subgroups. This occurs when measurements are expensive, production volume is low, or products have a long cycle time. Additionally, when data are collected as individual observations, you cannot calculate the standard deviation for each subgroup. The moving range is an alternate method to calculate process variation by computing the ranges of two consecutive observations (Groebner *et al.* 2011).

While a staged control chart may support the theory that a difference between throughput phase means appears to exist graphically, only comparative methods using hypothesis testing can statistically confirm a difference between the three phase means. In order to determine which comparative methods are appropriate to use, the normality of the throughput data for each of the three cell implementation phases must first be tested. Normality tests are used to determine whether a data set can be well modeled by a normal distribution.

A graphical approach to testing normality can be achieved through comparison of a histogram of the sample data to an overlay of the normal probability curve. An alternative graphical method is the use of a normal probability plot. For the purposes of the research, a graphical approach is employed and additionally, the normality of the data is tested using the Anderson-Darling test with an alpha risk of 5%. The Anderson-Darling test was invented in 1952 and is a statistical test of whether there is evidence that a sample of data can be modeled by a given probability distribution (Anderson and Darling 1952). Although there are numerous tests that may be used to assess goodness of fit, Stephens (1974) states that when the Anderson-Darling test is employed for a normal distribution, it is one of the most powerful tools for detecting deviation from normality. The null hypothesis (H_o) statement is: the data can be modeled by a normal distribution. The alternate hypothesis (H_a) statement is: the data cannot be modeled by a normal distribution.

First, comparative methods were employed for the variances of the throughput for the three phases. Variance testing is usually completed prior to means testing for normal data to determine if the assumption of equal variances is valid for the two-sample *t*-test or to meet the assumption of equal variances for ANOVA (Groebner *et al.* 2011). Considerations was made as to which type of comparison would be appropriate for the variances. In this case, a multiple comparison is required to represent the three defined phases of cell implementation. Since we are testing more than two variances, the *F*-test statistic is not appropriate and we must use the Bartlett test which was published in 1937. Bartlett's test is utilized to test if three or more samples are from populations with equal variances, or exhibit homoscedasticity (Bartlett 1937). The null hypothesis (H_o) statement is: there is no difference between the variances of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the variances of the throughput for the three cell phases.

Next, comparative methods were conducted for the throughput means of the three phases. For cells that met the underlying test assumptions, ANOVA was used, and for the cells that did not, Kruskal-Wallis was used. ANOVA was first proposed by Fisher (1918), the first application was published in Fisher (1921), and it became widely accepted after publication in a statistical textbook (Fisher 1925). In its most basic form, ANOVA provides a statistical test of whether the means of several groups are all equal and is a generalization of the *t*-test (Student 1908) to more than two groups. Performing multiple two-sample *t*-tests would result in an increased chance of type I error. The assumptions that ANOVA is based upon are as follows: independence, normality, and equality of variances (Groebner *et al.* 2011). For ANOVA, the null hypothesis (H_o) statement is: there is no difference between the means of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the means of the throughput for the three cell phases.

In cases where the data is non-normal or the equal variance assumption is not met, the median is usually a better indicator of central tendency for the distribution than the mean. A multiple comparison of the medians using the Kruskal-Wallis test is conducted when the data was normal and the variances were not equal. The Kruskal-Wallis one-way analysis of variance by ranks is a non-parametric method that is used for comparing more than two samples that are independent. It is an extension of the Mann-Whitney *U* test (Mann and Whitney 1947) to three or more groups (Kruskal and Wallis 1952). For Kruskal-Wallis, the null hypothesis (H_o) statement is: there is no difference between the medians of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the medians of the throughput for the three cell phases.

When the ANOVA or Kruskal-Wallis tests leads to significant results, then at least one of the samples is different from the other samples. However, neither test identifies where the differences occur or how many differences actually occur. The Tukey-Kramer procedure, a pair-wise multiple comparison test for unequal sample sizes, is preferred to determine which pairs exhibit significant differences, but may only be employed if the samples have equal variances (Groebner *et al.* 2011). Only two of the four manufacturing cells exhibited equal variances across the three implementation phases. Therefore, although there is some risk of increased type I error, when the ANOVA or Kruskal-Wallis tests are significant, further testing is completed via the two-sample *t*-test with either pooled or non-pooled standard deviations depending on the Bartlett test results. This decision was made to ensure consistency in analysis across the four manufacturing cells.

The *t*-statistic was introduced in 1908 by Gosset (Student 1908), a chemist that worked for the Guinness brewery. When he first published the test, he was forced to use a pen name by his employer who guarded the fact that they were using statistics as a competitive edge, which explains why it is often referred to as the *Student's t*-test (Fisher Box 1987). A two-sample *t*-test is used when comparing sample means of two normally distributed populations for equality when the sample variances are also equal (Groebner *et al.* 2011). When the sample variances are not equal, it is referred to as Welch's t-test (Welch 1947). The two-sample *t*-test was used to determine where the differences existed between the throughput means by pair-wise phases, even though this testing does risk higher type I error. For both forms of the *t*-test used in the analysis, the null hypothesis (H_o) statement is: there is no difference between the means of the throughput for the two cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the means of the throughput for the two cell phases.

Once the comparative method test was run for all cases described, the p-value was listed and considered against the alpha risk to determine the statistical significance. The final step involved determining the practical significance of each theory tested. A much more detailed explanation follows as the theories are explained later in chapters five and six.

4.4.2 Assessment Questionnaire Analysis

Cell Specific System Variables (Section 2) and Lean Practices (Section 3) of the assessment questionnaire were analyzed using three different types of scoring: 1) counts, 2) averages of scores for each of the twelve elements, and 3) total scores for the two sections. While it would have been preferable to conduct a factor analysis (Spearman 1950) to calculate factor loadings for the items within the elements of the questionnaire, the small sample size was not conducive to this type of analysis (Groebner *et al.* 2011).

The implementation level and importance rating scales were both Likert scales, with the first being a four-point modified version from the traditional five-point scale (Allen and Seaman 2007, Likert 1932). The literature recommends that analysis of Likert scale data should consider the ordinal nature of the data and should employ non-parametric procedures based on rank and distribution free methods such as “tabulations, frequencies, contingency tables and chi-square statistics” (Allen and Seaman 2007). Pearson’s chi-square (χ^2) is the most widely know of several chi-square tests which measure the amount of deviation between expected values and observed values for each cell of a table to determine if an association exists for attribute data (Pearson 1900). This method was used to test for significance between the four manufacturing cells and the implementation level by questionnaire section and for the significance between the four manufacturing cells and the perceived importance by questionnaire section. Therefore, counts were tallied for Cell Specific System Variables (Section 2) and Lean Practices (Section 3) portions of the questionnaire for both the implementation level and importance rating in order to conduct a chi-square analysis.

It was assumed, as in Ramirez-de-Arellano *et al.* (2000), that all items were equally weighted in both the Cell Specific System Variables (Section 2) and Lean Practices (Section 3) areas of the questionnaire. Next, the average score was calculated for each element in both sections, and then averaged across all respondents for the cell to effectively calculate an average of averages for each of the 12 elements by cell. This data was presented in a number of graphical forms. Radar charts were employed for Cell Specific System Variables (Section 2) and Lean Practices (Section 3) to view the cell implementation level and importance scores by element in relation to the other cells. A radar chart plots the values of each category along a separate axis that starts in the center of the chart and ends on the outer ring. A line is drawn connecting the data values for each spoke, giving a star like appearance (Chambers *et al.* 1983). In some instances, radar charts are referred to as star charts, spider charts, or polar charts (Chambers *et al.* 1983) and were first introduced by Georg von Mayr in 1877.

The average of averages were also plotted using bar charts for Cell Specific System Variables (Section 2) and Lean Practices (Section 3) to visually display the cell implementation level and importance scores for each element in relation to the other cells and the grand average across all cells. Bar charts were first developed in 1786 by Playfair and are simply graphs that employ rectangular bars with lengths equal to the data values to which they correspond. Next, scatter plots were utilized to visually assess importance vs. implementation level for the twelve elements on an individual chart for each cell.

The final method of scoring, involved summing up a total score for the each of the two sections and averaging across the cell respondents to develop a score for Cell Specific System Variables (Section 2) and Lean Practices (Section 3) for each of the four cells. Additionally, a total overall score was obtained by using the method described above across both Section 2 and 3 of the questionnaire collectively. This was done to provide a basis for comparison when considering the relationships between the questionnaire implementation scores for each cell against percentage throughput improvement, product quality, and cell complexity.

4.4.3 Integration of Performance Measures and Assessment Questionnaire

A matrix plot and a correlation study, as described in subsection 4.4.1.1, are used to develop an understanding of the relationship between the cell performance measures and the questionnaire section scores by cell. Additionally, the same approach is used to develop an understanding of the relationship between cell complexity and the questionnaire section scores by cell.

4.5 DATA COLLECTION: FIELD STUDY

4.5.1 Selection

The first decision that had to be made was to choose the number of companies that would participate in the field study. Attempts were made to include three companies: a chemical manufacturer, a safety device manufacturer and an aero engine manufacturer. With limited time and resources to perform the research, studies with multiple companies did not seem feasible. Therefore, the decision was made to work with only one company. In addition, by choosing only one large company with multiple business units, the same research methodology could be consistently applied to multiple cells.

4.5.2 Cell Similarities

While there were many cells designed within the field study company in support of the engine model, the four specific cells were chosen based on their similarities, as follows:

- Make products for the same engine value stream (many variables could be controlled or held constant, while others could be varied in a more controlled manner)
- Are high volume, with level schedules and same growth patterns over time
- Were implemented within seven months of one another
- Were designed using the same lean facilitators
- Produce a comparable number of products (range from 3 to 14)
- Have the same union representation and contract
- Experience the same external variables (such as business changes)

4.5.3 Cell Dissimilarities

Conversely, the cells that were selected, were also chosen based on some key dissimilarities in that they:

- Have varying levels of product logistics complexity
- Have varying number of machines in each cell (range of 10 to 22)
- Have varying levels of manufacturing complexity (13 to 34 operations)
- Have varying levels of part complexity
- Report to three different business units (turbine, compressor and combustor)

4.5.4 Cell Design Approach

Countless approaches to cell design and implementation exist in the literature. The researchers could not influence the strategy that had been undertaken to transform the entire field study site factory from a functional to a cellular layout. The Head of Manufacturing Transformation had designed an overall layout that grouped product families into cells based on the subsystems of a turbine engine: fan and compressor, combustor, turbine, and transmission / structures. The cells were developed via blitz kaizen events using the same defined approach. A team of about 20 employees were brought together with two experienced lean manufacturing facilitators to participate in a nine day event. Three days of the event were spent training the participants in lean principles and the balance of the time was spent redesigning the process, laying out the physical cell, and developing detailed action plans. A wrap up meeting was conducted at the end of each day that was attended by senior management to keep them informed of key accomplishments and potential issues. A final review was conducted on the ninth day to provide a briefing on the expected improvements and to provide an overview of next steps. Implementation of the physical cell began immediately after the design event was completed, as the area had been refurbished to print the lighting and flooring up to new standards. After 30 days, a review meeting was held to determine progress against the implementation plans.

4.5.5 Definition of Cell Phases

Three phases of cell maturity have been defined as part of the research field study. These three phases are predecessed by a Phase 0 where the actual cell design occurs via the method described in Section 4.5.4. Phase I involves the physical implementation of the manufacturing cell. This phase includes the initial transition from a functional layout to a cellular layout and the physical transformation of the area to include painting, epoxying the floors and bringing the lighting up to an acceptable industry standard.

Phase 2 involves the population of the cell with employees and steady state operation of the cell. During this phase, all equipment, including any new capital is in place and fully operational. The cell is permanently staffed per the labor agreement to the designated level that was agreed in the cell design event. A training needs analysis has been conducted for all cell personnel to determine skills gaps and a related training plan has been developed and implemented. During Phase 2 the cell is able to operate at steady state in a predictable manner.

Phase 3 focuses on improvement activities within the manufacturing cell. In some cases, key members of the cell team have changed, and it is important to revisit the cell design and process via additional improvement events to ensure engagement of all employees. In addition, the control system may be reviewed and revised based on factors such as increases in cell volume and related changes to shift patterns to best utilize critical resources.

4.5.6 Cases to Consider

Table 4.4 provides an overview of characteristics of the four cells that were chosen to be studied. The cell parameters were defined and the cells selected via the same focus group comprised of Operations Directors, Capacity Owners, Team Leaders, and Manufacturing Engineers at the field study site described in section 4.1 above. These parameters were also validated through various sources in the literature (Bidanda *et al.* 1999, Dale 1999, Irani *et al*. 1999).

Table 4.4 Characteristics of Selected Cells

Code	Cell	A	B	C	D
FPN	# of Finished Part Numbers	3	14	1	3
MPD	# of Major Part Details	1	1	2	5
MAT	Material	Waspalloy	Titanium	Titanium	Titanium
MACH	# of Machines in Cell	15	22	11	10
OPS	# of Operations	24	13	34	33
OUTOPS	# of Outside Operations	2	4	3	4
SFT	# of Shifts	3	3	3	3
WKR	# of Workers	15	27	11	14
PCPLX	Part Complexity	1	1	2	3
CCPLX	Cell Complexity	2.2	6.3	4.2	11.4

The parameter of major part details was defined as additional part numbers in the bill of material of the finished part number other than simple part details such as fasteners, fittings, keys, etc. The requirement of additional major part details adds a level of complexity to the cell logistics as in most instances these details are being procured from different suppliers and not as a kit, which can greatly increase the time required on the part of management when an issue arises. The rest of the parameters are self-explanatory with the exception of part complexity and cell complexity.

Part complexity was rated by the same focus group on a scale from 1 to 3, with a conscious effort made to select products across that range. A one represented low part complexity and a three represented high part complexity. Factors that affected part complexity at the research site are as follows: number of dimensions, number of different materials used in an assembly, special processing (heat treatment, welding, brazing, plating, coating, metal spray, laser, etc.), peening requirements (shot, glass bead, etc.), special machining (broaching, explosive forming, etc.), inspection requirements (CMM, NDTs such as x-ray, fluorescent penetrant, etc.), base material, types of characteristics (internal passages, bearing surfaces, gear shapes), and close tolerance characteristics.

The manufacturing cell complexity is defined by the equation provided in Figure 4.3. The focus group participants determined the weights for each of the variables based on their combined experience in planning and managing manufacturing cells. They used a multi-voting technique to determine the highest contributing factors which were determined to be number of finished part numbers (FPN), number of major part details (MPD), number of machines in cell (MACH), number of operations (OPS), and part complexity (PCPLX). The focus group decided that these five factors should be considered first in developing the equation, and where possible their interactions should be considered, then the final factor of number of outside operations would be considered.

For instance, the logistics activities involved in managing finished part numbers and major part details are activities similar in nature, so they were grouped together in the equation and received a weight of 40% based on the group's experience. As as example, cell B, which has 14 finished part numbers made from a single piece of raw material ist considered to be as complex to manage as cell D which has 3 finished part numbers each made up of 5 major part details. Therefore, both cells B and D are more complex than cells A or C when we only consider these first two factors in the first portion of the cell complexity equation.

Additionally, the number of operations, part complexity and number of machines needed to be considered together in the development of the equation due to their inherent interactions. The number of machines in the cell may consume a fair amount of management effort, especially in terms of machine downtime when there is no alternative machine, or when scheduling across a bottleneck. Additionally, the number of manufacturing operations has a direct impact on cell complexity due to the need for changeovers that could involve issues with fixtures, tooling, programs, off-sets and a multitude of other issues. If only the number of machines in the cell were considered, then cells A and B would be considered more complex than cells C and D. However, if the number of operations is considered, we quickly realize that cells C and D are more complex than cells A and B, both due to the number of operations and the number of operations in ratio to the number of machines. When we further considered the part complexity factor, the focus group determined that the second portion of the equation should exist of multiplying the number of operations times the part complexity and then diving by the number of machines. The second portion of the equation received a weight of 50% based on the group's experience. For the third portion of the equation, the focus group members decided that the number of outside operations (OUTOPS) was a lesser contributor to the overall cell complexity than the other five factors. The outside operations were simply services performed outside the cell by other departments or subcontractors. For this reason, the focus group determined to weight this last factor at 10%. The equation was applied to the four cells to obtain the values for cell complexity that appear in Table 4.4. No normalization approach was employed as the cells all operate under the same management structure and within the same systems and procedures at the same company. If the research was extending across additional companies, ratios and a normalization approach would be recommended in order to draw comparisons between the cells.

Note that the number of workers and number of shifts were not considered in the cell complexity calculation because they are dynamic and can change drastically over time. In addition, material was not considered in the cell complexity calculation because in most cases the material was identical and machining properties were similar.

$$CCPLX = 0.4 * (FPN * MPD) + 0.5 * ((OPS*PCPLX) / MACH) + 0.1 * OUTOPS$$

Figure 4.3 Cell Complexity Equation

4.5.7 Data Collection and Timing

4.5.7.1 Performance Measures

Throughput was the primary performance measure and the focus of the lean effort at the research site. It is important to reiterate that the definition of throughput in this study is "the number of good parts produced over a period of time". Table 4.5 provides a summary of the data collection over a 45 month period for the four cells. For this research, throughput was collected on a monthly basis from the cell inspection logs, as they are the official Federal Aviation Authority records. All other performance measures were collected as Phase 1 began for each cell and at the end of Phase 3 for each cell.

Table 4.5 Months of Throughput Data Collection by Cell

Cell	A	B	C	D
Months of Data	39	45	36	29

Table 4.6 provides a summary of the timing of the three cell implementation phases that were defined in detail in section 4.5.5 for each of the manufacturing cells. Cells were designed and implemented on a staggered schedule due to resource constraints which explains why some cells have more data available than others. Recall, however, that all four cells were implemented within seven month of one another.

Table 4.6 Phase Timing of Throughput Data by Cell

Timing of Phases	A	B	C	D
Phase 1	Month 6 through 12	Month 1 through 14	Month 8 through 14	Month 12 through 17
Phase 2	Month 13 through 20	Month 15 through 31	Month 15 through 29	Month 18 through 29
Phase 3	Month 21 through 44	Month 32 through 45	Month 30 through 43	Month 30 through 45

4.5.7.2 Questionnaire Administration and Respondents

Due to a lag in approval from the Institutional Review Board, the assessment questionnaire was administered during month 56. Table 4.7 provides a summary of the questionnaire responses by cell and in regard to hourly and salaried employees. The goal was to obtain input from the four primary salaried employees, five operators chosen at random, and one inspector chosen from random for each cell. Cells A and B both had additional hourly employees ask to be included above the goal of six participants. Although there was some risk for bias, the researchers chose to include these additional respondents to maintain their engagement. Unfortunately, cell C had low hourly participation, the cause of which is not known.

Table 4.7 Questionnaire Response Rate

Cell	A	B	C	D	Totals	Possible	% Response
Hourly	8	7	2	6	23	24	96%
Salary	2	3	3	3	11	16	69%
Totals	10	10	5	9	34	40	85%

The demographic information from Section 1 of the questionnaire reveals that the respondents were bi-modally distributed in terms of their tenure with the field study site. Twenty-four of the respondents had been with the company between three and ten years and ten respondents had been with the company between 22 and 30 years. There were no respondents with tenure between the two group ranges. This gap in the tenure demographic can be explained by the fact that the field study site had been sold twice in the same decade. During that time, attrition occurred with no new hiring activities. Additionally, upon the sale, a number of employees were given the opportunity to find employment at other sites within the original corporation, which depleted the employees whose tenure would have fallen between the two ranges.

From an education standpoint, 35% of the respondents had only their High School Diploma / GED, 26% held a Bachelors degree, 15% had attended some college, 9% had completed Vocational Technical school, 6% held a Masters degree, 3% were Journeymen Machinists, and 3% held an Associate Degree. It is apparent that the field study site maintained a skilled workforce. In addition, operators and inspectors were required to attend cell specific training any time they would make a job move per the labor agreement to ensure they were sufficiently skilled to operate all the machines within their job classification in the new manufacturing cell.

On a final note, it was a bit discouraging to discover that only 32% of the respondents were involved in the initial design of their manufacturing cell, while 68% were not involved. However, it is equally encouraging to find that 82% of the respondents were subsequently involved in an improvement event within their manufacturing cell, while only 18% were not involved. We will consider this information when we examine the three cell implementation phases for each of the manufacturing cells.

5.0 ANALYSIS AND RESULTS

This chapter provides the results of the analysis that was performed on the data collected from the four manufacturing cells as part of the field study. The statistical results are reported and discussed and the practical implications are explained.

5.1 CELL PERFORMANCE MEASURES RESULTS

5.1.1 Relationship between Throughput, Lead-time and Inventory

As mentioned in section 4.2, the primary objective of the lean manufacturing cell strategy at the field study site was to increase output to meet a sudden upturn in the market, so throughput was chosen as the primary performance measure. Recall that the focus group agreed to define throughput as the number of good parts produced over a period of time, which was on a monthly basis for the purposes of this research. A matrix plot and a correlation study are used to develop an understanding of the relationships between the cell performance measures of throughput, lead-time and inventory for the four manufacturing cells (Galton 1890, Pearson 1900, Stigler 1989).

In Figure 5.1, the matrix plot illustrates a strong negative relationship between throughput improvement and lead-time reduction. In addition, a strong negative relationship exists between throughput improvement and inventory reduction. This is the outcome the field study site had desired and is also consistent with the literature. The graph shows that as the cell throughput increases, lead-time is reduced and so is the inventory on hand.

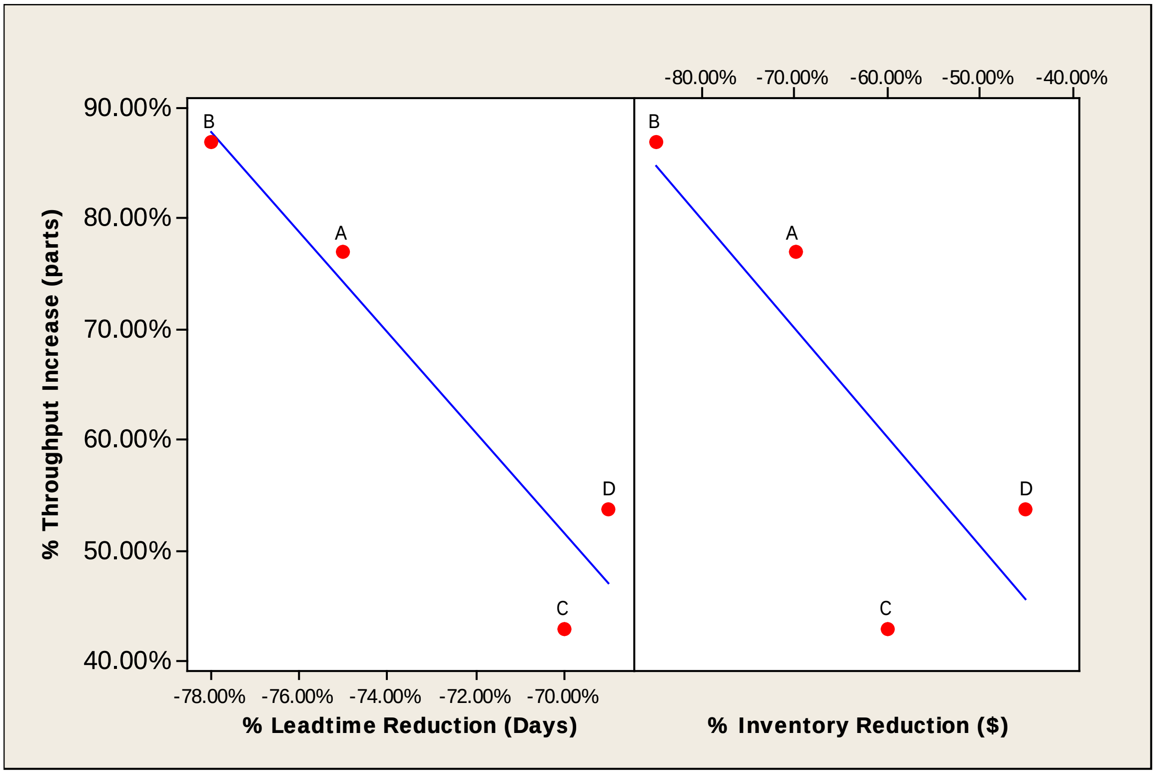

Figure 5.1 Matrix Plot of Throughput vs. Lead-time and Inventory

In addition to a graphical view of the relationships between these three performance measures, a mathematical understanding can be established through the use of the Pearson product moment correlation coefficient (Galton 1890, Pearson 1900, Stigler 1989).

The correlation table in Figure 5.2 provides Pearson product moment correlation coefficient between the cell performance measures of throughput, lead-time and inventory for the four manufacturing cells. The correlation coefficient between throughput improvement and lead-time reduction is -0.947. In addition, the correlation coefficient between throughput improvement and inventory reduction is -0.813. A Pearson correlation coefficient above 0.7 is generally accepted as a strong positive relationship (Groebner *et al.* 2011). Therefore, both of these instances are viewed as strong negative linear relationships.

	% Throughput Incr	% Leadtime Redu
% Leadtime Redu	-0.947	
% Inventory Redu	-0.813	0.957

Figure 5.2 Correlation Study of Throughput vs. Lead-time and Inventory

The detailed monthly data for each of these performance measures would have to be collected manually. During the data collection stage, it was observed that the records for throughput were the most accurate because the data was obtained from the formal cell inspection records and sales logs. Therefore, detailed monthly throughput data was collected, while only before Phase 1 and after Phase 3 implementation data was collected for lead-time and inventory. Throughput will be examined in much greater detail for each of the four manufacturing cells, while lead-time and inventory will be considered along with the analysis of the other two secondary performance measures, cost of non-quality and product cost.

5.1.2 Cell A Graphical and Comparative Results

An initial graphical analysis is conducted to begin to develop an understanding of the throughput performance measure over time through the use of box plots and control charts. Recall that the focus group agreed to define throughput as the number of good parts produced over a period of time, which was on a monthly basis for the purposes of this research. All of the analysis presented in this subsection is based on considering the raw monthly throughput data in terms of the three discrete phases of implementation that are summarized in Table 4.6.

The box plot for Cell A is provided in Figure 5.3. In addition to the five traditional measures: the lower limit, first quartile (Q1), median (Q2), third quartile (Q3), and largest upper limit, the mean is also included as a circle with a cross inside. The means are connected for the three implementation phases.

There appear to be no outliers in the data for any of the three phases. The box plot suggests a possible difference in means and variances for throughput across the three phases for Cell A. This will be tested using the appropriate comparative methods later in the section.

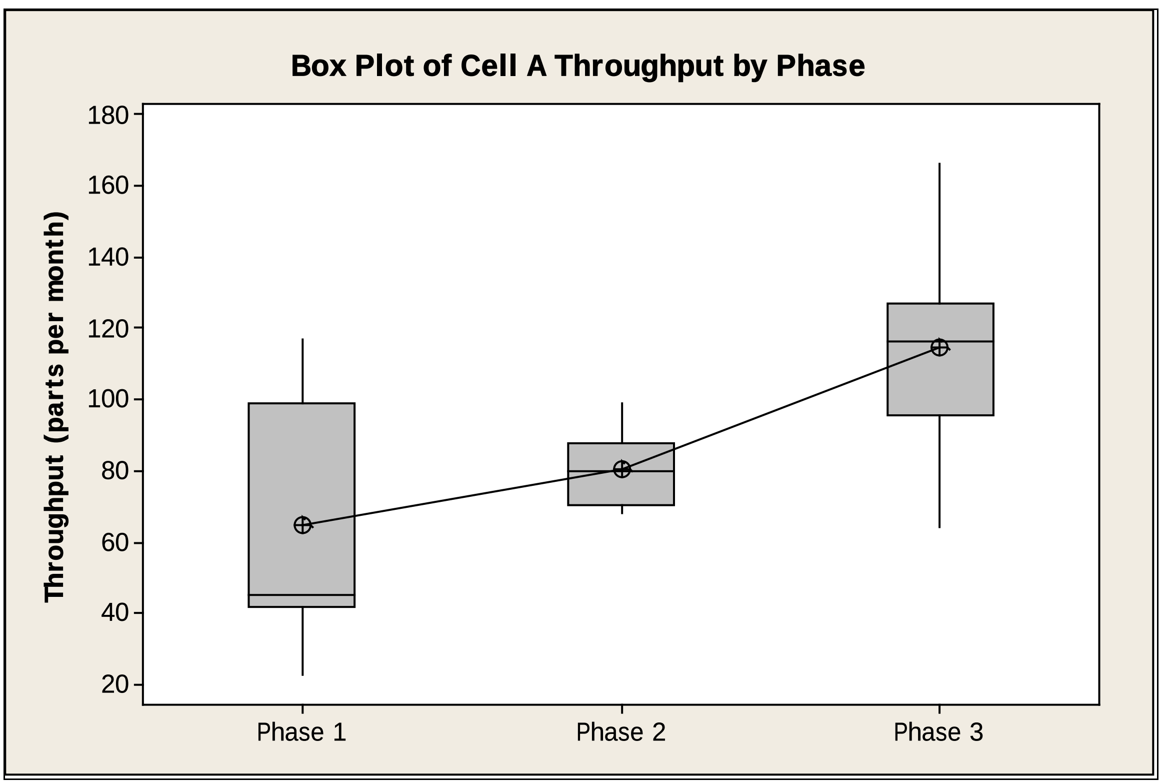

Figure 5.3 Box Plot of Cell A Throughput by Phase

For the purpose of the research, a staged Individual and Moving Range (I&MR) control chart is used with the stages defined by the three discrete cell implementation phases to gain visual insight and assist with theories regarding the throughput data by phase. The I&MR control chart for Cell A is provided in Figure 5.4. No points lie outside the 3 sigma control limits, so there is no violation of Rule 1 (Shewhart 1931). During phase 3, it appears as if the process shifted upward. A process shift may be indicated on the x-bar chart by the presence of a 2 above or below a data point which denotes that 8 points in a row were above or below the mean, which is a violation of Rule 2 (Shewhart 1931). In the first case, 8 points were below the mean. In the second occurrence, 8 points were above the mean. The I&MR control chart is congruent with the box plots and suggests a possible difference in means and variances for throughput across the three phases for Cell A. It appears as though the mean throughput increases from phase 1 to phase 2 and then again from phase 2 to phase 3 which is the desired outcome. From a variation standpoint, it appears as if the variation was the smallest during phase 2, but still exhibits improvement when comparing phases 1 and 3, which is also desired. This theory will be tested using the appropriate comparative methods later in the section.

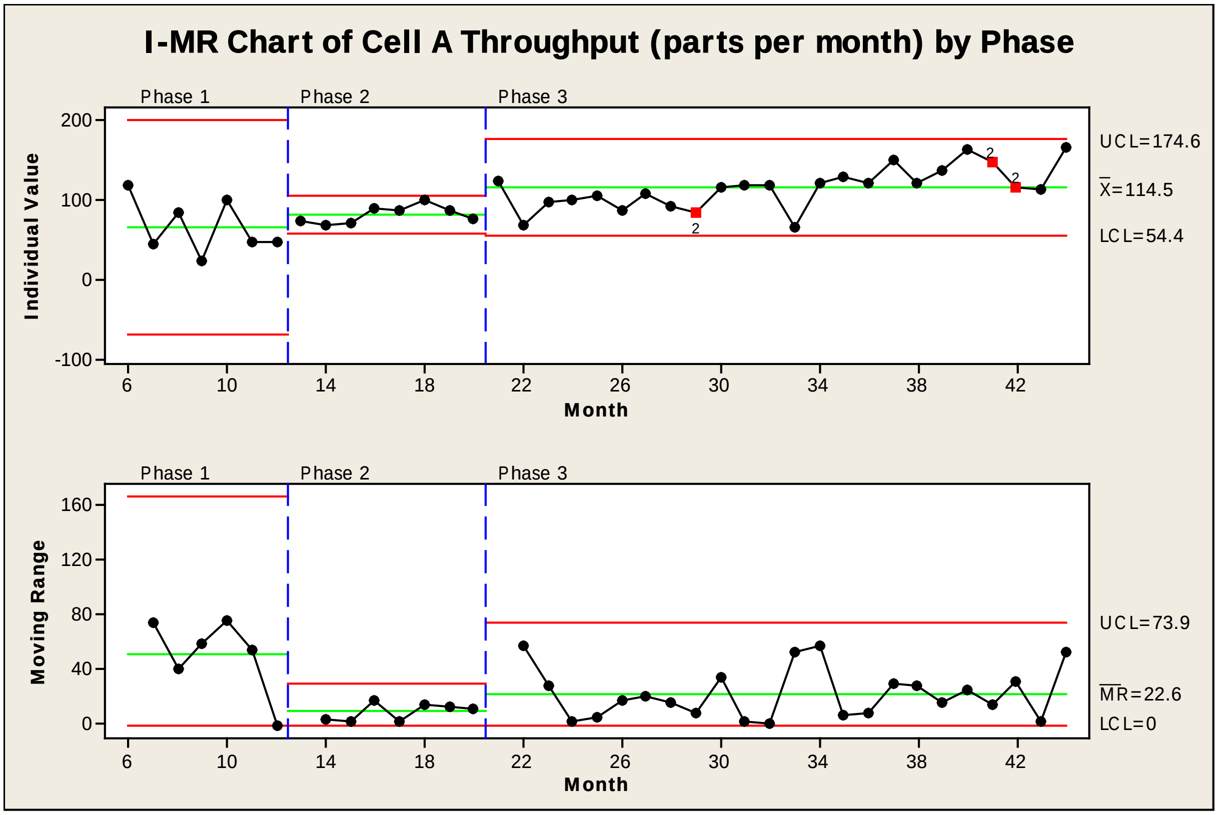

Figure 5.4 Staged Control Chart of Cell A Throughput by Phase

In order to determine which comparative methods are appropriate to use, the normality of the throughput data for each of the three cell implementation phases must first be tested. A graphical approach is employed through comparison of a histogram of the sample data to an overlay of the normal probability curve. In addition, the normality of the data is mathematically tested using the Anderson-Darling test with an alpha risk of 5%. The null hypothesis (H_o) statement is: the data can be modeled by a normal distribution. The alternate hypothesis (H_a) statement is: the data cannot be modeled by a normal distribution. Figures 5.5 through 5.7 provide the results of the graphical analysis and the Anderson-Darling normality test for phases 1 through 3 of Cell A, respectively. When the p-values of 0.277, 0.426, and 0.669 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in all three cases. Therefore all three phases of throughput data for Cell A can be modeled by a normal distribution.

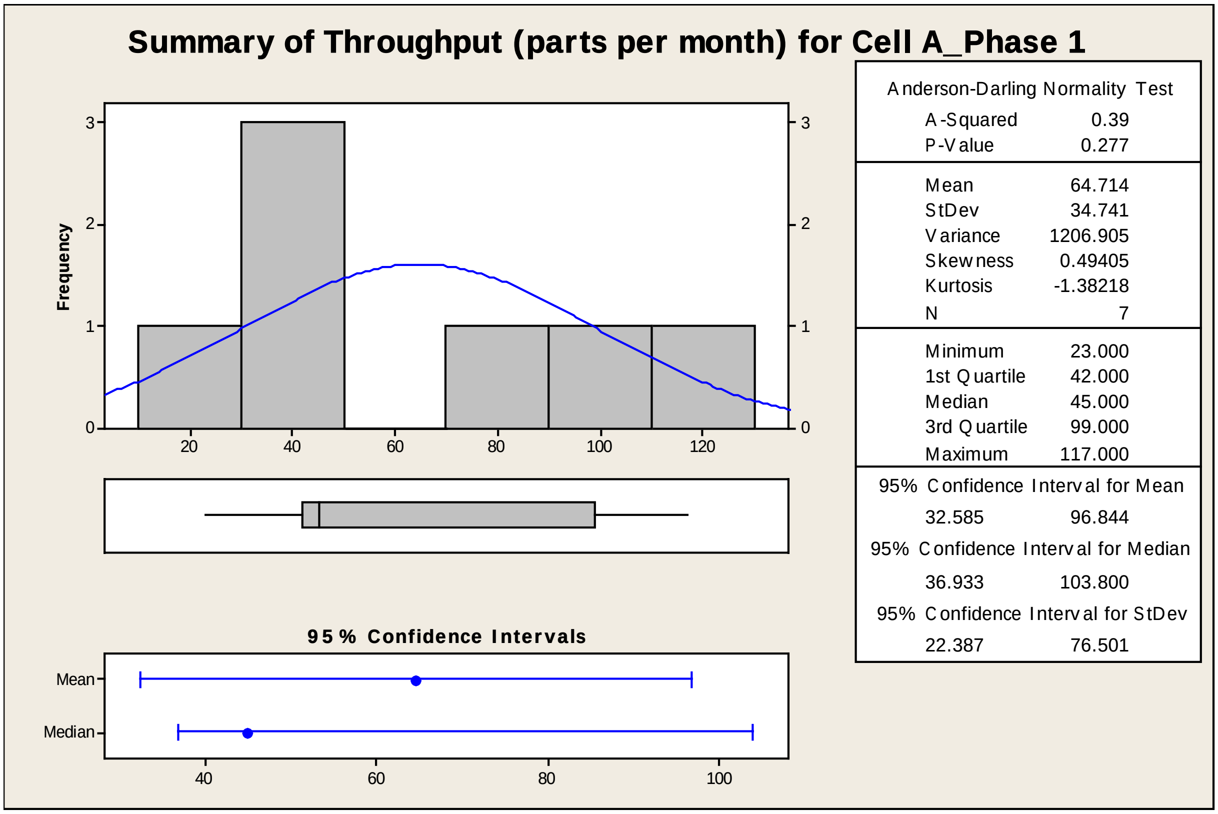

Figure 5.5 Histogram and Normality Test for Cell A Phase 1

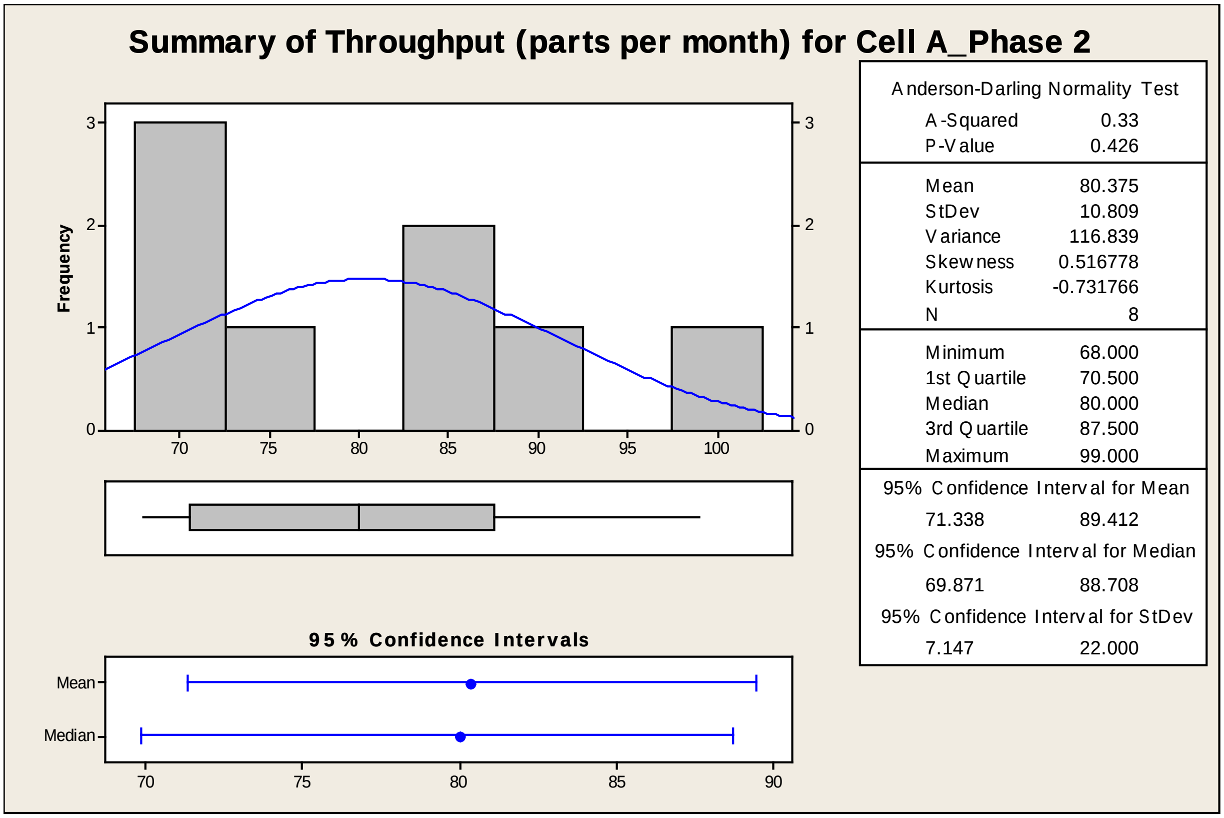

Figure 5.6 Histogram and Normality Test for Cell A Phase 2

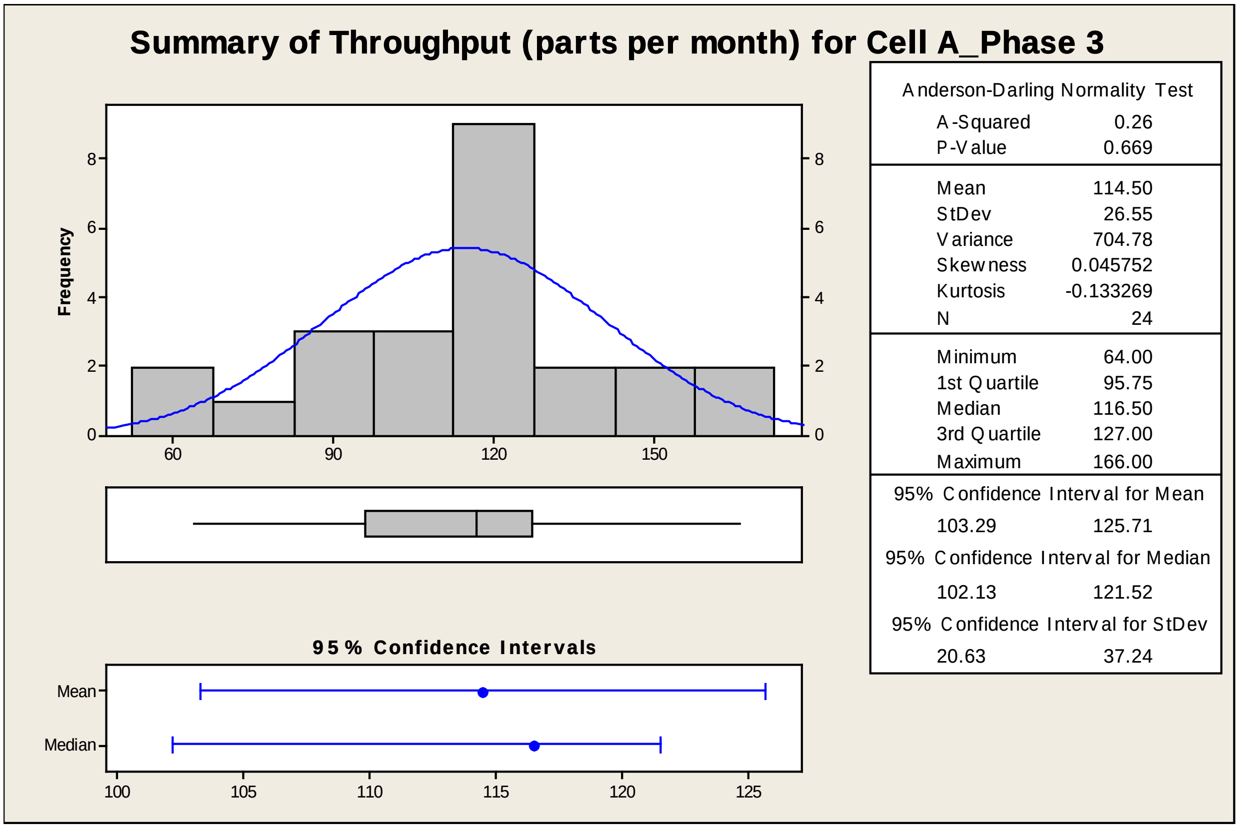

Figure 5.7 Histogram and Normality Test for Cell A Phase 3

Comparative methods were first employed for the variances of the throughput for the three cell implementation phases. Variance testing is usually completed prior to means testing for normal data to determine if the assumption of equal variances is valid for the two-sample *t*-test or to meet the assumption of equal variances for ANOVA (Groebner *et al.* 2011).

In this case, a multiple comparison is required to represent the three defined phases of cell implementation. Since we are testing more than two variances, the *F*-test statistic is not appropriate, and Bartlett's test is utilized. The null hypothesis (H_o) statement is: there is no difference between the variances of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the variances of the throughput for the three cell phases. Figure 5.8 provides the results of the graphical analysis and Bartlett's test for phases 1 through 3 of Cell A. Figure 5.9 provides the additional mathematical detail for Bartlett's test. When the p-value of 0.025 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a difference in the variances of the three cell implementation phases. Bartlett's test does not provide the detail as to between which phases the difference in variation exists. However, based on our insight in reviewing the I&MR control chart, it appear as though the variation is the highest during phase 1 of implementation and exhibits a reduction during phases 2 and 3, which is the targeted outcome.

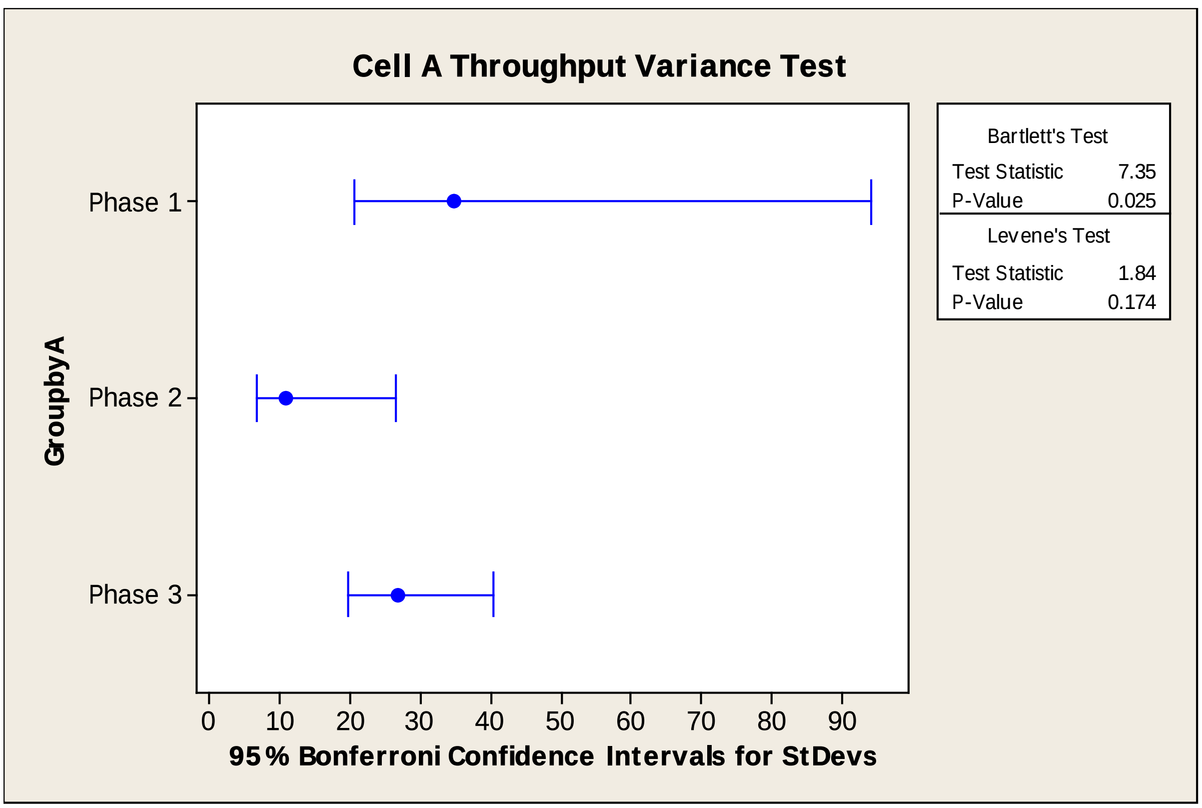

Figure 5.8 Cell A Graphical Throughput Variance Test by Phase

```
Test for Equal Variances: A1 versus GroupbyA

95% Bonferroni confidence intervals for standard deviations

GroupbyA   N    Lower    StDev    Upper
 Phase 1   7     20.5     34.7     94.3
 Phase 2   8      6.6     10.8     26.5
 Phase 3  24     19.6     26.5     40.4


Bartlett's Test (Normal Distribution)
Test statistic = 7.35, p-value = 0.025


Levene's Test (Any Continuous Distribution)
Test statistic = 1.84, p-value = 0.174
```

Figure 5.9 Cell A Throughput Variance Test by Phase - Detail

Next, comparative methods were conducted for the throughput medians of the three cell implementation phases for cell A. Since the underlying test assumption of equal variances was not met, ANOVA could not be employed. In cases where the equal variance assumption is not met, the median is usually a better indicator of central tendency for the distribution than the mean. The Kruskal-Wallis one-way analysis of variance by ranks is a non-parametric method that is used for comparing more than two samples that are independent and have similar shapes. For the Kruskal-Wallis test, the null hypothesis (H_o) statement is: there is no difference between the throughput medians for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput medians for the three cell phases. Figure 5.10 provides the results of the Kruskal-Wallis test for phases 1 through 3 of cell A. When the p-value of 0.001 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a difference in the medians of the three cell implementation phases for cell A.

```
Kruskal-Wallis Test: A1 versus GroupbyA

Kruskal-Wallis Test on A1

GroupbyA    N  Median  Ave Rank      Z
Phase 1     7   45.00       9.9  -2.58
Phase 2     8   80.00      12.3  -2.16
Phase 3    24  116.50      25.5   3.82
Overall    39              20.0

H = 14.78  DF = 2  P = 0.001
H = 14.79  DF = 2  P = 0.001  (adjusted for ties)
```

Figure 5.10 Cell A Throughput Medians Test by Phase

When the Kruskal-Wallis test leads to significant results, then at least one of the samples is different from the other samples. However, the test does not identify between which pairs of cell implementation phases the differences occur. Therefore, for cell A, further testing is completed via the two-sample *t*-test with non-pooled standard deviations based on the Bartlett test results of unequal variances between phases.

A two-sample *t*-test is used when comparing sample means of two normally distributed populations for equality when the sample variances are also equal (Groebner *et al.* 2011). For both forms of the *t*-test used in the analysis, the null hypothesis (H_o) statement is: there is no difference between the throughput means for the two cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput means for the two cell phases. Figures 5.11 through 5.13 provide the results of the two-sample *t*-test for the pair-wise comparisons of phases 1 through 3 of cell A, respectively. When the p-values of 0.290, 0.000, and 0.008 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in the case of phase 1 vs. phase 2. Therefore, there is no difference in the throughput means for phase 1 and phase 2. However, in the cases of phase 2 vs. phase 3 and phase 1 vs. phase 3, we reject the null hypothesis. Therefore, there is a difference in the throughput means in these two cases. The results are summarized in Table 5.1.

This is a disappointing result as the field study site had hoped that there would be a statistically significant difference in throughput means between phases 1 and 2 of cell implementation for all cells. However, based on our insight in reviewing the I&MR control chart, and the throughput means testing, we do observe a steady increase from 64.7 to 80.4 to 114.5 mean throughput parts per month for phases 1 through 3 respectively. When the demographic information is considered for cell A, it is seen that only 20% of the respondents were involved in the initial cell design and implementation during phase 1, which could account for the lag in mean throughput improvement. In addition, 70% of the respondents were involved in the phase 3 improvement event, which further explains the marked throughput increase and the statistical significance between phases 2 and 3.

```
Two-Sample T-Test and CI: A1_Phase 1, A1_Phase 2

Two-sample T for A1_Phase 1 vs A1_Phase 2

            N  Mean  StDev  SE Mean
A1_Phase 1  7  64.7   34.7       13
A1_Phase 2  8  80.4   10.8      3.8


Difference = mu (A1_Phase 1) - mu (A1_Phase 2)
Estimate for difference:  -15.7
95% CI for difference:  (-48.0, 16.7)
T-Test of difference = 0 (vs not =): T-Value = -1.15
P-Value = 0.290  DF = 7
```

Figure 5.11 Cell A Throughput Mean Comparison for Phase 1 vs. Phase 2

```
Two-Sample T-Test and CI: A1_Phase 2, A1_Phase 3

Two-sample T for A1_Phase 2 vs A1_Phase 3

             N   Mean  StDev  SE Mean
A1_Phase 2   8   80.4   10.8      3.8
A1_Phase 3  24  114.5   26.5      5.4


Difference = mu (A1_Phase 2) - mu (A1_Phase 3)
Estimate for difference:  -34.13
95% CI for difference:  (-47.71, -20.54)
T-Test of difference = 0 (vs not =): T-Value = -5.15
P-Value = 0.000  DF = 28
```

Figure 5.12 Cell A Throughput Mean Comparison for Phase 2 vs. Phase 3

```
Two-Sample T-Test and CI: A1_Phase 1, A1_Phase 3

Two-sample T for A1_Phase 1 vs A1_Phase 3

             N   Mean  StDev  SE Mean
A1_Phase 1   7   64.7   34.7       13
A1_Phase 3  24  114.5   26.5      5.4


Difference = mu (A1_Phase 1) - mu (A1_Phase 3)
Estimate for difference:  -49.8
95% CI for difference:  (-82.5, -17.0)
T-Test of difference = 0 (vs not =): T-Value = -3.50
P-Value = 0.008  DF = 8
```

Figure 5.13 Cell A Throughput Mean Comparison for Phase 1 vs. Phase 3

Table 5.1 Summary of Cell A Throughput Mean Comparison by Phase

Cell	Phase 1 v. Phase 2	Phase 2 v. Phase 3	Phase 1 v. Phase 3
A	Fail to Reject H_0	Reject H_0	Reject H_0
	No difference in mean throughput	Difference in mean throughput	Difference in mean throughput

5.1.3 Cell B Graphical and Comparative Results

An initial graphical analysis is conducted to begin to develop an understanding of the throughput performance measure over time through the use of box plots and control charts. Recall that the focus group agreed to define throughput as the number of good parts produced over a period of time, which was on a monthly basis for the purposed of this research. All of the analysis presented in this subsection is based on considering the raw monthly throughput data in terms of the three discrete phases of implementation that are summarized in Table 4.6.

Similar to the analysis for cell A, the box plot for cell B is provided in Figure 5.14. There appears to be one high outlier in phase 2 and one low outlier in phase 3. After reviewing the detailed data, no assignable cause was noted for either. However, the control chart will be examined to see how these outliers behave with respect to the +/- 3 sigma control limits. The box plot suggests a possible difference in means and variances for throughput across the three phases for cell B. This will be tested using the appropriate comparative methods later in the section.

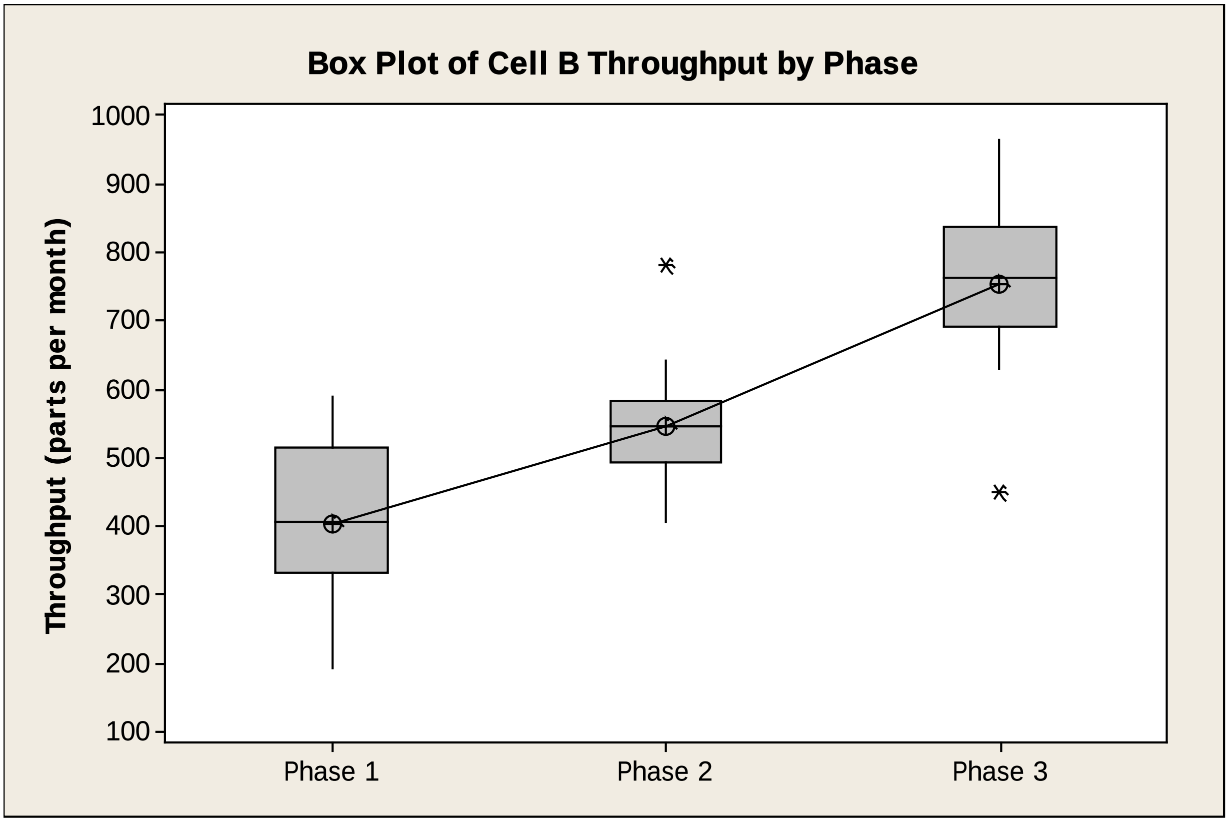

Figure 5.14 Box Plot of Cell B Throughput by Phase

Similar to the analysis for cell A, the I&MR control chart for cell B is provided in Figure 5.15. Although the box plot depicts one high outlier in phase 2 and one low outlier in phase 3, no points lie outside the 3 sigma control limits, so there is no violation of Rule 1 (Shewhart 1931). The I&MR control chart is congruent with the box plots and suggests a possible difference in means and variances for throughput across the three phases for cell B. It appears as though the mean throughput increases from phase 1 to phase 2 and then from phase 2 to phase 3 which is the desired outcome. From a variation standpoint, it appears as if the variation was the smallest during phase 2, but still exhibits improvement when comparing phases 1 and 3. This will be tested using the appropriate comparative methods later in the section.

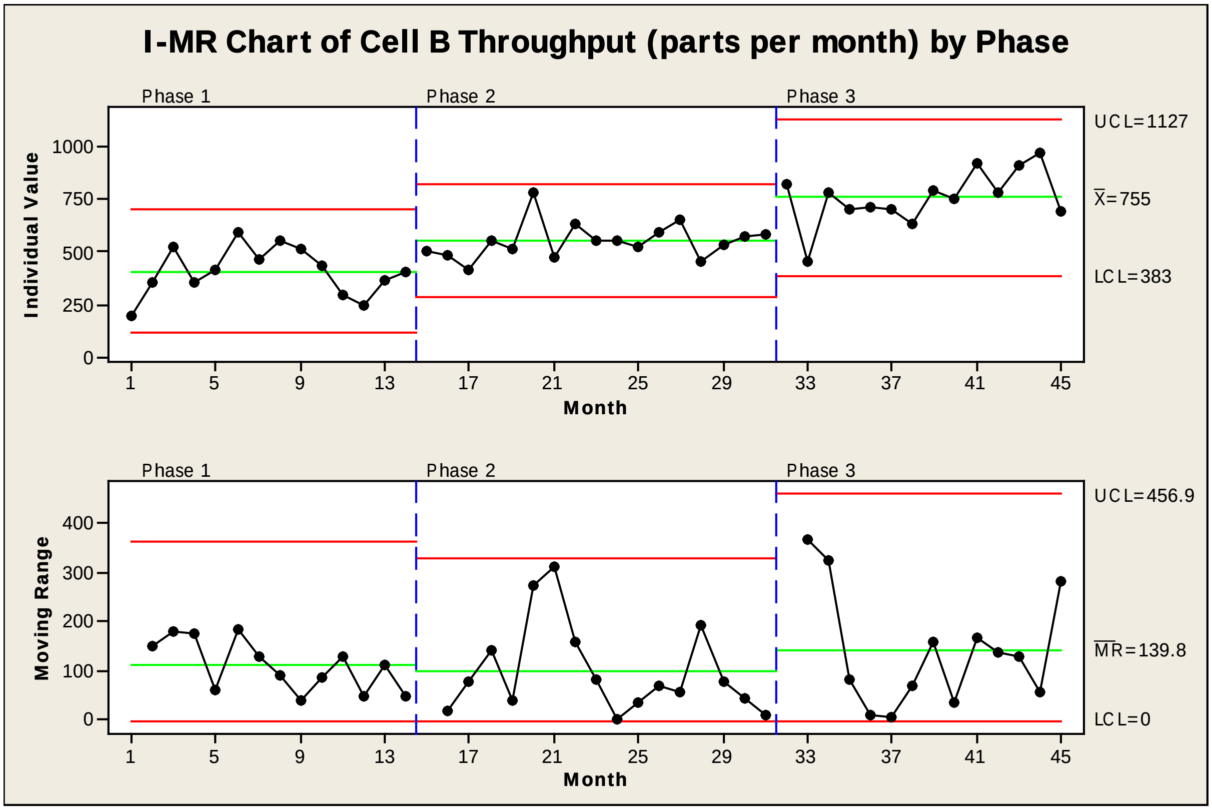

Figure 5.15 Staged Control Chart of Cell B Throughput by Phase

In order to determine which comparative methods are appropriate to use, the normality of the throughput data for each of the three cell implementation phases must first be tested. A graphical approach is employed through comparison of a histogram of the sample data to an overlay of the normal probability curve. In addition, the normality of the data is mathematically tested using the Anderson-Darling test with an alpha risk of 5%. The null hypothesis (H_o) statement is: the data can be modeled by a normal distribution. The alternate hypothesis (H_a) statement is: the data cannot be modeled by a normal distribution. Figures 5.16 through 5.18 provide the results of the graphical analysis and the Anderson-Darling normality test for phases 1 through 3 of cell B, respectively. When the p-values of 0.945, 0.349, and 0.459 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in all three cases. Therefore all three phases of throughput data for cell B can be modeled by a normal distribution.

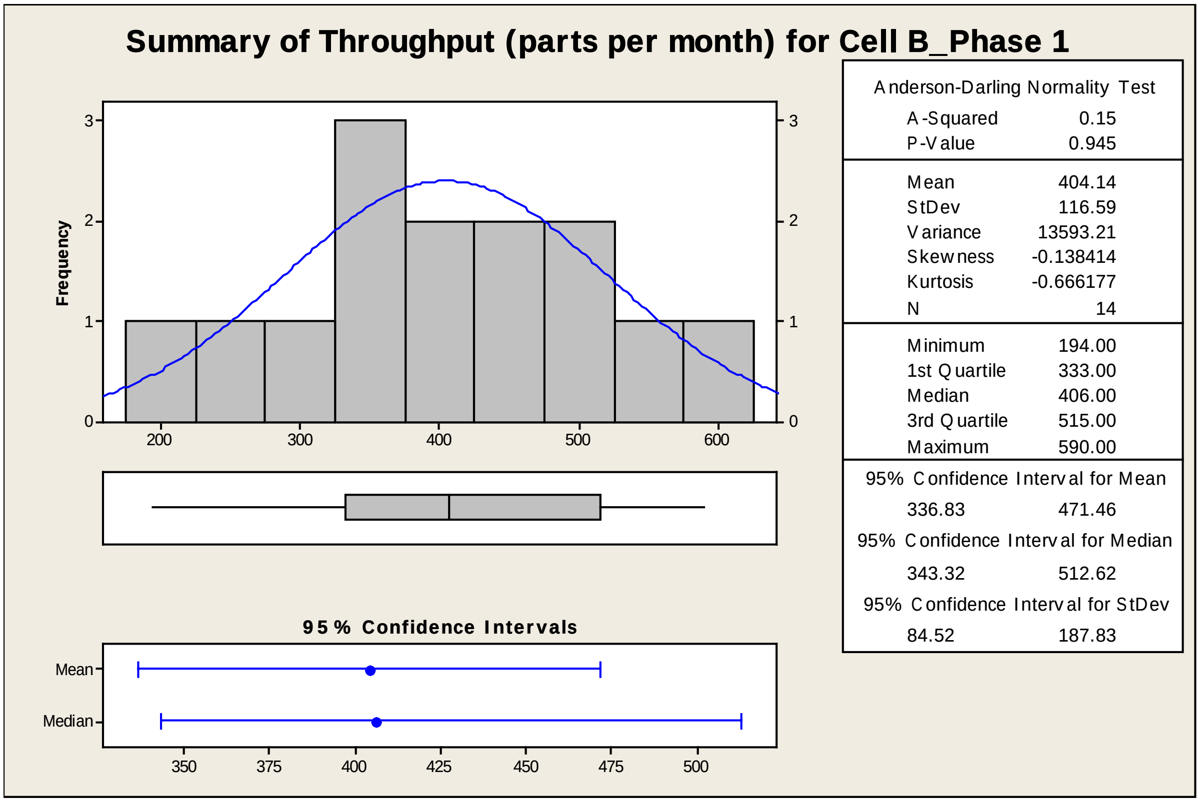

Figure 5.16 Histogram and Normality Test for Cell B Phase 1

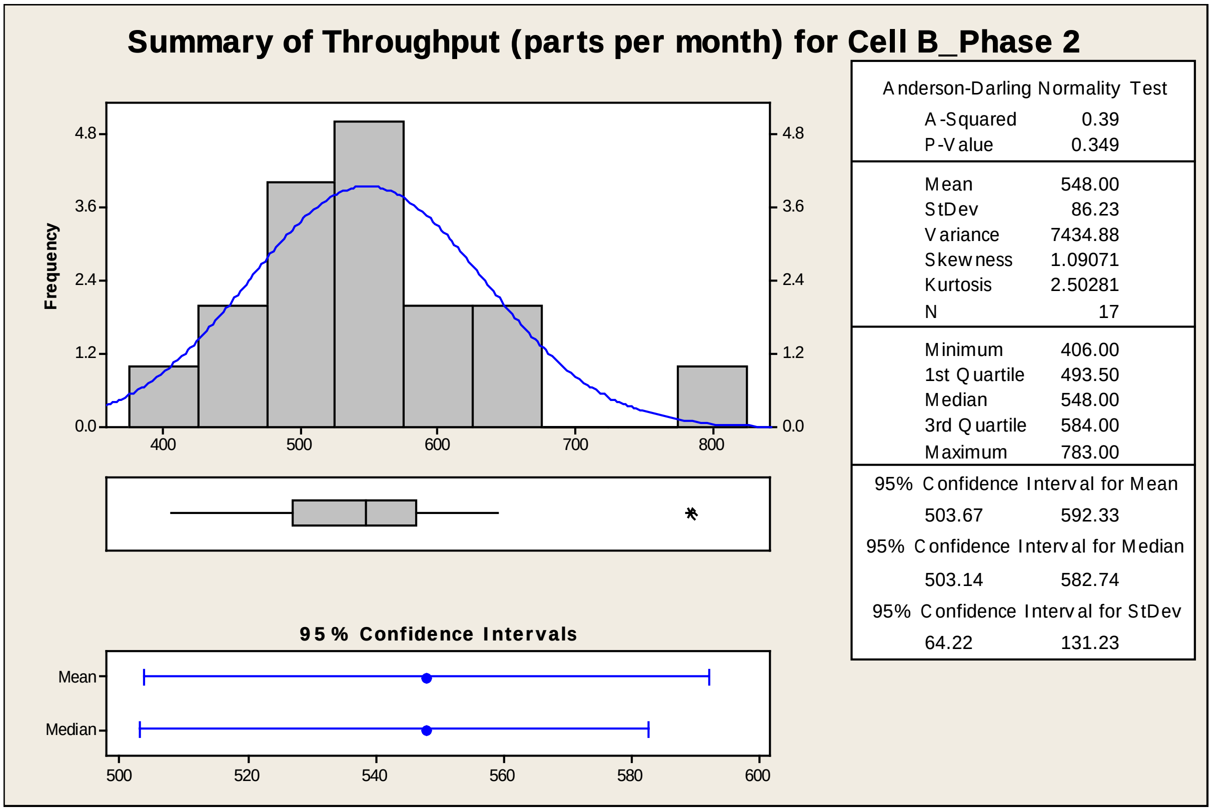

Figure 5.17 Histogram and Normality Test for Cell B Phase 2

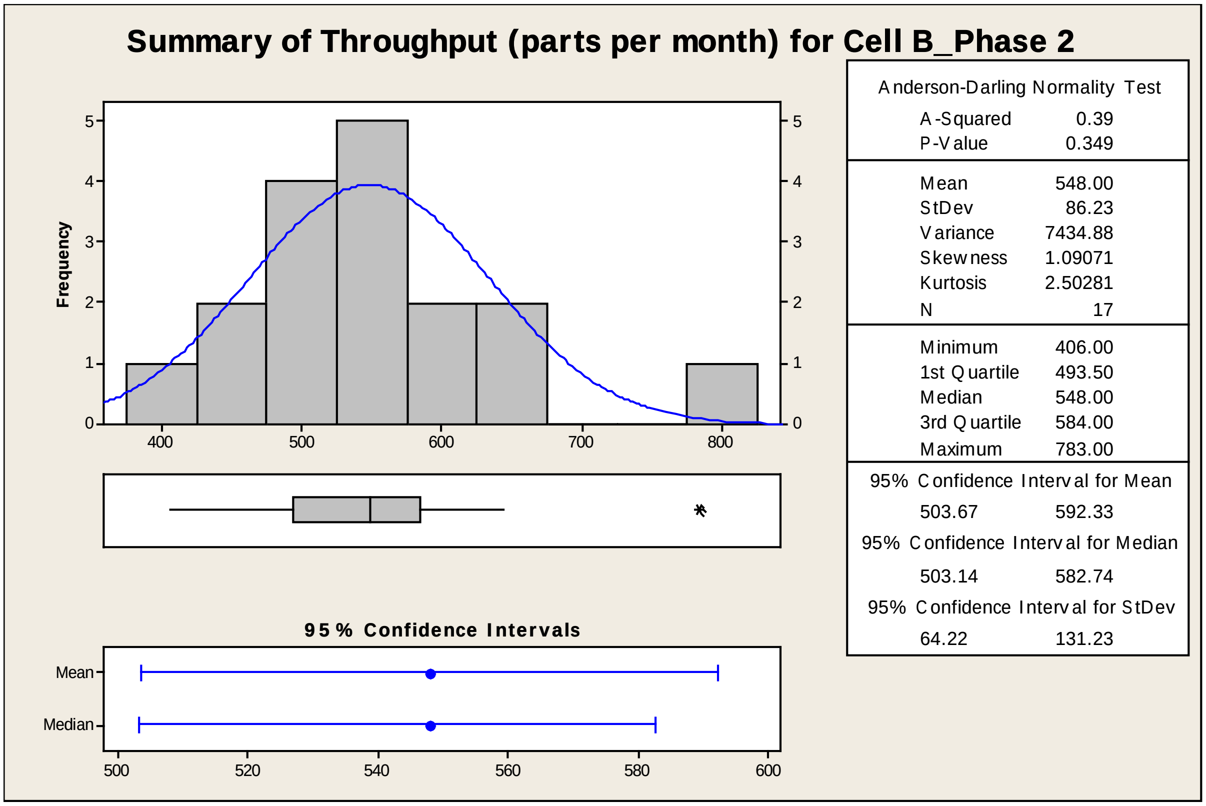

Figure 5.18 Histogram and Normality Test for Cell B Phase 3

Comparative methods were first employed for the variances of the throughput for the three cell implementation phases. The null hypothesis (H_o) statement is: there is no difference between the variances of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the variances of the throughput for the three cell phases. Figure 5.19 provide the results of the graphical analysis and Bartlett's test for phases 1 through 3 of cell B. Figure 5.20 provides the additional mathematical detail for Bartlett's test. When the p-value of 0.285 is compared against the alpha risk value of 0.05, we fail to reject the null hypothesis. Therefore, there is no difference in the variances of the three cell implementation phases. The field study site had hoped that the manufacturing cell implementation would lead to some reduction in variation for all cells in all phases. However, there are a few things to consider. First, the lean manufacturing strategy was focused on increasing output, so the examination of the throughput means is more relevant. Second, at least the process variation did not increase during the implementation phases. Finally, the field study site has aggressive plans to use six sigma techniques to target variation reduction once the factory has been fully transitioned from a functional to cellular layout.

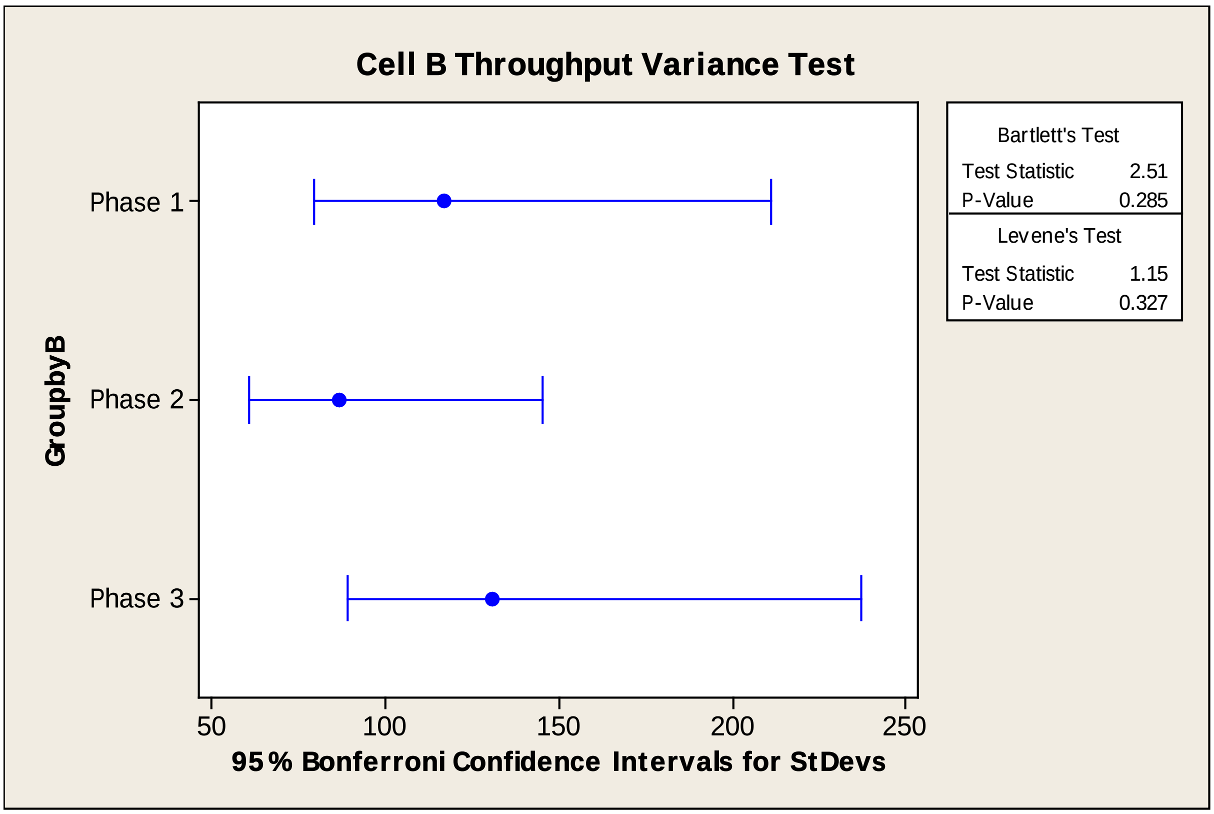

Figure 5.19 Cell B Graphical Throughput Variance Test by Phase

```
Test for Equal Variances: B1 versus GroupbyB

95% Bonferroni confidence intervals for standard deviations

GroupbyB    N    Lower    StDev    Upper
 Phase 1   14     79.1    116.6    211.4
 Phase 2   17     60.4     86.2    145.4
 Phase 3   14     88.7    130.8    237.2


Bartlett's Test (Normal Distribution)
Test statistic = 2.51, p-value = 0.285


Levene's Test (Any Continuous Distribution)
Test statistic = 1.15, p-value = 0.327
```

Figure 5.20 Cell B Throughput Variance Test by Phase - Detail

Next, comparative methods were conducted for the throughput means of the three cell implementation phases for cell B. The underlying test assumptions for ANOVA were met to include: independence, normality, and equality of variances. In its most basic form, ANOVA provides a statistical test of whether the means of several groups are all equal and is a generalization of the *t*-test to more than two groups. For ANOVA, the null hypothesis (H_o) statement is: there is no difference between the throughput means for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput means for the three cell phases. Figure 5.21 provides the results of the ANOVA for phases 1 through 3 of cell B. When the p-value of 0.00 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a difference in the means of the three cell implementation phases for cell B.

One-way ANOVA: B1 versus GroupbyB

```
Source    DF       SS      MS      F      P
GroupbyB   2   874499  437249  35.44  0.000
Error     42   518169   12337
Total     44  1392668

S = 111.1   R-Sq = 62.79%   R-Sq(adj) = 61.02%


                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level     N   Mean  StDev  -+---------+---------+---------+--------
Phase 1  14  404.1  116.6  (----*----)
Phase 2  17  548.0   86.2            (----*---)
Phase 3  14  755.4  130.8                            (----*----)
                           -+---------+---------+---------+--------
                           360       480       600       720

Pooled StDev = 111.1
```

Figure 5.21 Cell B Throughput Means Test by Phase

When the ANOVA leads to significant results, then at least one of the samples is different from the other samples. However, the test does not identify between which pairs of cell implementation phases the differences occur. Therefore, for cell B, further testing is completed via the two-sample *t*-test with pooled standard deviations based on the Bartlett test results of equal variances between phases.

For both forms of the *t*-test used in the analysis, the null hypothesis (H_o) statement is: there is no difference between the throughput means for the two cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput means for the two cell phases. Figures 5.22 through 5.24 provide the results of the two-sample *t*-test for the pair-wise comparisons of phases 1 through 3 of cell B, respectively. When the p-values of 0.000, 0.000, and 0.000 are compared against the alpha risk value of 0.05, we reject the null hypothesis in each case. Therefore, there is a difference in the throughput means in all three cases. The results are summarized in Table 5.2. This is an encouraging result as the field study site had hoped that there would be a statistically significant difference in throughput means between phases 1 vs. 2 and phases 2 vs. 3 of cell implementation for all cells. Obviously, if these two instances are true, then a statistically significant difference in throughput means between phases 1 vs. 3 exists through the transitive property of mathematics.

Based on our insight in reviewing the I&MR control chart, and the throughput means testing, we observe a steady increase from 404.1 to 548.0 to 755.4 mean throughput parts per month for phases 1 through 3 respectively. When the demographic information is considered for cell B, it is seen that 50% of the respondents were involved in the initial cell design and implementation, which could account for significant mean throughput improvement. In addition, 90% of the respondents were involved in the phase 3 improvement event, which further explains the marked throughput increase and the statistical significance between phases 2 and 3.

Two-Sample T-Test and CI: B1_Phase 1, B1_Phase 2

```
Two-sample T for B1_Phase 1 vs B1_Phase 2

                                     SE
              N    Mean  StDev   Mean
B1_Phase 1   14     404    117     31
B1_Phase 2   17   548.0   86.2     21


Difference = mu (B1_Phase 1) - mu (B1_Phase 2)
Estimate for difference:  -143.9
95% CI for difference:  (-218.4, -69.3)
T-Test of difference = 0 (vs not =): T-Value = -3.95
P-Value = 0.000  DF = 29
Both use Pooled StDev = 100.9728
```

Figure 5.22 Cell B Throughput Mean Comparison for Phase 1 vs. Phase 2

Two-Sample T-Test and CI: B1_Phase 2, B1_Phase 3

```
Two-sample T for B1_Phase 2 vs B1_Phase 3

                                   SE
             N   Mean  StDev    Mean
B1_Phase 2  17  548.0   86.2      21
B1_Phase 3  14    755    131      35


Difference = mu (B1_Phase 2) - mu (B1_Phase 3)
Estimate for difference:  -207.4
95% CI for difference:  (-287.5, -127.3)
T-Test of difference = 0 (vs not =): T-Value = -5.30
P-Value = 0.000  DF = 29
Both use Pooled StDev = 108.5099
```

Figure 5.23 Cell B Throughput Mean Comparison for Phase 2 vs. Phase 3

Two-Sample T-Test and CI: B1_Phase 1, B1_Phase 3

```
Two-sample T for B1_Phase 1 vs B1_Phase 3

                                SE
             N  Mean  StDev   Mean
B1_Phase 1  14   404    117     31
B1_Phase 3  14   755    131     35


Difference = mu (B1_Phase 1) - mu (B1_Phase 3)
Estimate for difference:  -351.3
95% CI for difference:  (-447.6, -255.0)
T-Test of difference = 0 (vs not =): T-Value = -7.50
P-Value = 0.000  DF = 26
```

Figure 5.24 Cell B Throughput Mean Comparison for Phase 1 vs. Phase 3

Table 5.2 Summary of Cell B Throughput Mean Comparison by Phase

Cell	Phase 1 v. Phase 2	Phase 2 v. Phase 3	Phase 1 v. Phase 3
B	Reject H_0	Reject H_0	Reject H_0
	Difference in mean throughput	Difference in mean throughput	Difference in mean throughput

5.1.4 Cell C Graphical and Comparative Results

An initial graphical analysis is conducted to begin to develop an understanding of the throughput performance measure over time through the use of box plots and control charts. Recall that the focus group agreed to define throughput as the number of good parts produced over a period of time, which was on a monthly basis for the purposed of this research. All of the analysis presented in this subsection is based on considering the raw monthly throughput data in terms of the three discrete phases of implementation that are summarized in Table 4.6.

Similar to the analysis for cell A, the box plot for cell C is provided in Figure 5.25. There appears to be one low outlier in phase 1. After reviewing the detailed data, no assignable cause was noted. However, the control chart will be examined to see how this outlier behaves with respect to the +/- 3 sigma control limits. The box plot suggests a possible difference in means and variances for throughput across the three phases for cell C. This will be tested using the appropriate comparative methods later in the section.

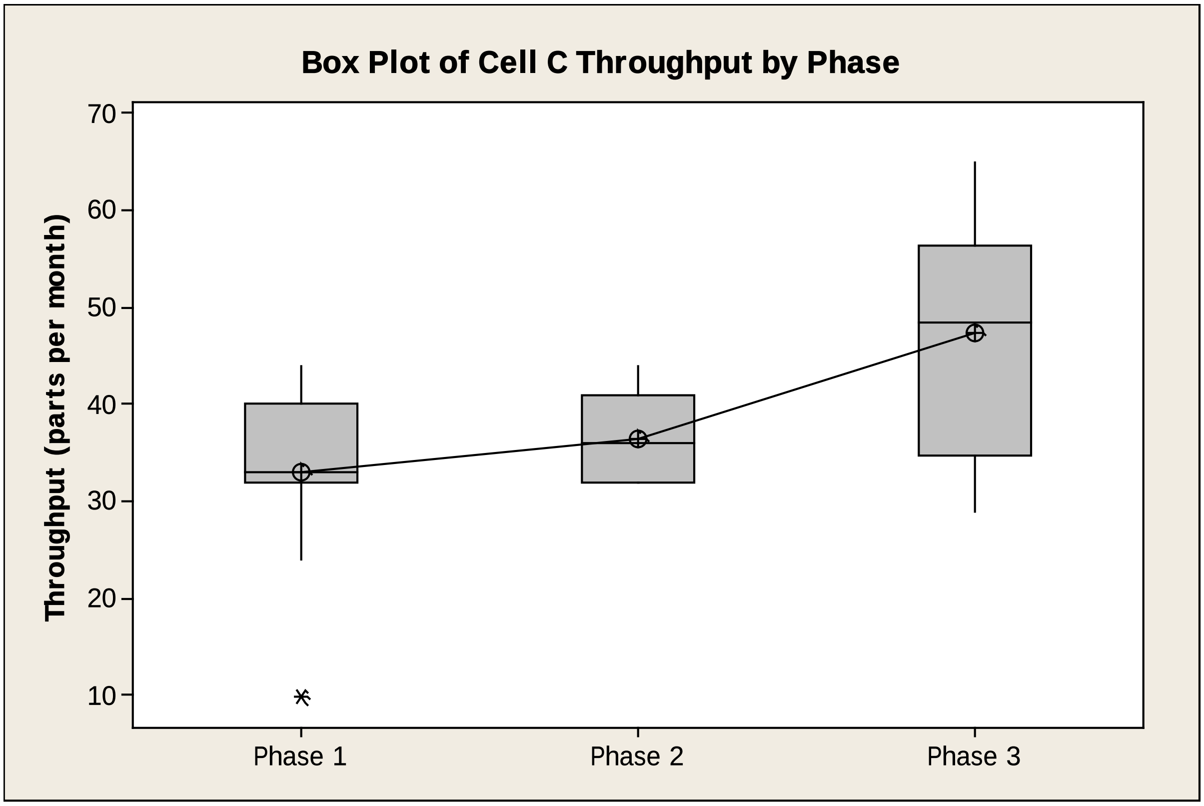

Figure 5.25 Box Plot of Cell C Throughput by Phase

Similar to the analysis for cell A, the I&MR control chart for cell C is provided in Figure 5.26. Although the box plot depicts one low outlier in phase 1, no points lie outside the 3 sigma control limits, so there is no violation of Rule 1 (Shewhart 1931). The I&MR control chart is congruent with the box plots and suggests a possible difference in means and variances for throughput across the three phases for cell C. It appears as though the mean throughput increases from phase 1 to phase 2 and then from phase 2 to phase 3 which is the desired outcome. From a variation standpoint, it appears as if the variation was the smallest during phase 2, and does not exhibit improvement when comparing phases 1 and 3. This will be tested using the appropriate comparative methods later in the section.

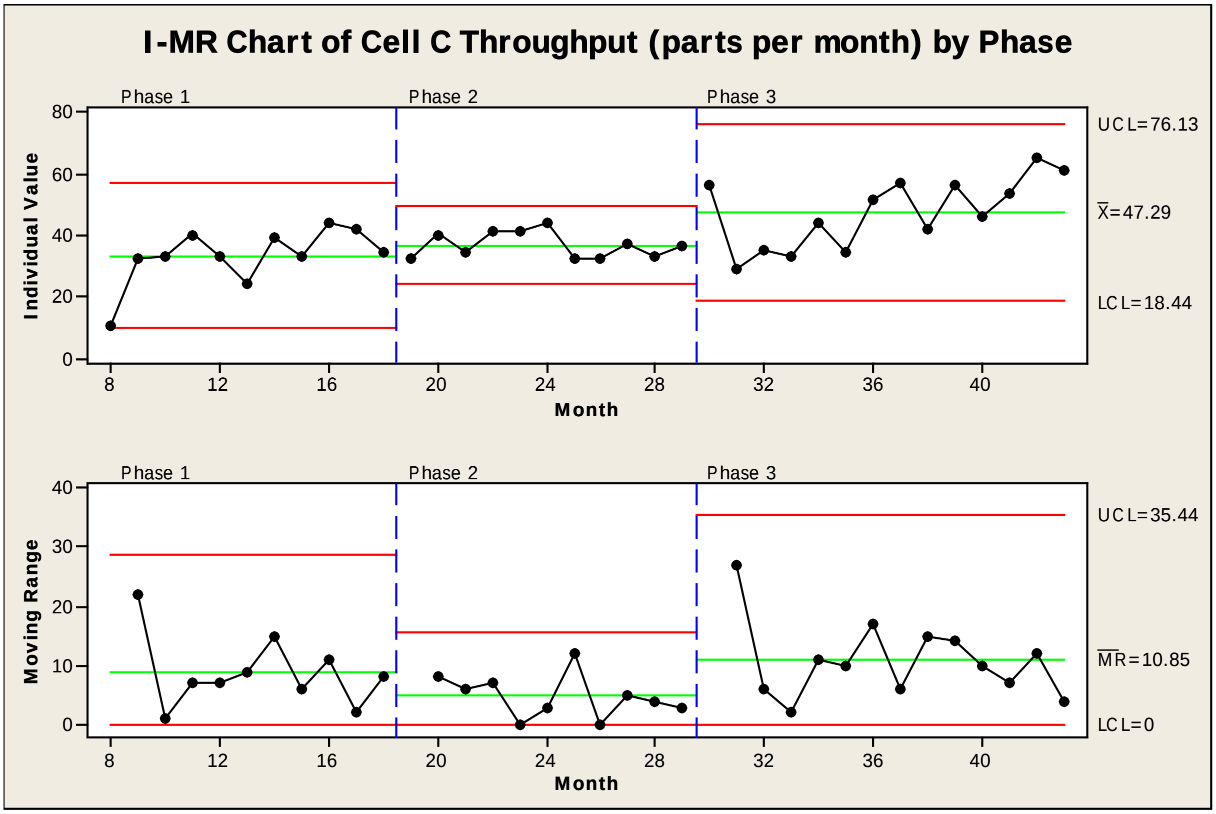

Figure 5.26 Staged Control Chart of Cell C Throughput by Phase

In order to determine which comparative methods are appropriate to use, the normality of the throughput data for each of the three cell implementation phases must first be tested. A graphical approach is employed through comparison of a histogram of the sample data to an overlay of the normal probability curve. In addition, the normality of the data is mathematically tested using the Anderson-Darling test with an alpha risk of 5%. The null hypothesis (H_o) statement is: the data can be modeled by a normal distribution. The alternate hypothesis (H_a) statement is: the data cannot be modeled by a normal distribution. Figures 5.27 through 5.29 provide the results of the graphical analysis and the Anderson-Darling normality test for phases 1 through 3 of cell C, respectively. When the p-values of 0.061, 0.172, and 0.509 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in all three cases. Therefore all three phases of throughput data for cell C can be modeled by a normal distribution.

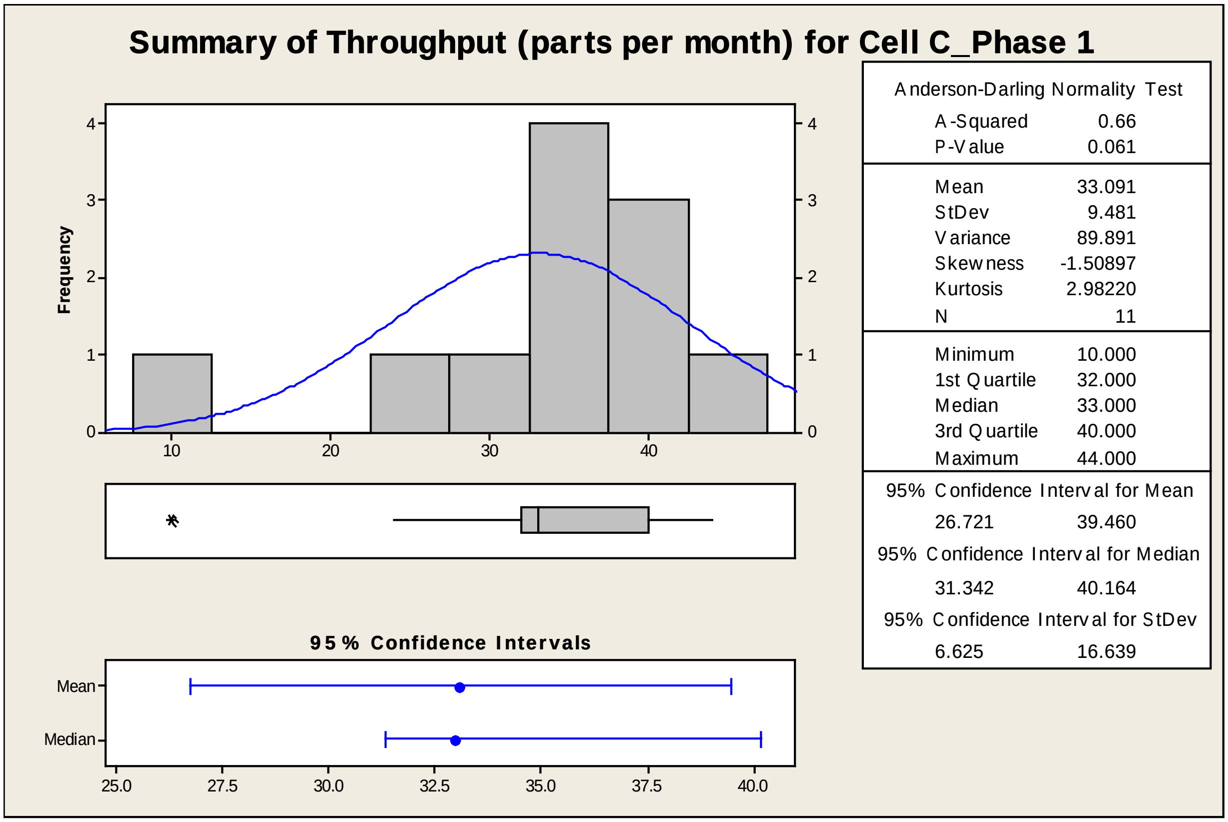

Figure 5.27 Histogram and Normality Test for Cell C Phase 1

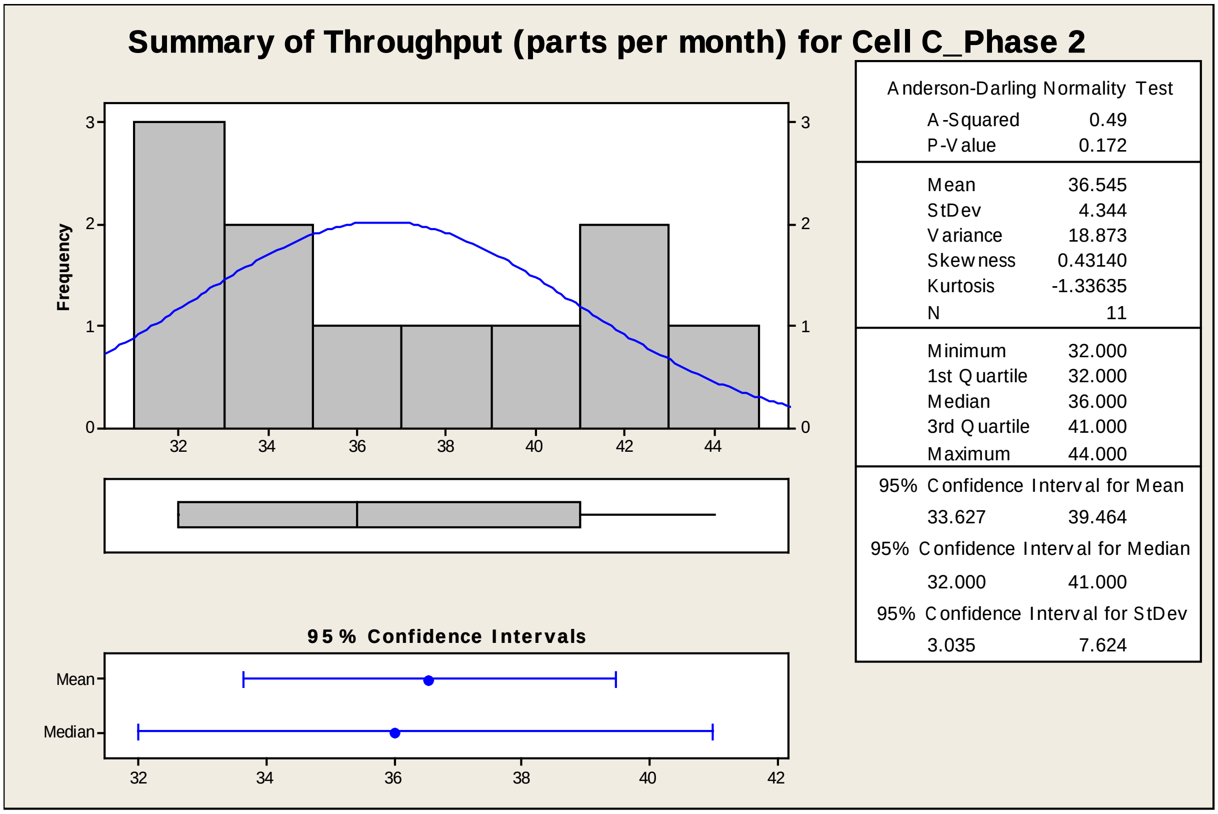

Figure 5.28 Histogram and Normality Test for Cell C Phase 2

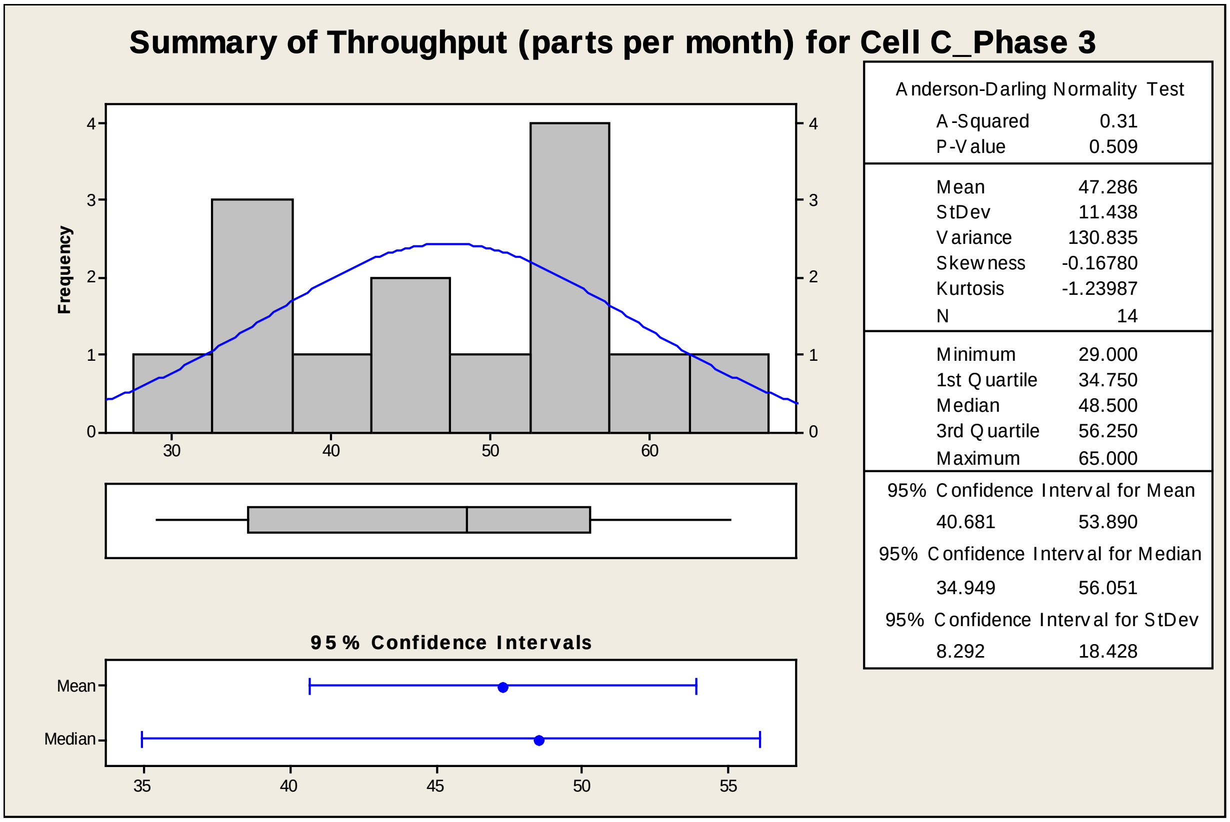

Figure 5.29 Histogram and Normality Test for Cell C Phase 3

Comparative methods were first employed for the variances of the throughput for the three cell implementation phases. The null hypothesis (H_o) statement is: there is no difference between the variances of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the variances of the throughput for the three cell phases. Figure 5.30 provides the results of the graphical analysis and Bartlett's test for phases 1 through 3 of cell C. Figure 5.31 provides the additional mathematical detail for Bartlett's test. When the p-value of 0.015 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a difference in the variances of the three cell implementation phases. Bartlett's test does not provide the detail as to between which phases the difference in variation exists. However, based on our insight in reviewing the I&MR control chart, it appears as though the variation is the highest during Phases 1 and 3 of implementation and exhibits a reduction during phases 2, which is not the targeted outcome.

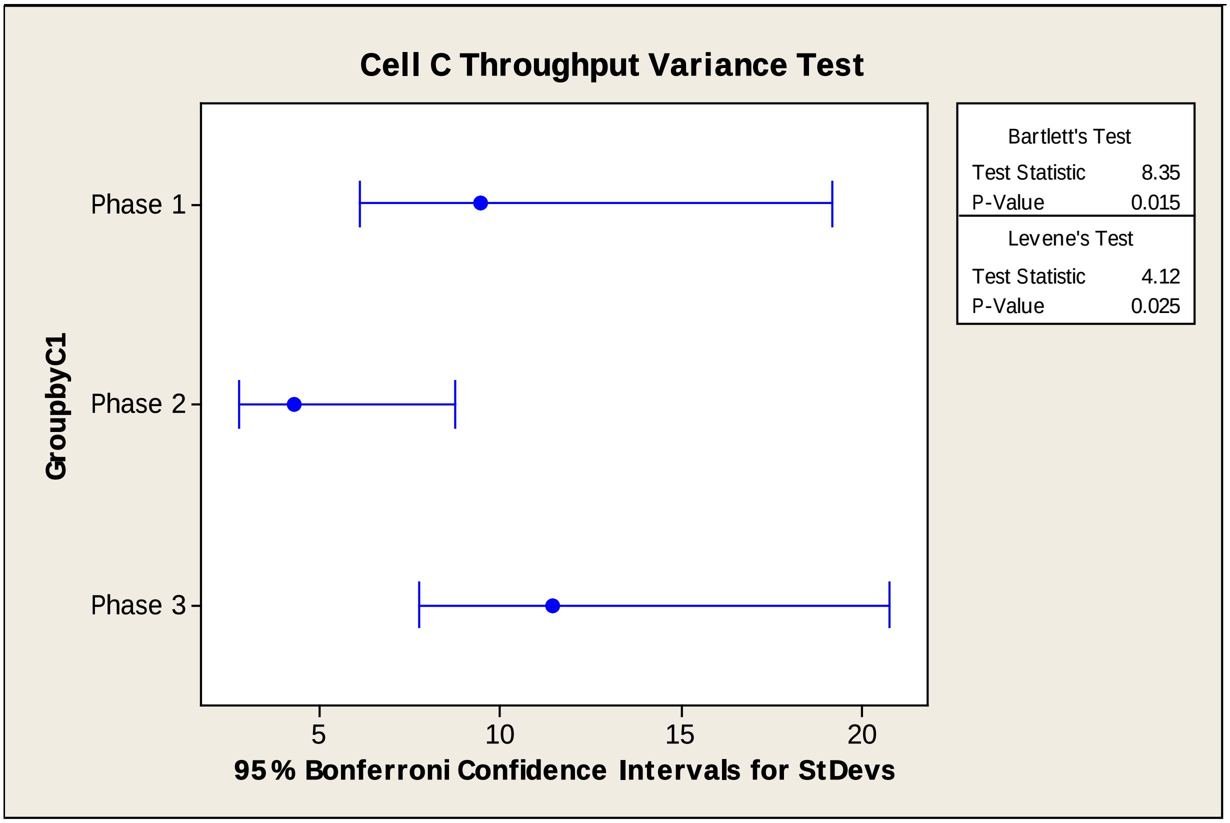

Figure 5.30 Cell C Graphical Throughput Variance Test by Phase

Test for Equal Variances: C1 versus GroupbyC1

```
95% Bonferroni confidence intervals for standard deviations

GroupbyC1   N   Lower   StDev   Upper
  Phase 1  11     6.2     9.5    19.2
  Phase 2  11     2.8     4.3     8.8
  Phase 3  14     7.8    11.4    20.7


Bartlett's Test (Normal Distribution)
Test statistic = 8.35, p-value = 0.015


Levene's Test (Any Continuous Distribution)
Test statistic = 4.12, p-value = 0.025
```

Figure 5.31 Cell C Throughput Variance Test by Phase - Detail

Next, comparative methods were conducted for the throughput medians of the three cell implementation phases for cell C. Since the underlying test assumption of equal variances was not met, ANOVA could not be employed, as with cell A. For the Kruskal-Wallis test, the null hypothesis (H_o) statement is: there is no difference between the throughput medians for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput medians for the three cell phases. Figure 5.32 provides the results of the Kruskal-Wallis test for phases 1 through 3 of cell C. When the p-value of 0.007 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a difference in the medians of the three cell implementation phases for cell C.

Kruskal-Wallis Test: C1 versus GroupbyC1

```
Kruskal-Wallis Test on C1

GroupbyC1   N  Median  Ave Rank      Z
Phase 1    11   33.00      13.0  -2.06
Phase 2    11   36.00      15.3  -1.22
Phase 3    14   48.50      25.3   3.10
Overall    36              18.5

H = 9.85  DF = 2  P = 0.007
H = 9.90  DF = 2  P = 0.007  (adjusted for ties)
```

Figure 5.32 Cell C Throughput Medians Test by Phase

When the Kruskal-Wallis test leads to significant results, then at least one of the samples is different from the other samples. However, the test does not identify between which pairs of cell implementation phases the differences occur. Therefore, for cell C, further testing is completed via the two-sample *t*-test with non-pooled standard deviations based on the Bartlett test results of unequal variances between phases.

For both forms of the *t*-test used in the analysis, the null hypothesis (H_o) statement is: there is no difference between the throughput means for the two cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput means for the two cell phases. Figures 5.33 through 5.35 provide the results of the two-sample *t*-test for the pair-wise comparisons of phases 1 through 3 of cell C, respectively. When the p-values of 0.290, 0.005, and 0.003 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in the case of phase 1 vs. phase 2. Therefore, there is no difference in the throughput means for phase 1 and phase 2. However, in the cases of phase 2 vs. phase 3 and phase 1 vs. phase 3, we reject the null hypothesis. Therefore, there is a difference in the throughput means in these two cases. The results are summarized in Table 5.3.

This is a disappointing result as the field study site had hoped that there would be a statistically significant difference in throughput means between phases 1 and 2 of cell implementation for all cells. However, based on our insight in reviewing the I&MR control chart, and the throughput means testing, we do observe a steady increase from 33.0 to 36.0 to 48.5 mean throughput parts per month for phases 1 through 3 respectively. When the demographic information is considered for cell C, it is seen that only 20% of the respondents were involved in the initial cell design and implementation, which could account for the lag in mean throughput improvement. In addition, 80% of the respondents were involved in the phase 3 improvement event, which further explains the marked throughput increase and the statistical significance between phases 2 and 3.

Two-Sample T-Test and CI: C1_Phase 1, C1_Phase 2

```
Two-sample T for C1_Phase 1 vs C1_Phase 2

             N   Mean  StDev  SE Mean
C1_Phase 1  11  33.09   9.48      2.9
C1_Phase 2  11  36.55   4.34      1.3


Difference = mu (C1_Phase 1) - mu (C1_Phase 2)
Estimate for difference:  -3.45
95% CI for difference:  (-10.20, 3.29)
T-Test of difference = 0 (vs not =): T-Value = -1.10
P-Value = 0.290  DF = 14
```

Figure 5.33 Cell C Throughput Mean Comparison for Phase 1 vs. Phase 2

```
Two-Sample T-Test and CI: C1_Phase 2, C1_Phase 3

Two-sample T for C1_Phase 2 vs C1_Phase 3

              N   Mean  StDev  SE Mean
C1_Phase 2   11  36.55   4.34      1.3
C1_Phase 3   14   47.3   11.4      3.1


Difference = mu (C1_Phase 2) - mu (C1_Phase 3)
Estimate for difference:  -10.74
95% CI for difference:  (-17.76, -3.72)
T-Test of difference = 0 (vs not =): T-Value = -3.23
P-Value = 0.005  DF = 17
```

Figure 5.34 Cell C Throughput Mean Comparison for Phase 2 vs. Phase 3

```
Two-Sample T-Test and CI: C1_Phase 1, C1_Phase 3

Two-sample T for C1_Phase 1 vs C1_Phase 3

              N   Mean  StDev  SE Mean
C1_Phase 1   11  33.09   9.48      2.9
C1_Phase 3   14   47.3   11.4      3.1


Difference = mu (C1_Phase 1) - mu (C1_Phase 3)
Estimate for difference:  -14.19
95% CI for difference:  (-22.87, -5.51)
T-Test of difference = 0 (vs not =): T-Value = -3.39
P-Value = 0.003  DF = 22
```

Figure 5.35 Cell C Throughput Mean Comparison for Phase 1 vs. Phase 3

Table 5.3 Summary of Cell C Throughput Mean Comparison by Phase

Cell	Phase 1 v. Phase 2	Phase 2 v. Phase 3	Phase 1 v. Phase 3
C	Fail to Reject H_0	Reject H_0	Reject H_0
	No difference in mean throughput	Difference in mean throughput	Difference in mean throughput

5.1.5 Cell D Graphical and Comparative Results

An initial graphical analysis is conducted to begin to develop an understanding of the throughput performance measure over time through the use of box plots and control charts. Recall that the focus group agreed to define throughput as the number of good parts produced over a period of time, which was on a monthly basis for the purposed of this research. All of the analysis presented in this subsection is based on considering the raw monthly throughput data in terms of the three discrete phases of implementation that are summarized in Table 4.6.

Similar to the analaysis for cell A, the box plot for cell D is provided in Figure 5.36. There appears to be one high outlier in phase 3. After reviewing the detailed data, no assignable cause was noted. However, the control chart will be examined to see how this outlier behave with respect to the +/- 3 sigma control limits. The box plot suggests a possible difference in means and variances for throughput across the three phases for cell D. This will be tested using the appropriate comparative methods later in the section.

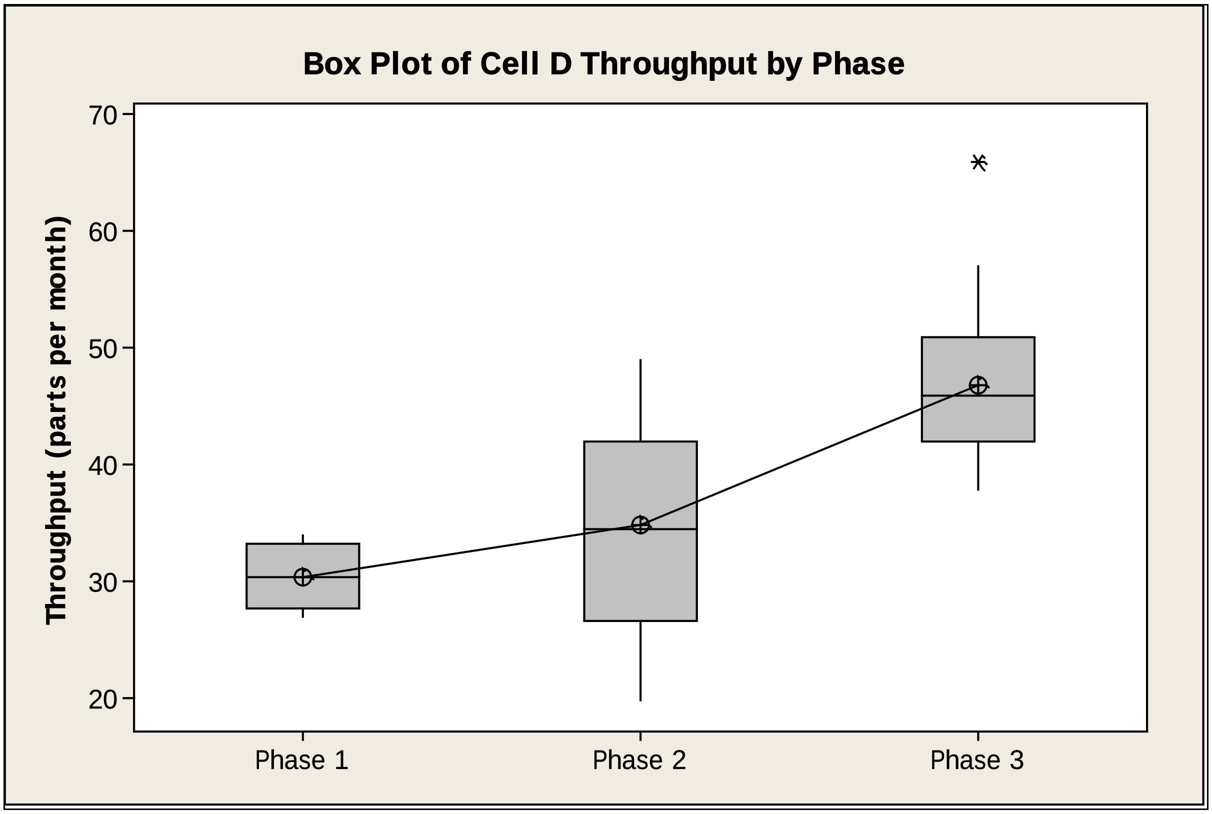

Figure 5.36 Box Plot of Cell D Throughput by Phase

For the purpose of the research, a staged Individual and Moving Range (I&MR) control chart is used with the stages defined by the three discrete cell implementation phases to gain visual insight and assist with theories regarding the throughput data by phase. The I&MR control chart for cell D is provided in Figure 5.37. Although the box plot depicts one high outlier in phase 3, no points lie outside the 3 sigma control limits, so there is no violation of Rule 1 (Shewhart 1931). The I&MR control chart is congruent with the box plots and suggests a possible difference in means and variances for throughput across the three phases for cell D. It appears as though the mean throughput increases from phase 1 to phase 2 and then from phase 2 to phase 3 which is the desired outcome. It is worth noting that the supplier of one of the detail part castings experienced quality and subsequent delivery issues to the cell due to a porosity issue, which caused the last six months of throughput to drop at the end of phase 2. From a variation standpoint, it appears as if the variation was the smallest during phase 1, with no improvement in phases 2 and 3 as had been hoped. This will be tested using the appropriate comparative methods later in the section.

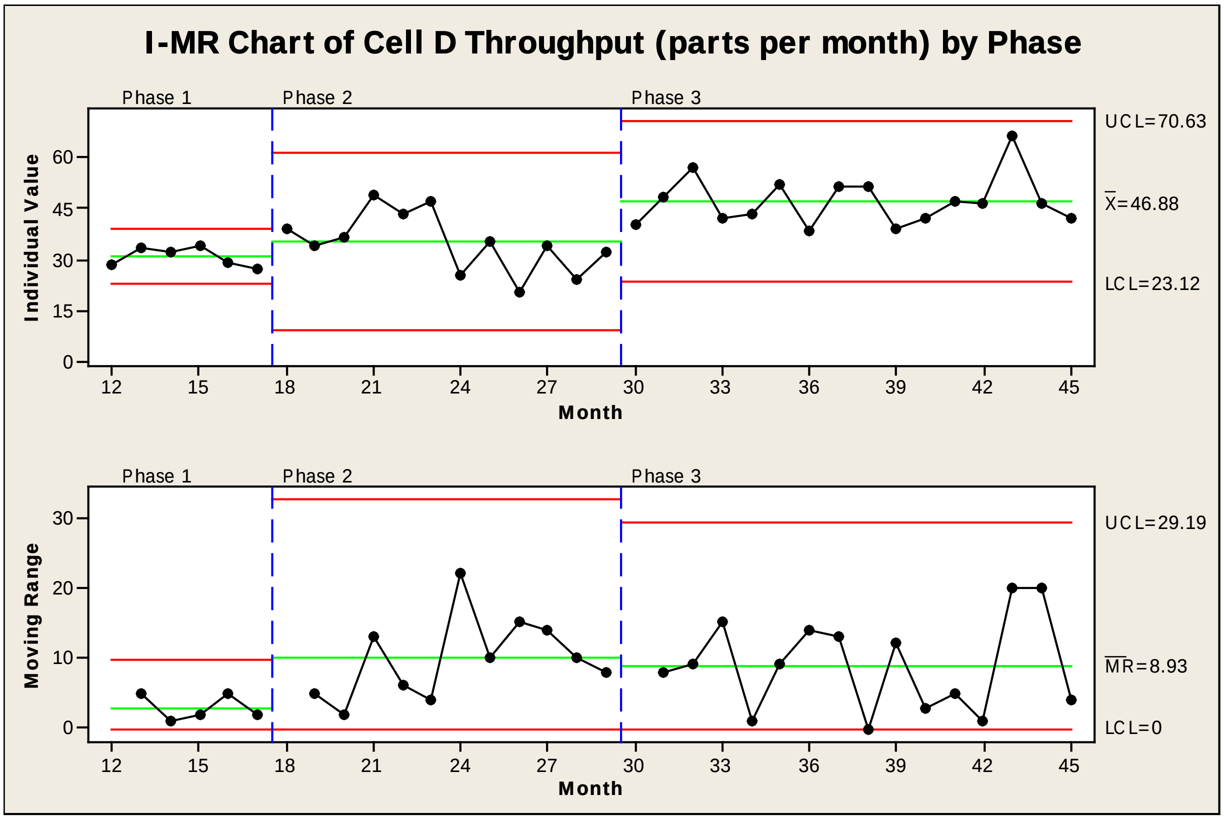

Figure 5.37 Staged Control Chart of Cell D Throughput by Phase

In order to determine which comparative methods are appropriate to use, the normality of the throughput data for each of the three cell implementation phases must first be tested. A graphical approach is employed through comparison of a histogram of the sample data to an overlay of the normal probability curve. In addition, the normality of the data is mathematically tested using the Anderson-Darling test with an alpha risk of 5%. The null hypothesis (H_o)

statement is: the data can be modeled by a normal distribution. The alternate hypothesis (H_a) statement is: the data cannot be modeled by a normal distribution. Figures 5.38 through 5.40 provide the results of the graphical analysis and the Anderson-Darling normality test for phases 1 through 3 of cell D, respectively. When the p-values of 0.486, 0.758, and 0.176 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in all three cases. Therefore all three phases of throughput data for cell D can be modeled by a normal distribution.

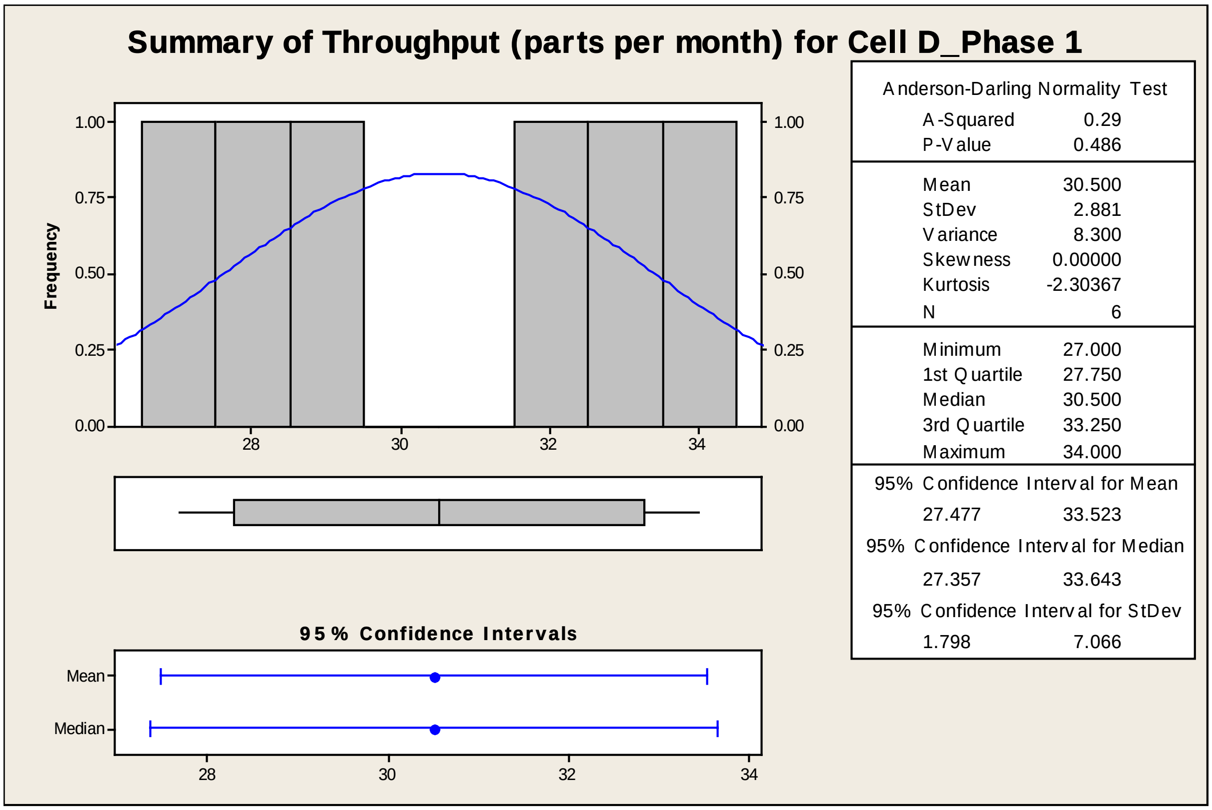

Figure 5.38 Histogram and Normality Test for Cell D Phase 1

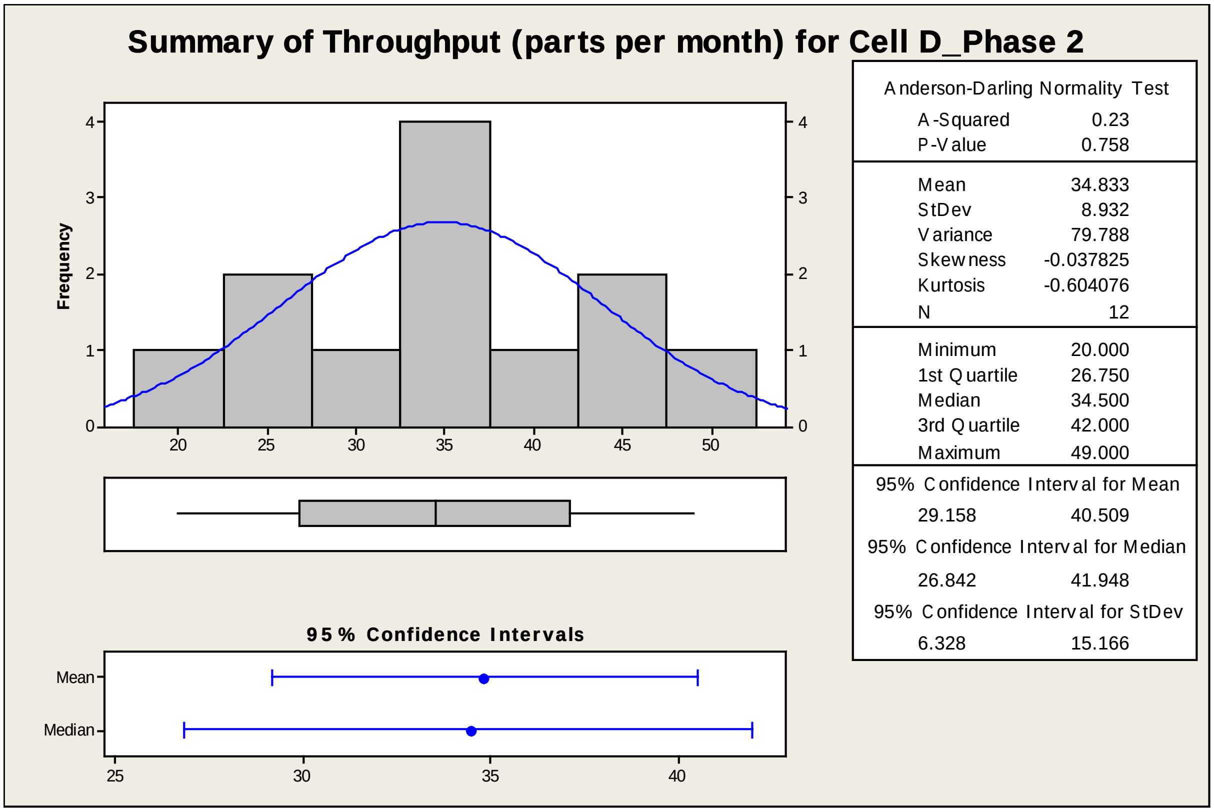

Figure 5.39 Histogram and Normality Test for Cell D Phase 2

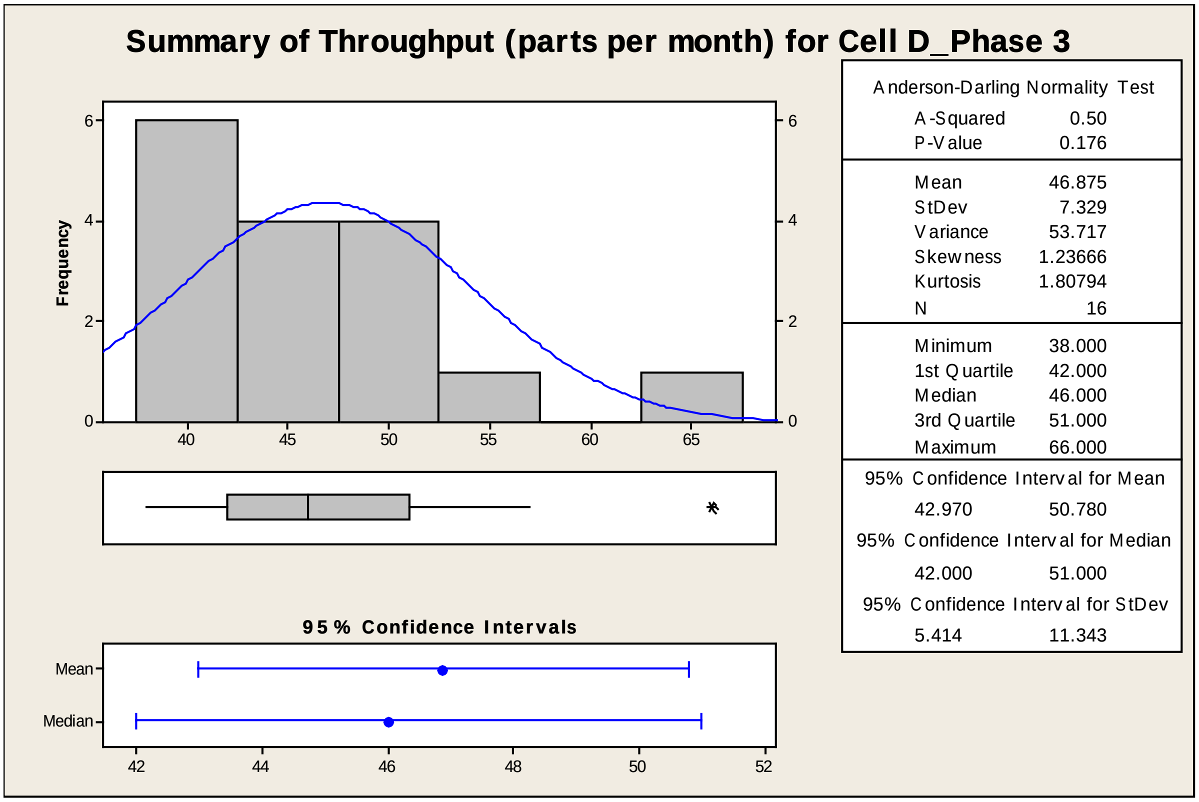

Figure 5.40 Histogram and Normality Test for Cell D Phase 3

Comparative methods were first employed for the variances of the throughput for the three cell implementation phases. Since we are testing more than two variances, the *F*-test statistic is not appropriate, and Bartlett's test is utilized. The null hypothesis (H_o) statement is: there is no difference between the variances of the throughput for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the variances of the throughput for the three cell phases. Figure 5.41 provide the results of the graphical analysis and Bartlett's test for phases 1 through 3 of cell D. Figure 5.42 provides the additional mathematical detail for Bartlett's test. When the p-value of 0.056 is compared against the alpha risk value of 0.05, we fail to reject the null hypothesis. Therefore, there is no difference in the variances of the three cell implementation phases.

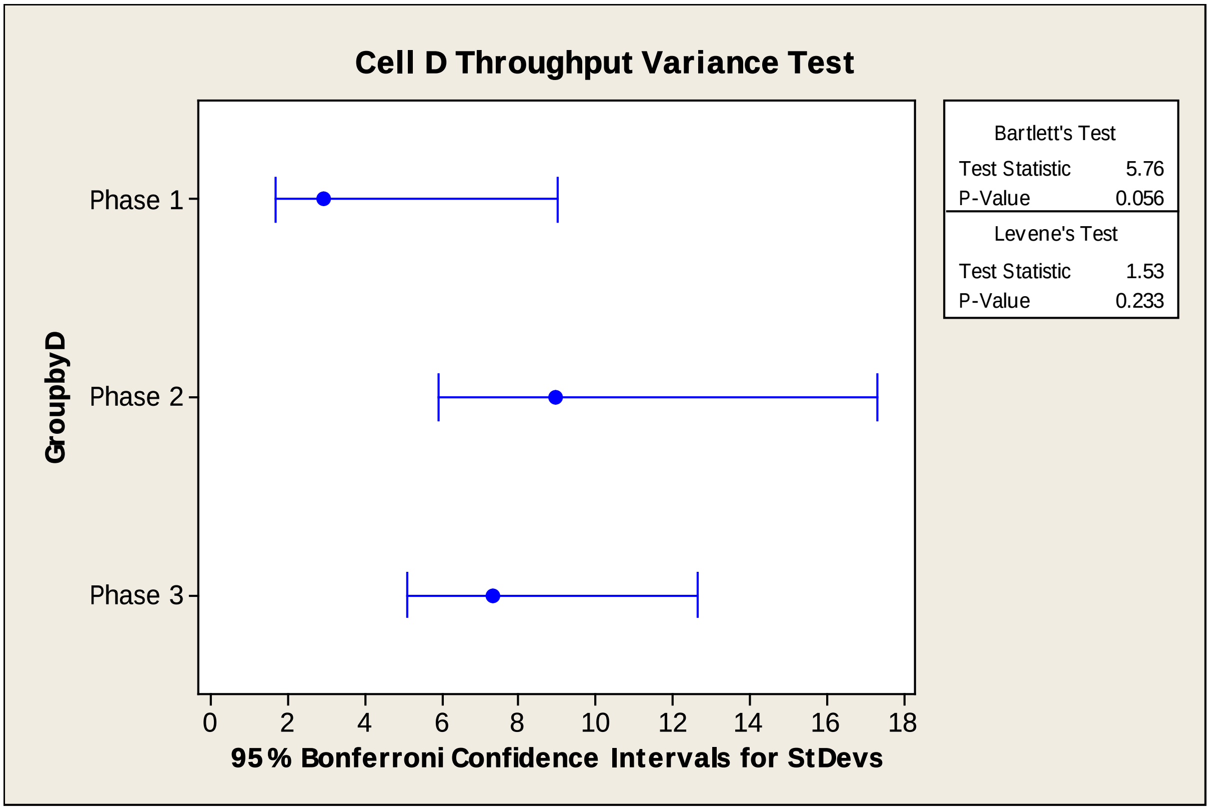

Figure 5.41 Cell D Graphical Throughput Variance Test by Phase

Test for Equal Variances: D1 versus GroupbyD

```
95% Bonferroni confidence intervals for standard deviations

GroupbyD    N    Lower   StDev   Upper
 Phase 1    6      1.6     2.9     9.0
 Phase 2   12      5.9     8.9    17.3
 Phase 3   16      5.1     7.3    12.6


Bartlett's Test (Normal Distribution)
Test statistic = 5.76, p-value = 0.056


Levene's Test (Any Continuous Distribution)
Test statistic = 1.53, p-value = 0.233
```

Figure 5.42 Cell D Throughput Variance Test by Phase - Detail

Next, comparative methods were conducted for the throughput means of the three cell implementation phases for cell D. The underlying test assumptions for ANOVA were met to include: independence, normality, and equality of variances. For ANOVA, the null hypothesis (H_o) statement is: there is no difference between the throughput means for the three cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput means for the three cell phases. Figure 5.43 provides the results of the ANOVA for phases 1 through 3 of cell D. When the p-value of 0.000 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a difference in the means of the three cell implementation phases for cell D.

One-way ANOVA: D1 versus GroupbyD

```
Source    DF      SS     MS      F      P
GroupbyD   2  1615.7  807.9  14.52  0.000
Error     31  1724.9   55.6
Total     33  3340.6

S = 7.459   R-Sq = 48.37%   R-Sq(adj) = 45.03%


                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level     N   Mean  StDev  -----+---------+---------+---------+----
Phase 1   6   30.5    2.9  (--------*-------)
Phase 2  12   34.8    8.9          (------*-----)
Phase 3  16   46.9    7.3                             (----*----)
                           -----+---------+---------+---------+----
                             28.0      35.0      42.0      49.0

Pooled StDev = 7.5
```

Figure 5.43 Cell D Throughput Means Test by Phase

Similar to cell A, for cell D, further testing is completed via the two-sample *t*-test with pooled standard deviations based on the Bartlett test results of equal variances between phases.

For both forms of the *t*-test used in the analysis, the null hypothesis (H_o) statement is: there is no difference between the throughput means for the two cell phases. The alternate hypothesis (H_a) statement is: there is a difference between the throughput means for the two cell phases. Figures 5.44 through 5.46 provide the results of the two-sample *t*-test for the pair-wise comparisons of phases 1 through 3 of cell D, respectively. When the p-values of 0.270, 0.001, and 0.000 are compared against the alpha risk value of 0.05, we fail to reject the null hypothesis in the case of phase 1 vs. phase 2. Therefore, there is no difference in the throughput means for phase 1 and phase 2. However, in the cases of phase 2 vs. phase 3 and phase 1 vs. phase 3, we reject the null hypothesis. Therefore, there is a difference in the throughput means in these two cases. The results are summarized in Table 5.4. This is a disappointing result as the field study site had hoped that there would be a statistically significant difference in throughput means between phases 1 and 2 of cell implementation for all cells. However, based on our insight in reviewing the I&MR control chart, and the throughput means testing, we do observe a steady increase from 30.5 to 34.8 to 46.9 mean throughput parts per month for phases 1 through 3 respectively. When the demographic information is considered for cell D, it is seen that only 33% of the respondents were involved in the initial cell design and implementation, which could account for the lag in mean throughput improvement. In addition, 100% of the respondents were involved in the phase 3 improvement event, which further explains the marked throughput increase and the statistical significance between phases 2 and 3.

Two-Sample T-Test and CI: D1_Phase 1, D1_Phase 2

```
Two-sample T for D1_Phase 1 vs D1_Phase 2

              N   Mean  StDev  SE Mean
D1_Phase 1    6  30.50   2.88      1.2
D1_Phase 2   12  34.83   8.93      2.6


Difference = mu (D1_Phase 1) - mu (D1_Phase 2)
Estimate for difference:  -4.33
95% CI for difference:  (-12.37, 3.70)
T-Test of difference = 0 (vs not =): T-Value = -1.14
P-Value = 0.270  DF = 16
Both use Pooled StDev = 7.5794
```

Figure 5.44 Cell D Throughput Mean Comparison for Phase 1 vs. Phase 2

Two-Sample T-Test and CI: D1_Phase 2, D1_Phase 3

```
Two-sample T for D1_Phase 2 vs D1_Phase 3

              N   Mean  StDev  SE Mean
D1_Phase 2   12  34.83   8.93      2.6
D1_Phase 3   16  46.87   7.33      1.8


Difference = mu (D1_Phase 2) - mu (D1_Phase 3)
Estimate for difference:  -12.04
95% CI for difference:  (-18.36, -5.73)
T-Test of difference = 0 (vs not =): T-Value = -3.92
P-Value = 0.001  DF = 26
Both use Pooled StDev = 8.0465
```

Figure 5.45 Cell D Throughput Mean Comparison for Phase 2 vs. Phase 3

```
Two-Sample T-Test and CI: D1_Phase 1, D1_Phase 3

Two-sample T for D1_Phase 1 vs D1_Phase 3

              N   Mean  StDev  SE Mean
D1_Phase 1    6  30.50   2.88      1.2
D1_Phase 3   16  46.87   7.33      1.8


Difference = mu (D1_Phase 1) - mu (D1_Phase 3)
Estimate for difference:  -16.37
95% CI for difference:  (-22.87, -9.88)
T-Test of difference = 0 (vs not =): T-Value = -5.26
P-Value = 0.000  DF = 20
Both use Pooled StDev = 6.5086
```

Figure 5.46 Cell D Throughput Mean Comparison for Phase 1 vs. Phase 3

Table 5.4 Summary of Cell D Throughput Mean Comparison by Phase

Cell	Phase 1 v. Phase 2	Phase 2 v. Phase 3	Phase 1 v. Phase 3
D	Fail to Reject H_0	Reject H_0	Reject H_0
	No difference in mean throughput	Difference in mean throughput	Difference in mean throughput

5.1.6 Comparison of Cell Phase Mean Throughput

Table 5.5 provides a summary of the throughput means hypothesis testing by phase for the four manufacturing cells involved in the field study. As mentioned above, an unexpected and disappointing result occurred in three of the four cells when a statistically significant difference in throughput means was not proven between implementation phases 1 and 2 for cells A, C, and D. Cell B was the only one that achieved a step change in throughput means between phases 1 and 2. It is important to note that cell B had the highest percentage (50%) of the respondents that had been involved in the phase 0 cell design activities. Cell B was higher than cells A, C, and D which had 20%, 20%, and 33% respondent involvement in phase 1, respectively. Additionally, in every case, a statistically significant difference was seen between phase 2 and 3 and then logically between phase 1 and 3 which met the corporation's objective of increased throughput. Note that the cells A, B, C, and D had 70%, 90%, 80% and 100% of the respondents that had been involved in the phase 3 improvement activities for the cells. This engagement of respondents in the phase 3 improvement activities appears to strongly contribute to the marked improvement in cell throughput performance between phases 2 and 3.

Of course there are other factors that may contribute to the lack of statistical significance in throughput mean improvement between phase 1 and phase 2. There may be an impact due to the learning curve, because in phase 1 most of the workers were in place from the old functional layout. Although they were knowledgeable of the product and machining processes, they were learning how the new process flowed and cells were to be operated. Additionally, when the cells were formally populated via the UAW agreement at the beginning of phase 2, often new employees entered the cells that neither had experience with the products and the machining processes nor how the cell was designed to operate. Regrettably, the data is not available to determine how much personnel movement occurred between any of the phases. One possible reason for significant througput mean improvement may be that the team had become more cohesive and engaged, and were ready to meet the management challenge to make more significant improvements. Additionally, many of the cells had benefitted from some capital investment, varying from mistake proofing and fixture improvements to completely new machines in some cases. These improvements were all in place and stabilized during phase 2. Finally, it should be noted that when sample sizes are small, only large effects will appear to be statistically significant (Groebner *et al.* 2011). Cell B had the largest sample sizes in comparison with the other three cells for phase 1 and phase 2. The phase 1 sample sizes for cells A, B, C, and D were 7, 14, 11 and 6, respectively and the phase 2 samples sizes were 8, 17, 11, and 12, respectively.

Table 5.5 Summary of Throughput Mean Comparison by Phase for All Cells

Cell	Phase 1 v. Phase 2	Phase 2 v. Phase 3	Phase 1 v. Phase 3
A	Fail to Reject H_0	Reject H_0	Reject H_0
	No difference in mean throughput	Difference in mean throughput	Difference in mean throughput
B	Reject H_0	Reject H_0	Reject H_0
	Difference in mean throughput	Difference in mean throughput	Difference in mean throughput
C	Fail to Reject H_0	Reject H_0	Reject H_0
	No difference in mean throughput	Difference in mean throughput	Difference in mean throughput
D	Fail to Reject H_0	Reject H_0	Reject H_0
	No difference in mean throughput	Difference in mean throughput	Difference in mean throughput

Table 5.6 provides a summary of the throughput means for phases 1 and 3 for the four manufacturing cell involved in the field study. In addition, a percentage throughput improvement is calculated in order to compare the performance of the cells on a standardized basis. It can be observed that cells A and B achieved higher overall percentage improvements in the throughput means over the course of the study than cells C and D. This information will be considered later in the document and drivers for the performance differences will be determined at that time.

Table 5.6 Percentage Throughput Improvement for all Cells

Cell	A	B	C	D
Phase 1 Mean	64.71	404.10	33.09	30.50
Phase 3 Mean	114.50	755.40	47.29	46.90
% Improvement	77%	87%	43%	54%

5.1.7 Comparison of Cell Secondary Performance Measures

In addition to the primary cell performance measure of throughput, the secondary cell performance measures are lead-time, inventory, cost of non-quality, and product cost. For these secondary performance measures, the value of the measure before phase 1 implementation and the value of the measure at the end of phase 3 are provided in Table 5.7 and the resulting percentage improvement is calculated for each measure. The results are promising as all performance measures improved or at a minimum stayed the same.

As shown in Figure 5.1 above, there is a strong negative relationship between throughput, lead-time and inventory. Although improvements ranged from 43% to 87% for throughput, the cells achieved a range from -69% to -78% for lead-time reduction and a range of -45% to -80% for inventory reduction. One might question why cell C had the lowest throughput improvement, but the related inventory improvement was not the worst of the four cells. When investigated, it was discovered that the cell D finished products cost three times that of cell C products and were the most expensive of all four cell products. Therefore, although cell D achieved better throughput improvement and very similar lead-time improvement to cell C, the inventory improvement task was more challenging due to the logistics complexity and supplier management for cell D. Cell C only interfaced with two suppliers while cell D interfaced with five suppliers.

Although cost of non-quality and product cost were not the focus of the lean initiative at the field study site, in most cases improvements did result. From a quality perspective, three of the four cells made cost of non-quality reductions ranging from -25% to -50%, with cells A and D achieving the best results. This is encouraging when we consider that cell A products cost two-and-a-half times that of cell B and C products and cell D products cost three times that of cell B and C products. From a product cost perspective, three of the four cells made improvements in product cost with reductions ranging from -10% to -20%. Product cost was the most challenging performance measure to improve due to the high fixed overhead costs related to the corporation infrastructure and the high material costs. Ideally, it would have been preferrable to understand the underlying components of the product cost, including details such as direct labor, material, and overhead costs. However, due to the sensitive nature of this information, the company would not even provide the total cost for each product, but only the cost ratio as shown in Table 5.7. Therefore, the impact of the implementation of the lean manufacturing cells on the product cost is deemed to be conservative, as an increased benefit would most likely be observed if only the change in direct labor was considered, independent of material and overhead costs, as well as escalation due to the time horizon of the study.

Table 5.7 Secondary Performance Measure Percentage Improvement for all Cells

	Cell	A		B		C		D	
		Before	After	Before	After	Before	After	Before	After
Leadtime (days)	Actual	126	31	49	11	77	23	70	22
	Percentage Improvement	-75%		-78%		-70%		-69%	
Inventory $M	Actual	2.2	0.65	5	0.75	2.5	1	5.1	2.8
	Percentage Improvement	-70%		-85%		-60%		-45%	
Non-Quality Ratio	Actual	1	0.5	1	1	1	0.75	1	0.6
	Percentage Improvement	-50%		0%		-25%		-40%	
Cost Ratio	Actual	1	0.9	1	1	1	0.8	1	0.8
	Percentage Improvement	-10%		0%		-20%		-20%	

5.2 QUESTIONNAIRE RESULTS

The assessment questionnaire was developed as the primary method for gathering employee perceptions from the workers, supervisors, technical staff and managers that manage and operate the lean manufacturing cells. The following section provides the results from the analysis conducted on the data obtained from the assessment questionnaire at the field study site. It is structured into seven sub-sections. The first two sub-sections examine Cell Specific System Variables (Section 2) in terms of implementation levels achieved and then in terms of perceived importance for the four manufacturing cells. The next two sub-sections examine Lean Practices (Section 3) in terms of implementation levels achieved and then in terms of perceived importance for the four manufacturing cells. The fifth sub-section considers overall questionnaire implementation levels achieved across both Cell Specific System Variables (Section 2) and Lean Practices (Section 3) for the four manufacturing cells. Next, the sixth sub-section explores overall questionnaire perceived importance across both Cell Specific System Variables (Section 2) and Lean Practices (Section 3) for the four manufacturing cells. The final sub-section considers a view of implementation level vs. importance for each of the twelve elements contained in Cell Specific System Variables (Section 2) and Lean Practices (Section 3) for the four manufacturing cells.

5.2.1 Questionnaire: Cell Specific System Variables (Section 2) Implementation Level

The implementation level scale is a four-point modified version from the traditional five-point Likert type scale for both Cell Specific System Variables (Section 2) and Lean Practices (Section 3) of the questionnaire (Allen and Seaman 2007, Likert 1932). Pearson's chi-square (χ^2) is the most widely know of several chi-square tests which measure the amount of deviation between expected values and observed values for each cell of a table to determine if an association exists for attribute data (Pearson 1900). This method of contingency analysis was used to test for significance between the four manufacturing cells and the Cell Specific System Variables (Section 2) implementation level and counts were tallied in order to conduct this analysis.

Data representing implementation level scores for Cell Specific System Variables (Section 2) were analyzed to determine if a relationship exists between cells (A, B, C or D) and implementation levels (0, 1, 2, or 3). The null hypothesis (H_o) statement is: no significant association exists between cells and implementation level. The alternate hypothesis (H_a) statement is: a significant association exists between cells and implementation level. Figure 5.47 provides the contingency table and Chi-Square analysis for Cell Specific System Variables (Section 2) implementation level across the four manufacturing cells. When the p-value of 0.000 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a relationship between cells and implementation level for Cell Specific System Variables (Section 2).

For reference, the critical value for Pearson's Chi-Square with 9 degrees of freedom is 16.919 (Groebner *et al.* 2011) and is not provided in the Minitab analysis in Figure 5.47. The two highest contributors to the total Chi Square value of 70.901 are circled to determine the practical significance of this test. It can be observed that cell A has unexpectedly high 3s with

110 observed vs. the 76.4 expected. All other cells have lower than expected 3s. This suggests that cell A has higher implementation scores than the other three cells for Cell Specific System Variables (Section 2). It can also be observed that cell D has unexpectedly low 0s with 27 observed vs. the 54.7 expected. All other cells have higher than expected 0s. This suggests that cell D has higher implementation scores than the other three cells for Cell Specific System Variables (Section 2). One method to confirm these theories is by summing up the total implementation score for all items in Cell Specific System Variables (Section 2) of the questionnaire and averaging across the respondents for each cell. When the total Cell Specific System Variables (Section 2) implementation level score is examined for the four manufacturing cells, cell A scores 69 and cell D scores 70 vs. both cell B and C scoring 62. This validates the idea that cells A and D achieved higher implementation levels on the Cell Specific System Variables (Section 2) than cells B and C.

```
Contingency table of Section 2 Implementation data

                Implementation Level

               0      1      2       3     All

Cell A        87    102    131     110     430
            62.6  131.8  159.2    76.4   430.0
           9.521  6.737  4.989  14.744       *

Cell B        61    136    149      62     408
            59.4  125.1  151.0    72.5   408.0
           0.044  0.958  0.027   1.526       *

Cell C        33     81     75      26     215
            31.3   65.9   79.6    38.2   215.0
           0.093  3.460  0.265   3.905       *

Cell D        27    119    174      56     376
            54.7  115.2  139.2    66.8   376.0
          14.049  0.122  8.705   1.756       *

All          208    438    529     254    1429
           208.0  438.0  529.0   254.0  1429.0
               *      *      *       *       *


Cell Contents:      Count
                    Expected count
                    Contribution to Chi-square


Pearson Chi-Square = 70.901, DF = 9, P-Value = 0.000
Likelihood Ratio Chi-Square = 72.004, DF = 9, P-Value = 0.000
```

Figure 5.47 Chi Square Analysis for Section 2 Implementation Level for All Cells

To develop a further understanding of the cell implementation levels, another view of the data is considered. For the Cell Specific System Variables (Section 2) an average implementation level was calculated for each of the six elements in reference to the four manufacturing cells. This information is depicted on the radar chart provided in Figure 5.48. It is interesting that the plots for each of the four cells take quite different shapes, indicating the cells focused on and achieved implementation success in different elements of Cell Specific System Variables (Section 2).

Cell C exhibited a markedly lower score than the other cells on Machines, Equipment, and Outside Services (Element 1), which was validated through the data collection and attributed to the age and condition of the cell input lathes. Cells A and B scored higher than cells C and D on Materials (Element 2), indicating that there may be supplier issues for the latter two cells. Additionally, it is worth noting that cell D products were comprised of five major details that were obtained from three different suppliers which greatly complicated the cell logistics. Cell C products were comprised of two major details, while cell A and B products were manufacturing from one piece of raw material. Cell A scored the highest and cell D scored the lowest on Environment (Element 3). All four cells scored similarly on Methods (Element 4). This is understandable as the manufacturing process, or method, underpins the technical success of any manufacturing cell. Cells A and D scored higher than cells B and C on People (Element 5). Finally, cells C and D achieved the highest averages on Cell Measurement and Improvement (Element 6).

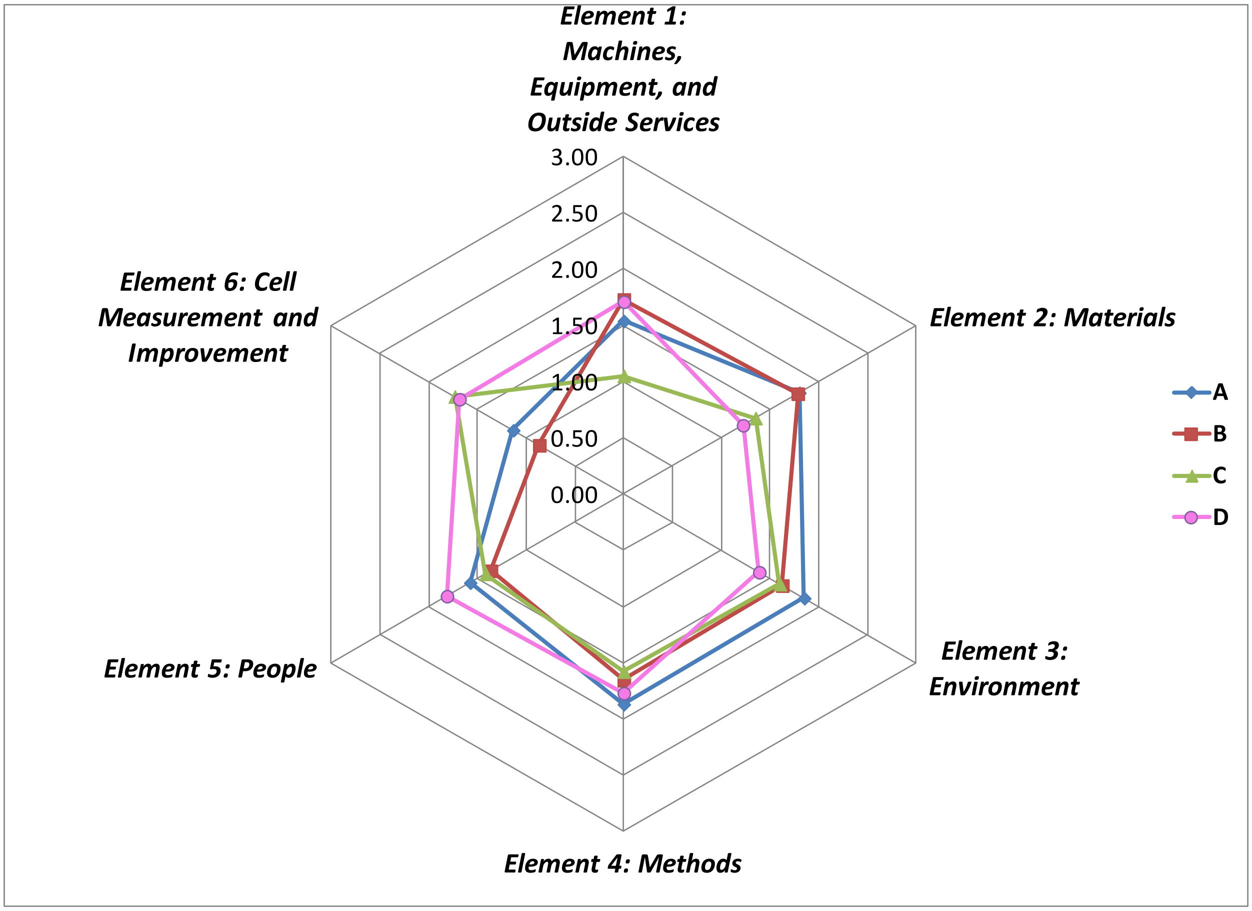

Figure 5.48 Radar Chart for Section 2 Implementation Level for All Cells

Data representing implementation level scores for Cell Specific System Variables (Section 2) were analyzed to determine if a relationship exists between employee type (H = hourly, S = salaried) and implementation levels (0, 1, 2, or 3). The null hypothesis (H_o) statement is: no significant association exists between employee type and implementation level. The alternate hypothesis (H_a) statement is: a significant association exists between employee type and implementation level. Figure 5.49 provides the contingency table and Chi-Square analysis for Cell Specific System Variables (Section 2) implementation level across employee type. When the p-value of 0.001 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a relationship between employee type and implementation level for Cell Specific System Variables (Section 2).

For reference, the critical value for Pearson's Chi-Square with 3 degrees of freedom is 7.814 (Groebner *et al.* 2011) and is not provided in the Minitab analysis in Figure 5.49. The two highest contributors to the total Chi Square value of 17.590 are circled to determine the practical significance of this test. It can be observed that hourly employees have unexpectedly high 0s with 165 observed vs. the 139.2 expected. This suggests that hourly employees, or workers, perceive the cell implementation level achievement to be lower than the salaried employees for Cell Specific System Variables (Section 2).

```
Contingency table of Section 2 Implementation data

                Implementation Level

            0       1       2       3     All

H         165     283     348     160     956
        139.2   293.0   353.9   169.9   956.0
       4.8014  0.3428  0.0984  0.5798       *

S          43     155     181      94     473
         68.8   145.0   175.1    84.1   473.0
       9.7044  0.6928  0.1988  1.1718       *

All       208     438     529     254    1429
        208.0   438.0   529.0   254.0  1429.0
            *       *       *       *       *

Cell Contents:      Count
                    Expected count
                    Contribution to Chi-square


Pearson Chi-Square = 17.590, DF = 3, P-Value = 0.001
Likelihood Ratio Chi-Square = 18.784, DF = 3, P-Value = 0.000
```

Figure 5.49 Chi Square Analysis for Section 2 Implementation Level for Employee Type

It can also be observed that salaried employees have unexpectedly low 0s with 43 observed vs. the 68.8 expected. This suggests that salaried employees perceive the cell implementation level achievement to be higher than the hourly employees for Cell Specific System Variables (Section 2). Table 5.8 provides the total Cell Specific System Variables (Section 2) implementation level scores by employee type for the four manufacturing cells.

One method to confirm these theories is by summing up the total score for all items in Cell Specific System Variables (Section 2) of the questionnaire and averaging across the two types of employee respondents. When the total Cell Specific System Variables (Section 2) implementation level perception scores are examined, hourly employees scored lower (66) in comparison with their salaried counterparts (73). This further validates the idea that hourly employees scored implementation levels lower than salaried employees on the Cell Specific System Variables (Section 2).

Cell C was the only cell where the salaried employees scored lower than the hourly employees. As can be seen from Figure 5.48, cell C had the lowest implementation score on Machines (Element 1) which pulled down the overall Section 2 total score. This was due to the fact that the primary input lathes were antiquated and suffered numerous breakdowns. The management team was frustrated by this situation and put forward a capital scheme to replace the equipment, but the questionnaire implementation scores were affected nonetheless.

Table 5.8 Section 2 Implementation Level Scores by Employee Type

Cell	**A**	**B**	**C**	**D**	**Average**
Hourly	67	64	64	69	66
Salary	80	78	61	74	73

5.2.2 Questionnaire: Cell Specific System Variables (Section 2) Importance Ratings

The importance rating scale is a traditional five-point Likert type scale for both Cell Specific System Variables (Section 2) and Lean Practices (Section 3) of the questionnaire (Allen and Seaman 2007, Likert 1932). Pearson's chi-square (χ^2) method of contingency analysis was used to test for significance between the four manufacturing cells and the Cell Specific System Variables (Section 2) perceived importance and counts were tallied in order to conduct this analysis.

Data representing importance ratings for Cell Specific System Variables (Section 2) were analyzed to determine if a relationship exists between cells (A, B, C or D) and importance ratings (1, 2, 3, 4, or 5). The null hypothesis (H_o) statement is: no significant association exists between cells and importance rating. The alternate hypothesis (H_a) statement is: a significant association exists between cells and importance rating. When then the expected values for calculated cells in the contingency table drop below five, the calculated chi-square tends to become inflated and could potentially inflate the true probability of a Type I error beyond the stated significance level (Groebner *et al.* 2011). Therefore, since there were no 1s as responses, it was acceptable practice to combine the 1s and 2s categories into a single column labeled 2 to enable the analysis. Figure 5.50 provides the contingency table and Chi-Square analysis for Cell Specific System Variables (Section 2) importance ratings across the four manufacturing cells. When the p-value of 0.000 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a relationship between cells and importance rating for Cell Specific System Variables (Section 2).

For reference, the critical value for Pearson's Chi-Square with 9 degrees of freedom is 16.919 (Groebner *et al.* 2011) and is not provided in the Minitab analysis in Figure 5.50. The three highest contributors to the total Chi Square value of 70.134 are circled to determine the practical significance of this test. It can be observed that cell B has unexpectedly low 5s with 122 observed vs. the 168.6 expected and unexpectedly high 4s with 192 observed vs. the 152.8 expected. This suggests that cell B has lower importance ratings than other cells for Cell Specific System Variables (Section 2). It can also be observed that cell C has unexpectedly high 5s with 117 observed vs. the 87.1 expected. This suggests that cell C has higher importance ratings than other cells for Cell Specific System Variables (Section 2).

One method to confirm these theories is by summing up the total importance rating score for all items in Cell Specific System Variables (Section 2) of the questionnaire and averaging across the respondents for each cell. When the total Cell Specific System Variables (Section 2) importance rating is examined for cells A, B, C, and D, they score 176, 166, 186, and 182, respectively. Therefore, cell B scored the lowest of all the cells and cell C scored the highest of the cells on importance ratings for Cell Specific System Variables (Section 2). In general, cells C and D perceived higher importance ratings on Cell Specific System Variables (Section 2) than cells A and B.

Contingency table of Section 2 Importance data

	IMPORTANCE				
	2	3	4	5	All
Cell A	12	106	137	173	428
	10.4	85.4	157.9	174.3	428.0
	0.243	4.990	2.775	0.010	*
Cell B	19	81	192	122	414
	10.1	82.6	152.8	168.6	414.0
	7.920	0.030	10.075	12.876	*
Cell C	2	40	55	117	214
	5.2	42.7	79.0	87.1	214.0
	1.973	0.168	7.274	10.227	*
Cell D	2	60	147	174	383
	9.3	76.4	141.3	156.0	383.0
	5.745	3.515	0.228	2.085	*
All	35	287	531	586	1439
	35.0	287.0	531.0	586.0	1439.0
	*	*	*	*	*

Cell Contents: Count
Expected count
Contribution to Chi-square

Pearson Chi-Square = 70.134, DF = 9, P-Value = 0.000
Likelihood Ratio Chi-Square = 72.279, DF = 9, P-Value = 0.000

Figure 5.50 Chi Square Analysis for Section 2 Importance Rating for All Cells

To develop a further understanding of the cell importance ratings, another view of the data is considered. For the Cell Specific System Variables (Section 2) an average importance rating is calculated for each of the six elements in reference to the four manufacturing cells. This information is depicted on the radar chart provided in Figure 5.51. The plots for each of the four cells take similar shapes and are clustered between 3.5 and 4.5 for all elements. This indicates that there was not a wide spread in how the cell respondents viewed importance for Cell Specific

System Variables (Section 2). In addition, Cell B exhibited markedly lower importance scores on all elements in Cell Specific System Variables (Section 2). It is also worth noting that all four cells rated Machines (Element 1), Materials (Element 2), and Methods (Element 4) in their top three of the six elements from an importance standpoint, which is quite intuitive as these three elements form the technical foundation for a manufacturing cell's success.

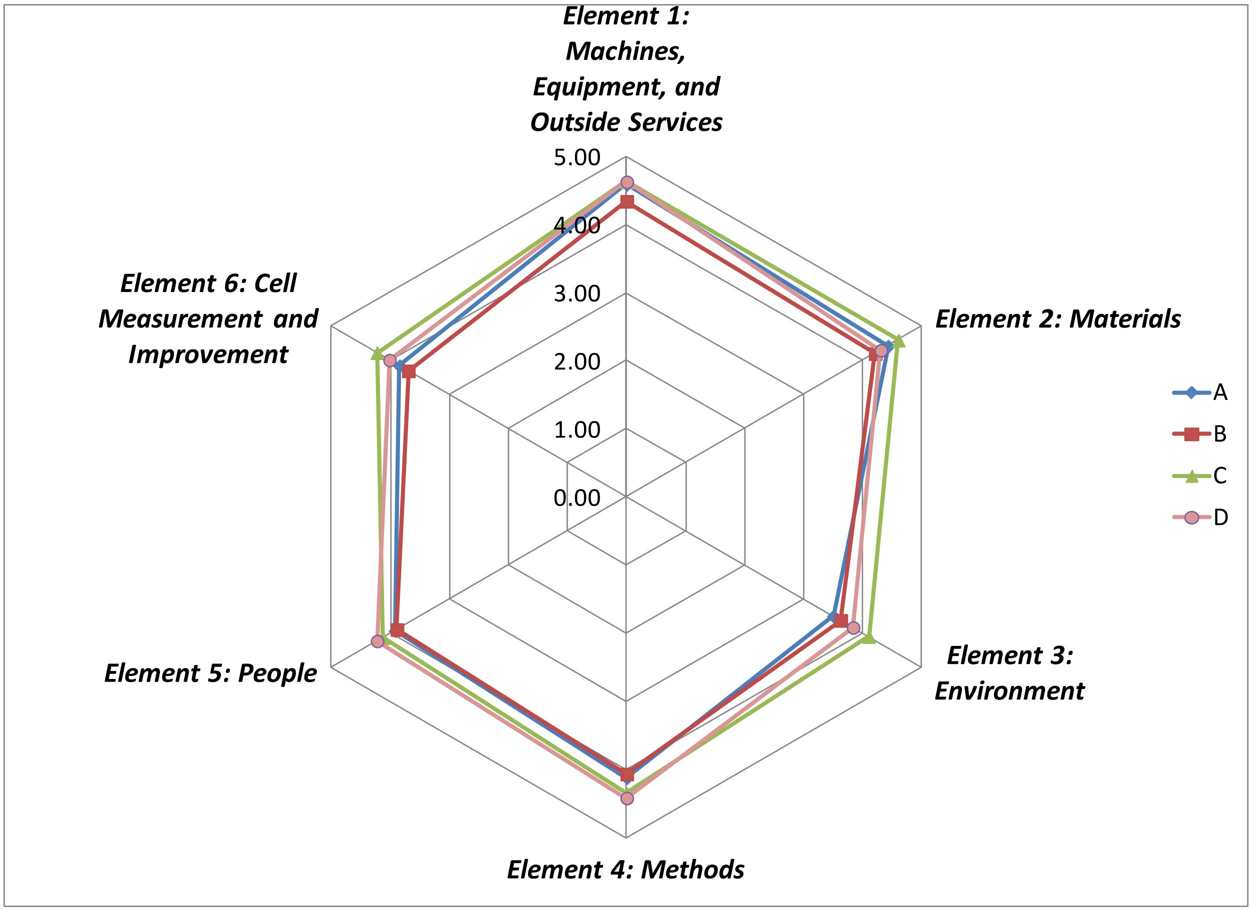

Figure 5.51 Radar Chart for Section 2 Importance Rating for All Cells

Data representing importance ratings for Section Cell Specific System Variables (Section 2) were analyzed to determine if a relationship exists between employee type (H = hourly, S = salaried) and importance ratings (1, 2, 3, 4, or 5). The null hypothesis (H_o) statement is: no significant association exists between employee type and importance rating. The alternate hypothesis (H_a) statement is: a significant association exists between employee type and importance rating. When then the expected values for calculated cells in the contingency table drop below five, the calculated chi-square tends to become inflated and could potentially inflate the true probability of a Type I error beyond the stated significance level (Groebner *et al.* 2011). Therefore, it was acceptable practice to combine the 1s and 2s categories into a single column labeled 1+2 to enable the analysis. Figure 5.52 provides the contingency table and Chi-Square analysis for Cell Specific System Variables (Section 2) importance score across employee type. When the p-value of 0.216 is compared against the alpha risk value of 0.05, we fail to reject the null hypothesis. Therefore, there is no relationship between employee type and importance score for Section 2. From a practical standpoint, hourly and salaried employees viewed importance level in a similar manner for Section Cell Specific System Variables (Section 2).

Contingency table of Section 2 Importance data

	IMPORTANCE				
	1+2	3	4	5	All
H	28	194	365	381	968
	23.5	193.1	357.2	394.2	968.0
	0.8433	0.0046	0.1704	0.4417	*
S	7	93	166	205	471
	11.5	93.9	173.8	191.8	471.0
	1.7332	0.0094	0.3502	0.9079	*
All	35	287	531	586	1439
	35.0	287.0	531.0	586.0	1439.0
	*	*	*	*	*

Cell Contents: Count
Expected count
Contribution to Chi-square

Pearson Chi-Square = 4.461, DF = 3, P-Value = 0.216
Likelihood Ratio Chi-Square = 4.683, DF = 3, P-Value = 0.197

Figure 5.52 Chi Square Analysis for Section 2 Importance Rating for Employee Type

5.2.3 Questionnaire: Lean Practices (Section 3) Implementation Level

The implementation level scale is a four-point modified version from the traditional five-point Likert type scale for both Cell Specific System Variables (Section 2) and Lean Practices (Section 3) of the questionnaire (Allen and Seaman 2007, Likert 1932). Pearson's chi-square (χ^2) method of contingency analysis was used to test for significance between the four manufacturing cells and the Lean Practices (Section 3) implementation level and counts were tallied in order to conduct this analysis.

Data representing implementation level scores for Lean Practices (Section 3) were analyzed to determine if a relationship exists between cells (A, B, C or D) and implementation levels (0, 1, 2, or 3). The null hypothesis (H_o) statement is: no significant association exists between cells and implementation level. The alternate hypothesis (H_a) statement is: a significant association exists between cells and implementation level. Figure 5.53 provides the contingency table and Chi-Square analysis for Lean Practices (Section 3) implementation level across the four manufacturing cells. When the p-value of 0.000 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a relationship between cells and implementation level for Lean Practices (Section 3).

For reference, the critical value for Pearson's Chi-Square with 9 degrees of freedom is 16.919 (Groebner *et al.* 2011) and is not provided in the Minitab analysis in Figure 5.53. The three highest contributors to the total Chi Square value of 162.309 are circled to determine the practical significance of this test. It can be observed that cell D has unexpectedly high 0s with 67 observed vs. the 29.56 expected. All other cells have lower than expected 0s. This suggests that cell D has achieved lower implementation scores than the other three cells for Lean Practices (Section 3). It can also be observed that cell A has unexpectedly high 3s with 29 observed vs. the 10.09 expected. This suggests that cell A has achieved higher implementation scores than the other three cells for Lean Practices (Section 3). In addition, cell B has unexpectedly high 4s with 102 observed vs. the 67.87 expected. This suggests that cell B did not achieve the highest implementation scores in Lean Practices (Section 3).

One method to confirm these theories is by summing up the total implementation level score for all items in Lean Practices (Section 3) of the questionnaire and averaging across the respondents for each cell. When the total Lean Practices (Section 3) implementation level score is examined for cells A, B, C, and D, they score 123, 111, 97 and 82, respectively. This validates that cell A scored the highest, cell D scored the lowest, and cell B did not score the highest for implementation levels on the Lean Practices (Section 3). In general, cells A and B achieved higher implementation levels on the Lean Practices (Section 3) than cells C and D.

Contingency table of Section 3 Implementation data

	Implementation Level				
	0	1	2	3	All
Cell A	14	66	47	29	156
	19.45	81.78	44.67	10.09	156.00
	1.530	3.046	0.121	35.456	*
Cell B	10	123	102	2	237
	29.56	124.25	67.87	15.33	237.00
	12.940	0.013	17.162	11.587	*
Cell C	17	152	61	6	236
	29.43	123.72	67.58	15.26	236.00
	5.251	6.463	0.641	5.620	*
Cell D	67	113	38	19	237
	29.56	124.25	67.87	15.33	237.00
	47.435	1.018	13.146	0.881	*
All	108	454	248	56	866
	108.00	454.00	248.00	56.00	866.00
	*	*	*	*	*

Cell Contents: Count
Expected count
Contribution to Chi-square

Pearson Chi-Square = 162.309, DF = 9, P-Value = 0.000
Likelihood Ratio Chi-Square = 151.813, DF = 9, P-Value = 0.000

Figure 5.53 Chi Square Analysis for Section 3 Implementation Level for All Cells

To develop a further understanding of the cell implementation levels, another view of the data is considered. For Lean Practices (Section 3) an average implementation level was calculated for each of the six elements in reference to the four manufacturing cells. This information is depicted on the radar chart provided in Figure 5.54. It is interesting that the plots for each of the four cells take quite different shapes indicating the cells focused on and achieved implementation success in different elements of Lean Practices (Section 3). Cell A exhibited a markedly higher score than the other cells on People (Element 2), Information (Element 3), Product (Element 5) and Process / Flow (Element 6). In contrast, cell D achieved much lower scores than the other cells on People (Element 2), Information (Element 3), Supplier (Element 4) and Product (Element 5). One possible reason is that since cell D was the most complex of the cells and scored reasonably well on the Cell Specific System Variables (Section 2), the employees may not have been able to focus on the Lean Practices (Section 3) part of the implementation. This is further complicated by the fact that cell D was the last to be implemented of the four manufacturing cells, giving the cell team less time than their counterparts to achieve successful implementation on Lean Practices (Section 3). It is interesting to note that cell D did score very high on the Management / Trust (Element 1).

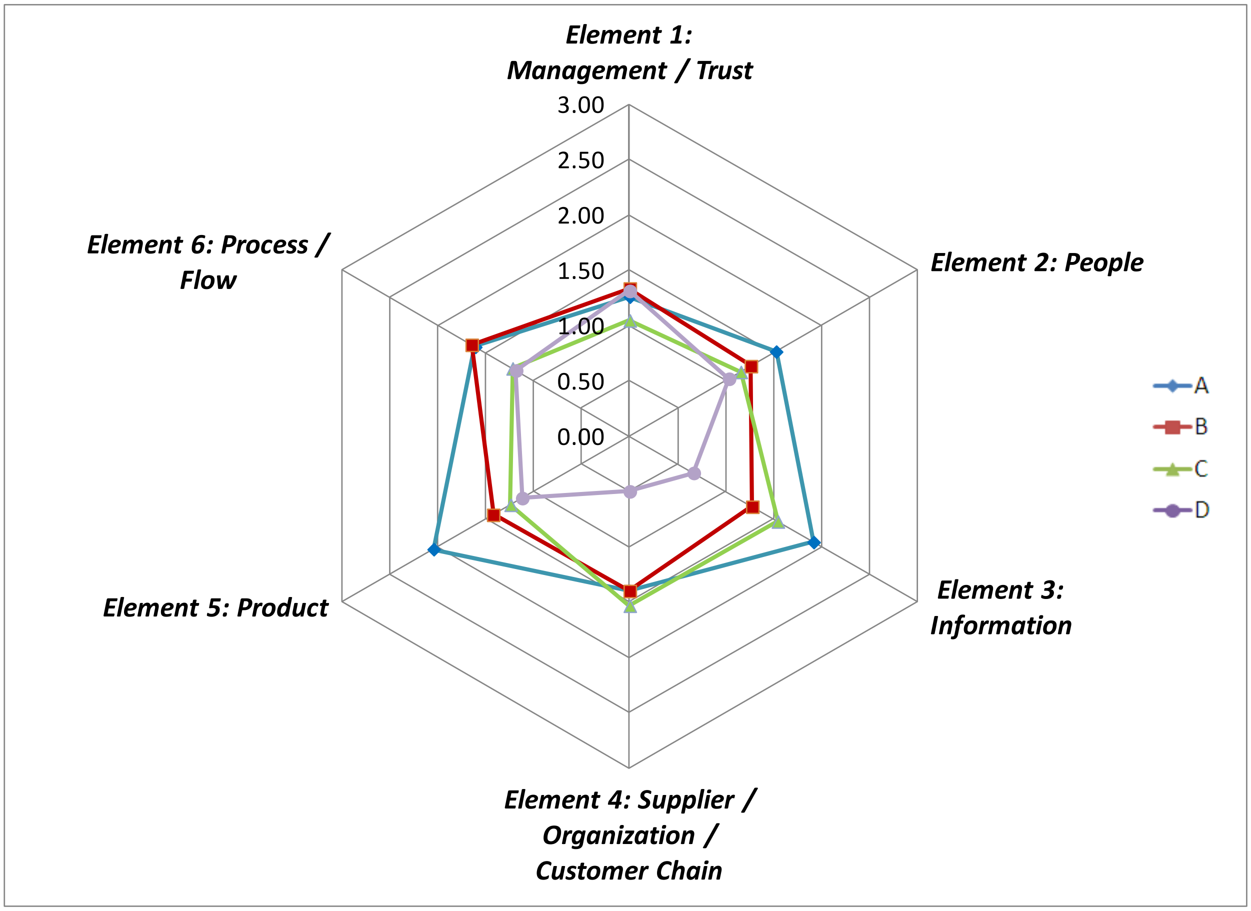

Figure 5.54 Radar Chart for Section 3 Implementation Level for All Cells

5.2.4 Questionnaire: Lean Practices (Section 3) Importance Ratings

The importance level scale is a traditional five-point Likert type scale for both Cell Specific System Variables (Section 2) and Lean Practices (Section 3) of the questionnaire (Allen and Seaman 2007, Likert 1932). Pearson's chi-square (χ^2) method of contingency analysis was used to test for significance between the four manufacturing cells and the Lean Practices (Section 3) perceived importance and counts were tallied in order to conduct this analysis.

Data representing importance scores for Lean Practices (Section 3) were analyzed to determine if a relationship exists between cells (A, B, C or D) and importance ratings (1, 2, 3, 4, or 5). The null hypothesis (H_o) statement is: no significant association exists between cells and importance rating. The alternate hypothesis (H_a) statement is: a significant association exists between cells and importance rating. When then the expected values for calculated cells in the contingency table drops below five, the calculated chi-square tends to become inflated and could potentially inflate the true probability of a Type I error beyond the stated significance level (Groebner *et al.* 2011). Therefore, based on the fact that there were no responses of 1 and some of the expected values for the 2s dropped below five, it was acceptable practice to combine the 2s and 3s categories into a single column labeled 2+3 to enable the analysis. Figure 5.55 provides the contingency table and Chi-Square analysis for Section 3 importance level across the four manufacturing cells. When the p-value of 0.000 is compared against the alpha risk value of 0.05, we reject the null hypothesis. Therefore, there is a relationship between cells and importance level for Lean Practices (Section 3).

For reference, the critical value for Pearson's Chi-Square with 6 degrees of freedom is 6 12.5916 (Groebner *et al.* 2011) and is not provided in the Minitab analysis in Figure 5.55. The four highest contributors to the total Chi Square value of 164.732 are circled to determine the practical significance of this test. It can be observed that cell A has unexpectedly low 5s with 9 observed vs. the 47.1 expected and unexpectedly high 2+3s with 65 observed vs. the 41.5 expected. This suggests that cell A has lower importance rating scores than the other cells for Lean Practices (Section 3). It can also be observed that cell D has unexpectedly high 5s with 140 observed vs. the 71.2 expected and unexpectedly low 4s with 59 observed vs. the 103.2 expected This suggests that cell D has higher importance rating scores than the other cells for Lean Practices (Section 3).

One method to confirm these theories is by summing up the total importance rating score for all items in Lean Practices (Section 3) of the questionnaire and averaging across the respondents for each cell. When the total Lean Practices (Section 3) importance score is examined for cells A, B, C, and D, they score 286, 302, 316, and 350, respectively. Cell D rated overall importance the highest and cell A rated overall importance the lowest on Lean Practices (Section 3) in comparison with the other cells.

```
Contingency table of Section 3 Importance data

                     IMPORTANCE

              2+3       4       5     All

Cell  A        65      83       9     157
             41.5    68.3    47.1   157.0
           13.284   3.141  30.855       *

Cell  B        79     112      46     237
             62.7   103.2    71.2   237.0
            4.255   0.755   8.893       *

Cell  C        47     123      65     235
             62.1   102.3    70.6   235.0
            3.690   4.187   0.437       *

Cell  D        38      59     140     237
             62.7   103.2    71.2   237.0
            9.712  18.913  66.611       *

All           229     377     260     866
            26.44   43.53   30.02  100.00
            229.0   377.0   260.0   866.0
                *       *       *       *

Cell Contents:      Count
                    Expected count
                    Contribution to Chi-square


Pearson Chi-Square = 164.732, DF = 6, P-Value = 0.000
Likelihood Ratio Chi-Square = 169.496, DF = 6, P-Value = 0.000
```

Figure 5.55 Chi Square Analysis for Section 3 Importance for All Cells

To develop a further understanding of the cell importance levels, another view of the data is considered. For Section Lean Practices (Section 3) an average implementation level was calculated for each of the six elements in reference to the four manufacturing cells. This information is depicted on the radar chart provided in Figure 5.56. The plots for each of the four cells take similar shapes but are somewhat dispersed for most of the elements. This indicates that the cells perceived importance of the six elements in a different manner for Lean Practices (Section 3). In addition, cell D rated the importance the highest for every one of the Lean Practices (Section 3) elements while cell A rated the importance the lowest on every element with the exception of Product (Element 5).

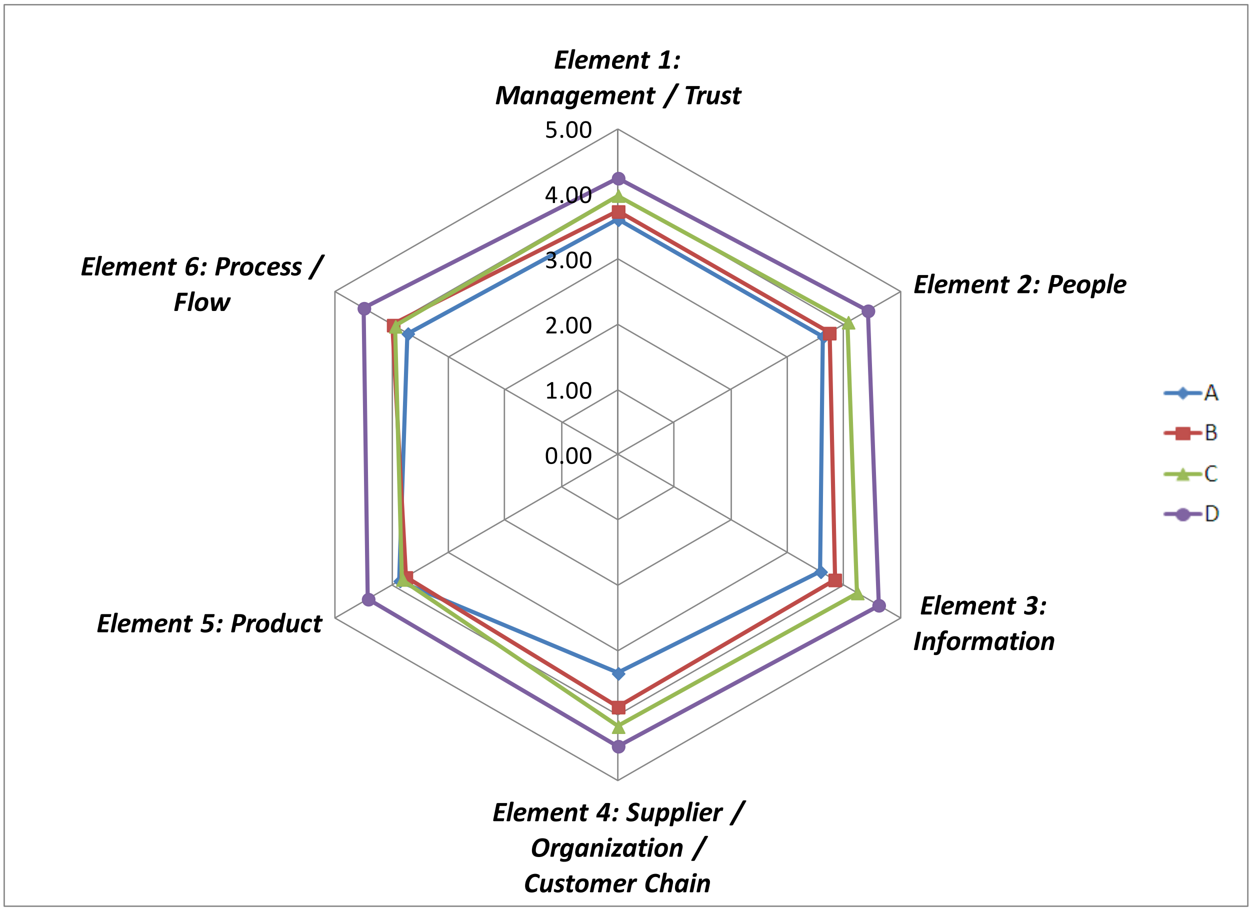

Figure 5.56 Radar Chart for Section 3 Importance for All Cells

5.2.5 Questionnaire: Overall Implementation Level Summary

Until this point, the implementation levels have been considered separately for Cell Specific System Variables (Section 2) and Lean Practices (Section 3). Figure 5.57 provides an average implementation ranking of all 12 elements from Cell Specific System Variables (Section 2) and Lean Practices (Section 3) as a grand average and then for each of the manufacturing cells. The elements are ordered from the highest average down to the lowest average. A few things quickly become apparent from the figure. First, the cells appear to have achieved higher average implementation levels on the Cell Specific System Variables (Section 2) elements in comparison with Lean Practices (Section 3) elements. This is completely intuitive as the cells have to be physically implemented and staffed as a priority to achieve the business goals associated with the implementation. It is worth noting that People (Element S2E5) had an average implementation score that was the third highest of the 12 elements. Next, cell A scores higher than the other cells on 6 of the 12 elements and scores above the average on 11 of the 12 elements. In contrast, cell D scores lower than the other cells on 7 of the 12 elements and scores below average on 7 of the 12 elements.

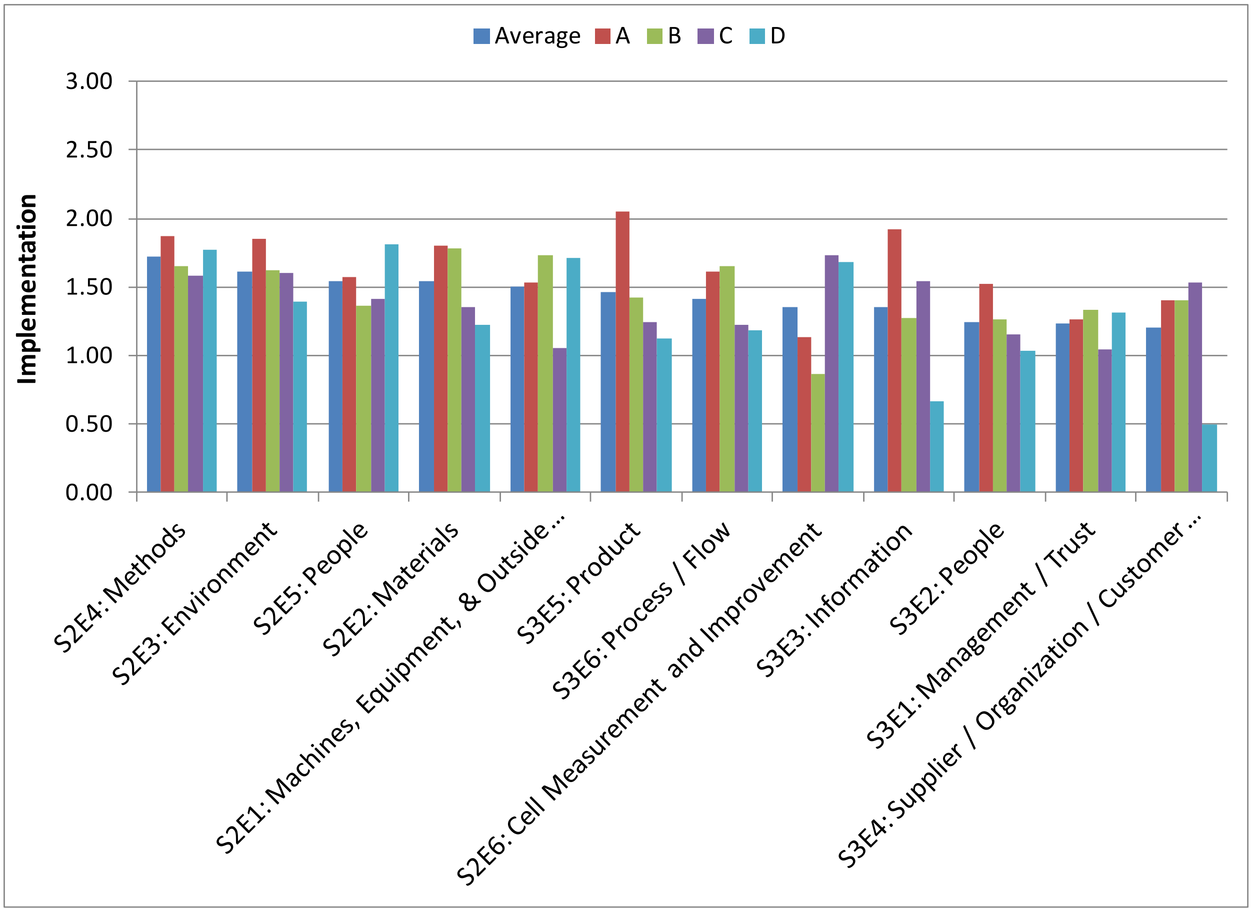

Figure 5.57 Bar Chart of Average Implementation Levels for All Cells

5.2.6 Questionnaire: Overall Importance Rating Summary

Until this point, the perceived importance scores have been considered separately for Cell Specific System Variables (Section 2) and Lean Practices (Section 3). Figure 5.58 provides an average importance ranking of all 12 elements from Cell Specific System Variables (Section 2) and Lean Practices (Section 3) as a grand average and then for each of the manufacturing cells. The elements are ordered from the highest average down to the lowest average. A few things quickly become apparent from the figure. First, the grand average ratings for all 12 elements are closely clustered between 3.5 and 4.5. However, the highest three overall element rankings are related to the basic technical aspects of the cells and include Machines (Element S2E1), Materials (Element S2E2), and Methods (S2E3).

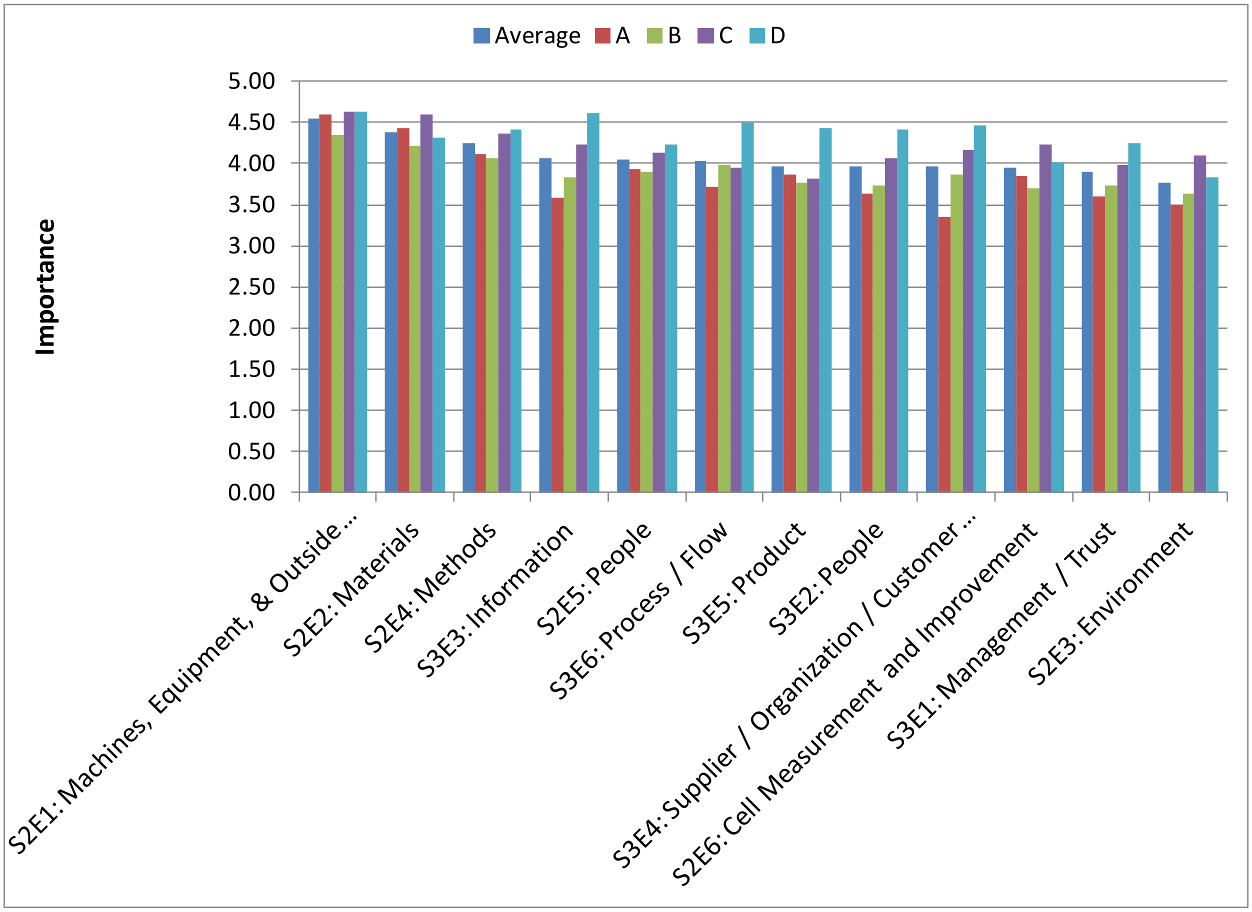

Figure 5.58 Bar Chart of Average Importance Ratings for All Cells

The human related elements People (Element S2E5), People (Element S3E2), Cell Measurement and Improvement (Element S2E6), and Management and Trust (Element S3E1) are ranked, fifth, eighth, tenth and eleventh, respectively. This may be due to the fact that when compared with the technical cell implementation aspects, these elements are perceived as more of a secondary step in the transformation, rather than less important.

5.2.7 Questionnaire: Overall Implementation Level vs. Importance Rating Summary

Scatter plots of implementation level vs. importance ratings were developed for the 12 questionnaire elements on separate graphs for each of the four manufacturing cells to understand this interaction and to prioritize which elements to address to improve the cell performance. Figure 5.59 provides a guide on how to address elements falling into the quadrants. For the elements that fall into the top right box, reinforcement from cell employees should continue to yield performance benefits. The goal is to maintain implementation levels in the two and three level ranges. This is difficult as level three requires improvement in the element within the past 12 months of questionnaire administration. The cells should then focus their efforts on the elements that fall into the bottom right box which are perceived as highly important, but have achieved low implementation scores. For instance, an element with an importance level of 5 and an implementation level score of zero would be addressed before an element with an importance level of 4 and an implementation level score of 1.

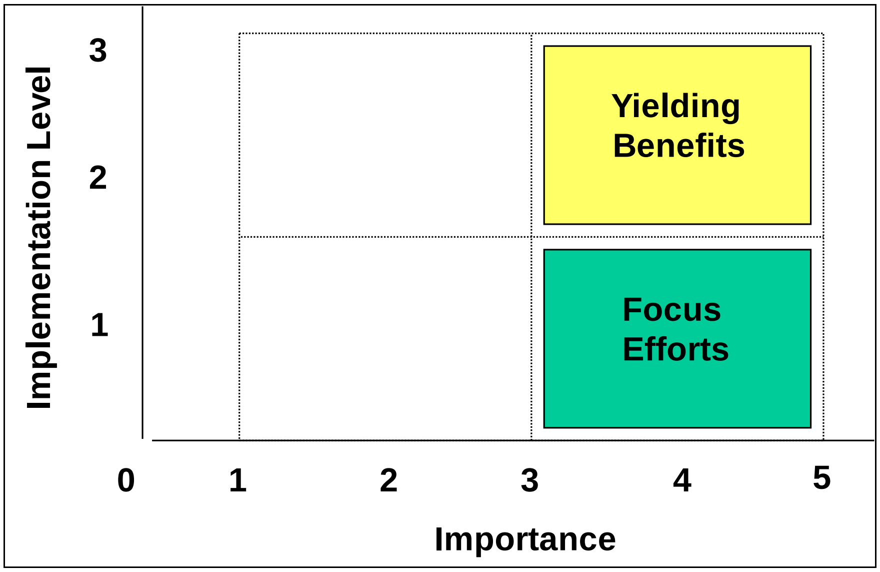

Figure 5.59 Quadrant Characteristics of Implementation Level vs. Importance Rating

The scatter plots were modified to shift the vertical quadrant dividing line from 3 to 4 due to high importance ratings. This resulted in more meaningful graphs that were somewhat more legible and simpler to interpret.

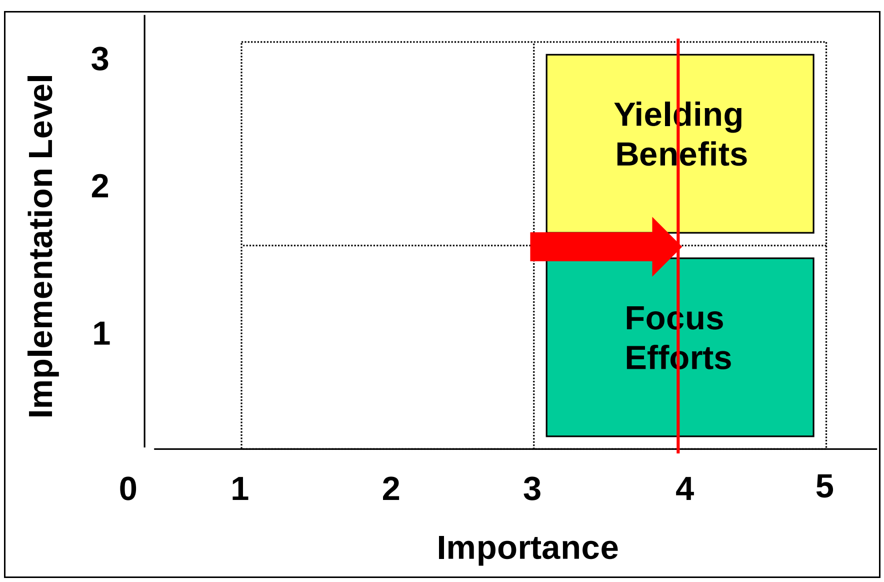

Figure 5.60 Quadrant Scale Shift of Implementation Level vs. Importance Rating

As a reminder, the Questionnaire Sections and Elements in support of scatter plot interpretation are provided in Table 4.1. Figure 5.61 provides the scatter plot for cell A and reveals that cell A scores above the midline (1.5 is midline between 0 and 3) on implementation level for nine of the twelve elements. The three elements that score below the midline on implementation level are Supplier (Element S3E4), Management / Trust (Element S3E1), and Cell Measurement and Improvement (Element S2E6). In contrast, cell A rates importance below the 4.0 threshold for nine of the twelve elements. The only three elements that score above the threshold are Machines (Element S2E1), Materials (Element S2E2), and Methods (Element S2E4). From the scatter plot, it appears that the next priority for cell A should be Cell Measurement and Improvement (Element S2E6). The rationale for choosing Cell Measurement and Improvement (Element S2E6) is because it has the highest importance rating and the lowest implementation level and sits below the implementation level midline of 1.5.

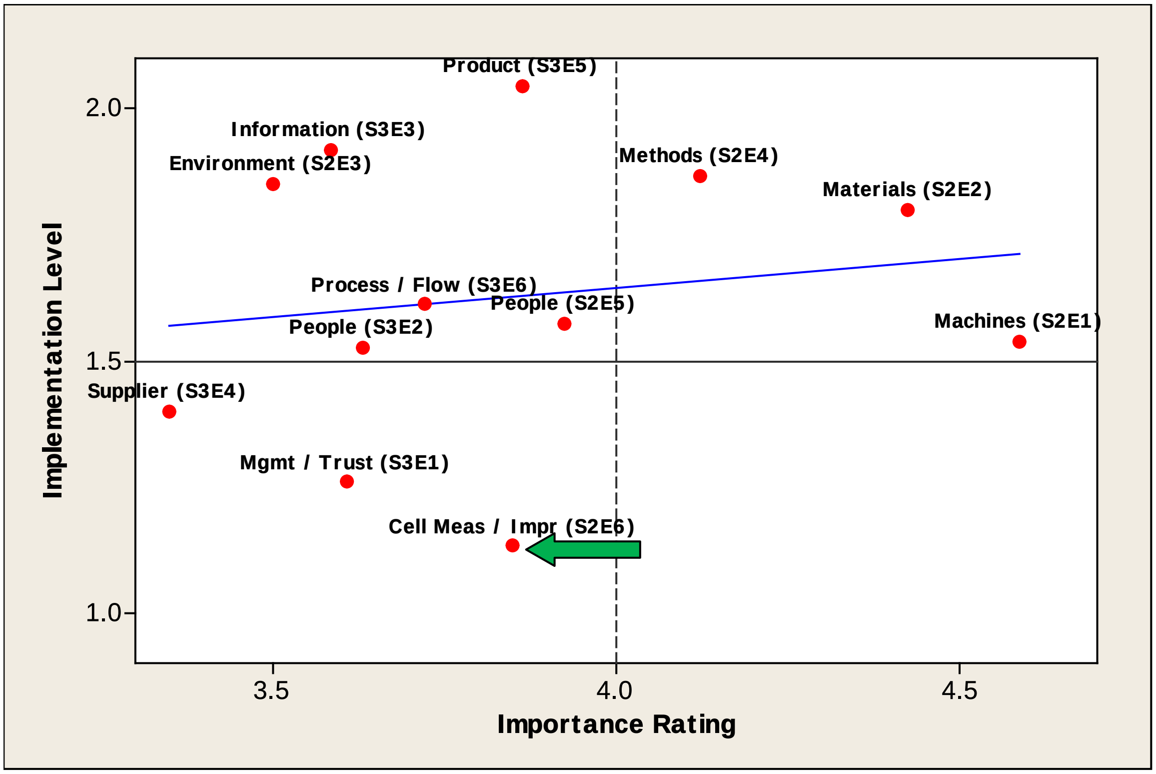

Figure 5.61 Cell A Scatter plot of Implementation Level vs. Importance Rating

Figure 5.62 provides the scatter plot for cell B and reveals that cell B scores above the midline (1.5 is midline between 0 and 3) on implementation level for five of the twelve elements, including Machines (Element S2E1), Materials (Element S2E2), Methods (Element S2E4), Process / Flow (Element S3E6), and Environment (Element S2E3). Cell B rates importance below the 4.0 threshold for nine of the twelve elements. The only three elements that score above the threshold are Machines (Element S2E1), Materials (Element S2E2), and Methods (Element S2E4). From the scatter plot, it appears that the next priority for cell B should be People (Element S2E5), which happens to be one of the human elements under Cell Specific System Variables (Section 2). The rationale for choosing People (Element S2E5) is because it has the highest importance rating and a low implementation level and sits below the implementation level midline of 1.5.

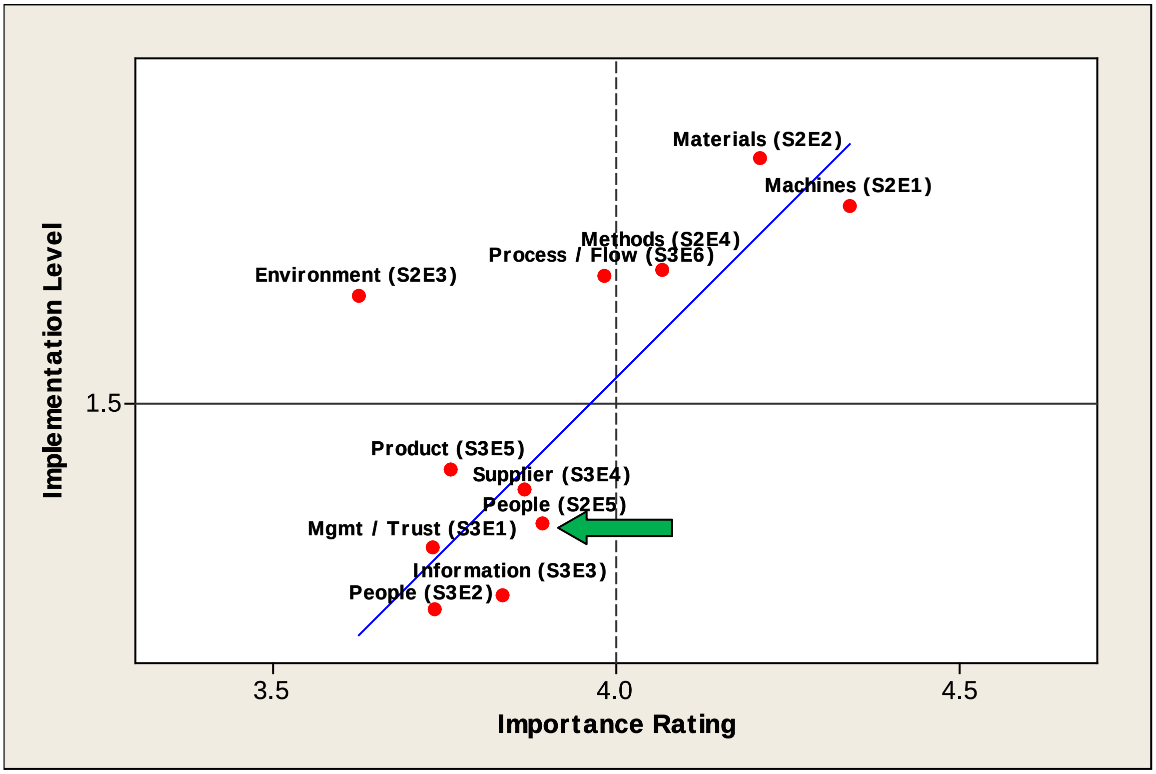

Figure 5.62 Cell B Scatter plot of Implementation Level vs. Importance Rating

Figure 5.63 provides the scatter plot for cell C and reveals that cell C scores above the midline (1.5 is midline between 0 and 3) on implementation level for five of the twelve elements, including Methods (Element S2E4), Cell Measurement and Improvement (Element S2E6), Information (Element S3E3), Supplier (Element S3E4), and Environment (Element S2E3). Cell C rates importance above the 4.0 threshold for nine of the twelve elements. The only three elements that score below the threshold are Management / Trust (Element S3E1), Process / Flow (Element S3E6), and Product (Element S3E5). From the scatter plot, it appears that the next priority for cell C should be Machines (Element S2E1) which happens to be technical element under Cell Specific System Variables (Section 2). The rationale for choosing Machines (Element S2E1) is because it has the highest importance rating and a low implementation level and sits below the implementation level midline of 1.5.

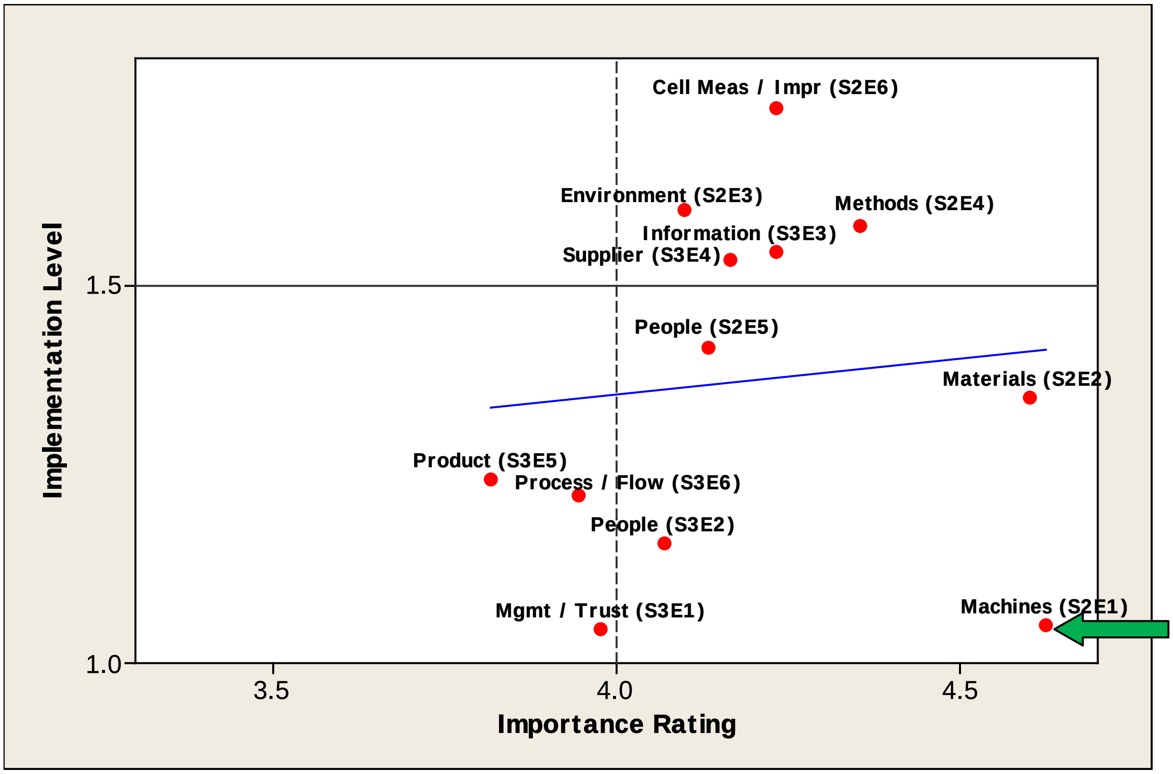

Figure 5.63 Cell C Scatter plot of Implementation Level vs. Importance Rating

Figure 5.64 provides the scatter plot for cell D and reveals that cell D scores above the midline (1.5 is midline between 0 and 3) on implementation level for four of the twelve elements, including Machines (Element S2E1), Methods (Element S2E4), People (Element S2E5), and Cell Measurement and Improvement (Element S2E6). Cell D rates importance above the 4.0 threshold for eleven of the twelve elements. The only element that scores below the threshold is Environment (Element S2E3). From the scatter plot, it appears that the next priority for cell D should be Information (Element S3E3) which happens to be technical element under Lean Practices (Section 3). The rationale for choosing Information (Element S3E3) is because it has the highest importance rating and a low implementation level and sits below the implementation level midline of 1.5.

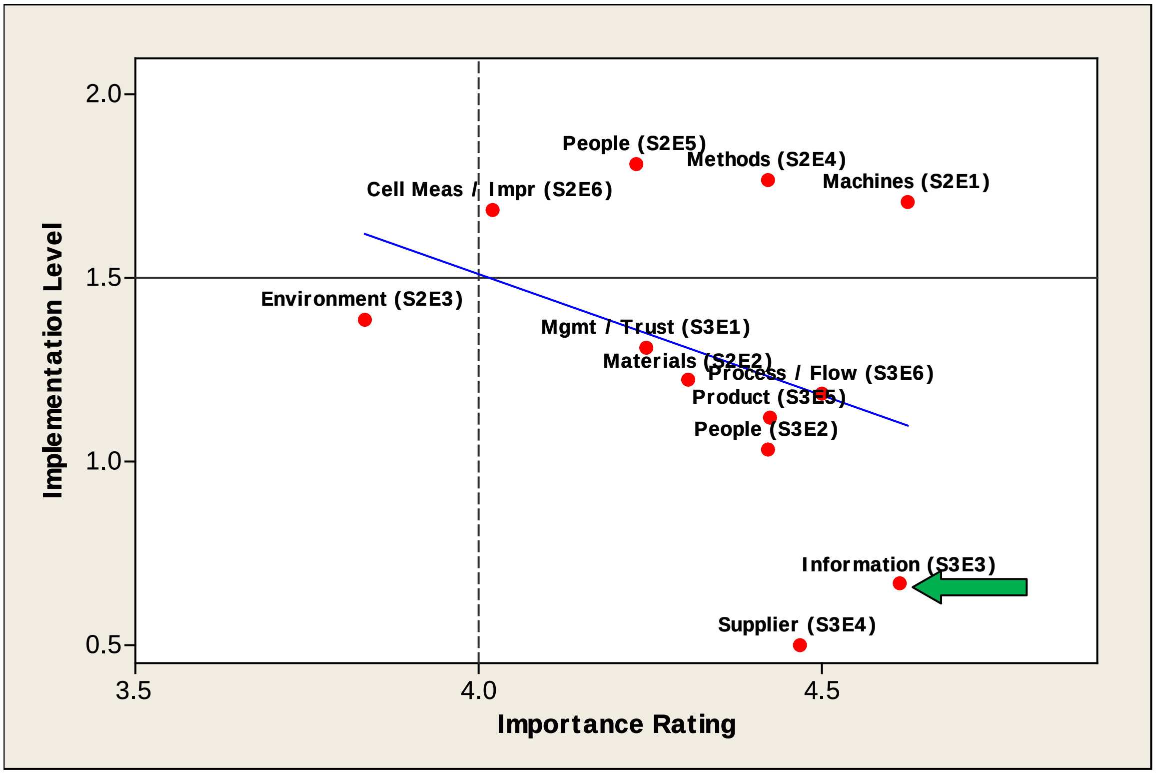

Figure 5.64 Cell D Scatter plot of Implementation Level vs. Importance Rating

5.3 COMPARISON OF PERFORMANCE MEASURES AND QUESTIONNAIRE

5.3.1 Cell Throughput Improvement vs. Total Questionnaire Scores

As mentioned in section 4.2, the primary objective of the lean manufacturing cell strategy at the field study site was to increase output to meet a sudden upturn in the market, so throughput was chosen as the primary performance measure. Recall, that a total Cell Specific System Variables (Section 2) implementation level score was calculated by summing up the total implementation score for all items in Cell Specific System Variables (Section 2) of the questionnaire and averaging across the respondents for each cell. Additionally, a total Lean Practices (Section 3) implementation level score was calculated by summing up the total implementation score for all items in Lean Practices (Section 3) of the questionnaire and averaging across the respondents for each cell. An overall questionnaire score was obtained by adding the Cell Specific System Variables (Section 2) and Lean Practices (Section 3) total implementation level scores together for a cell. A matrix plot and a correlation study are used to develop an understanding of the relationships between improvement in throughput, the individual questionnaire section scores, and the overall questionnaire score for the four manufacturing cells. Table 5.9 provides a summary of the cell throughput improvement vs. the assessment questionnaire section total scores.

Table 5.9 Summary of Throughput Improvement and Questionnaire Section Scores

Cell	A	B	C	D
% Throughput Improvement	77%	87%	43%	54%
Cell Specific System Variables (Section 2) score	69	62	62	70
Lean Practices (Section 3) score	123	111	97	82
Total (Section 2 plus 3) score	192	173	159	152

In Figure 5.65, the matrix plot illustrates a strong positive relationship between throughput improvement and the Lean Practices (Section 3) score. In addition, a strong positive relationship exists between throughput improvement and the combined Cell Specific System Variables (Section 2) and Lean Practices (Section 3) score which is more heavily influenced by the larger number of items in Lean Practices (Section 3). No relationship appears to exist between the throughput improvement and the Cell Specific System Variables (Section 2) score.

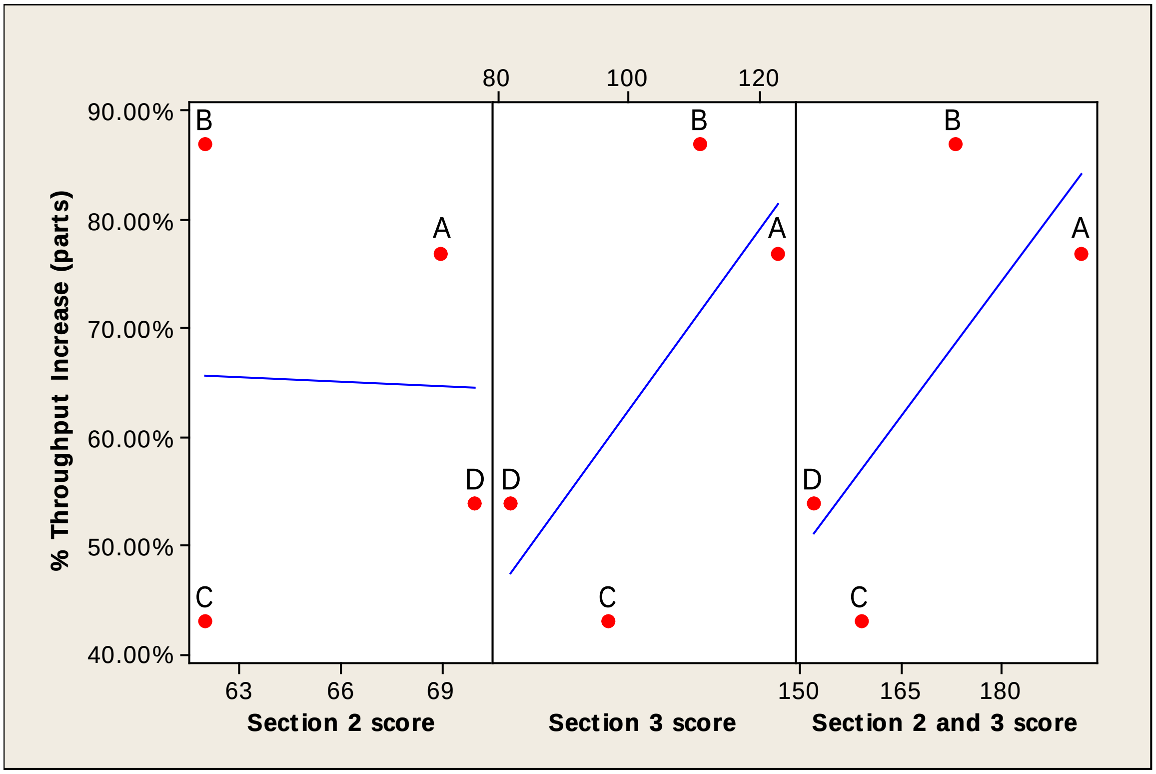

Figure 5.65 Matrix Plot of Throughput Improvement vs. Questionnaire Section Scores

In addition to a graphical view of the relationships between these variables, a mathematical understanding can be established through the use of the Pearson product moment correlation coefficient (Galton 1890, Pearson 1900, Stigler 1989). The correlation coefficient is a measure of the strength of the linear relationship between two variables.

The correlation table in Figure 5.66 provides Pearson product moment correlation coefficient between the throughput improvement, the individual questionnaire section scores, and the overall questionnaire score for the four manufacturing cells. The correlation coefficient between throughput improvement and Cell Specific System Variables (Section 2) is -0.031, indicating no relationship between these variables. Meanwhile, the correlation coefficient between throughput improvement and Lean Practices (Section 3) is 0.725. In addition, the correlation coefficient between throughput improvement and the combined Cell Specific System

Variables (Section 2) plus Lean Practices (Section 3) score is 0.720. A Pearson correlation coefficient above 0.7 is generally accepted as a strong positive relationship (Groebner *et al.* 2011). Therefore, both of the latter instances are viewed as strong positive linear relationships. From a practical standpoint, the cells that achieved a higher level of implementation on the Lean Practices (Section 3) portion of the questionnaire had a higher percentage improvement in throughput. Additionally, a high score on Lean Practices (Section 3) combined with a high score on Cell Specific System Variables (Section 2) resulted in similar related throughput improvement. However, a high implementation score on Cell Specific System Variables (Section 2) alone did not relate to any discernable increase in throughput improvement.

	% Throughput Impr	Sect 2 score	Sect 3 score
Section 2 score	-0.031		
Section 3 score	0.725	-0.137	
Section 2 and 3	0.720	0.109	0.970

Cell Contents: Pearson correlation

Figure 5.66 Correlation of Throughput Improvement vs. Questionnaire Section Scores

5.3.2 Cell Throughput Improvement vs. Human Element Scores

In section 5.3.1, it was established that a strong positive relationship existed between throughput inprovement and the Lean Practices (Section 3) portion of the questionnaire via a correlation coeficient of 0.725. The next logical research question is whether or not there is a relationship between the human elements of Lean Practices (Section 3) and throughput improvement. As discussed in Section 4.3.2, Management / Trust (S3E1), and People (S3E2) were viewed as the human elements from Lean Practices (Section 3). The correlation coefficient results exhibit a strong positive linear relationship between high scores on Management / Trust (S3E1) and People (S3E2) and improved throughput, with a value of 0.873. Figure 5.67 provides a graphical view of this relationship. This is quite encouraging as the correlation coefficient for the human element of Lean Practices (Section 3) is higher than the overall correlation coefficient for all elements of that section when considered in relation to throughput improvement.

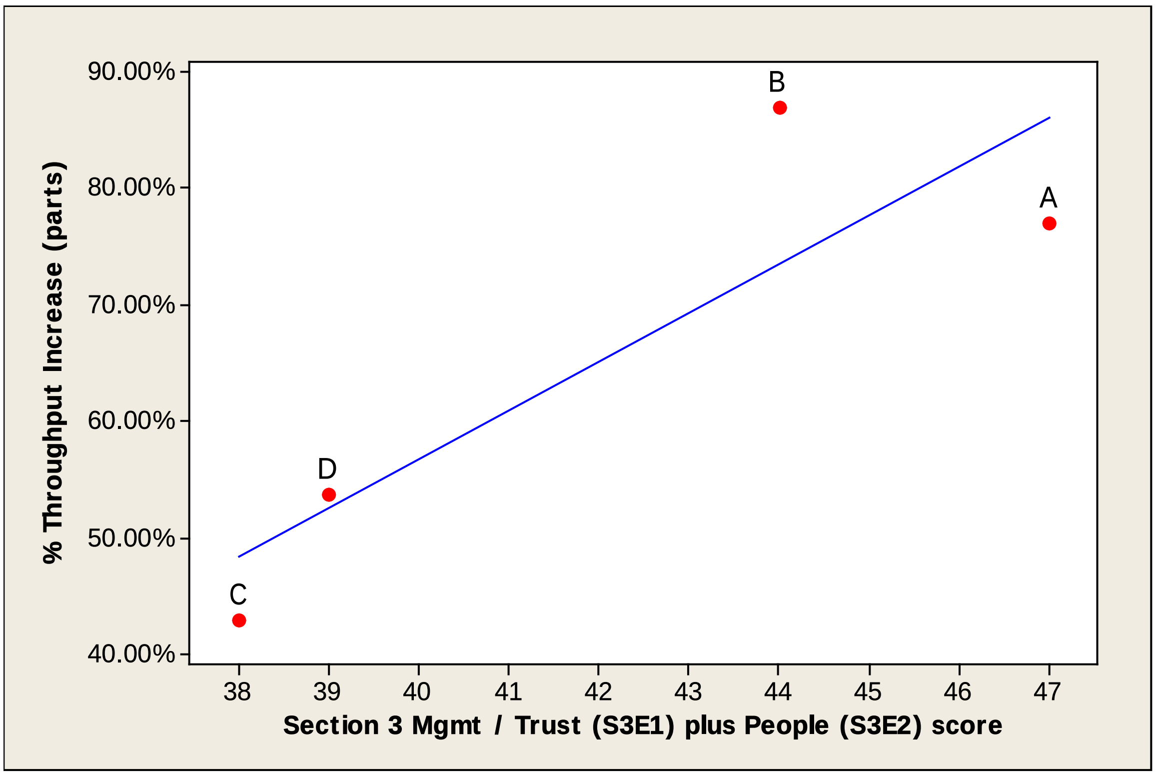

Figure 5.67 Throughput Improvement vs. Section 3 Human score

5.3.3 Cell Cost of Non-Quality Improvement vs. Human Element Scores

In section 5.3.1, it was established that a high implementation score on Cell Specific System Variables (Section 2) alone did not relate to any discernable increase in throughput improvement. However, an additional research question existed in regard to whether or not there was a relationship between Cell Specific System Variables (Section 2) and product quality improvement. When examined, the correlation coefficient results exhibited a strong negative linear relationship between high scores on Cell Specific System Variables (Section 2) and reduction in cost of non-quality, with a value of -0.841. Figure 5.68 provides a graphical view of this relationship.

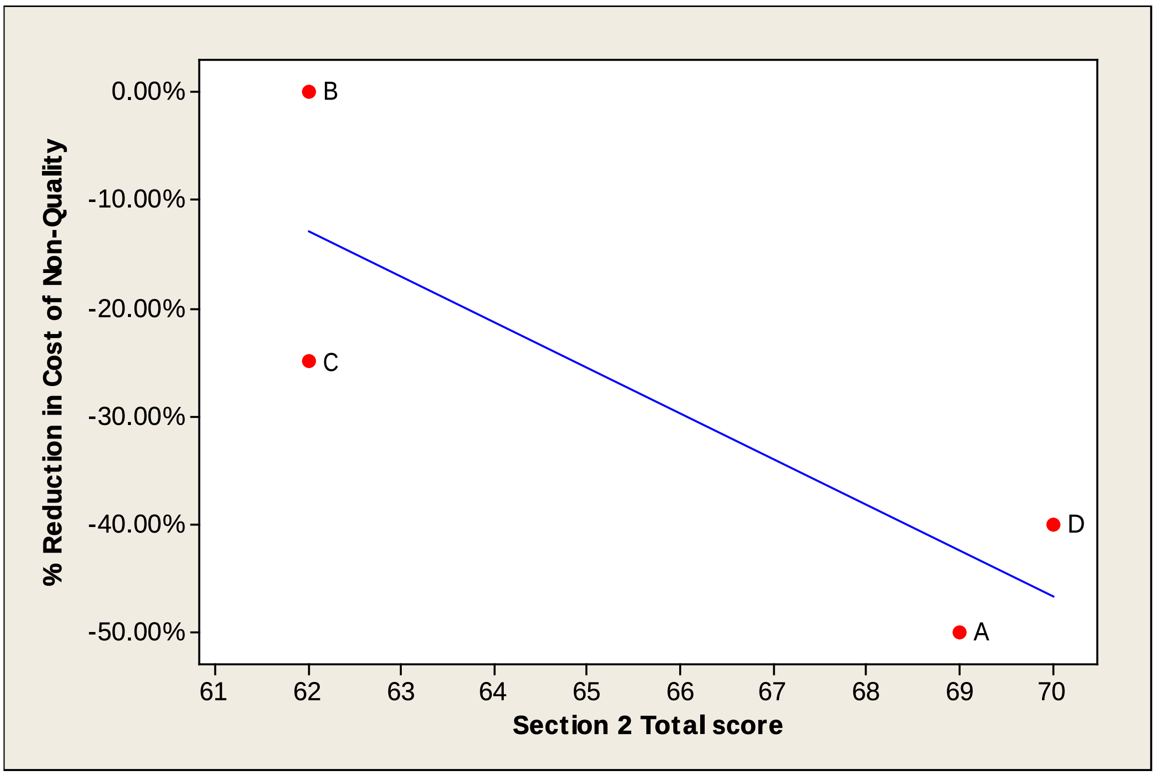

Figure 5.68 Scatter plot of Quality Improvement vs. Section 2 Total score

A further research question arose in regard to whether or not there was a relationship between the human elements of Cell Specific System Variables (Section 2) and product quality improvement. As discussed in Section 4.1, People (S2E5) was viewed as the human element from Cell Specific System Variables (Section 2). The correlation coefficient results exhibit a strong negative linear relationship between high scores on People (S2E5) and reduction in cost of non-quality, with a value of -0.804. Figure 5.69 provides a graphical view of this relationship. This is encouraging as the correlation coefficients are quite similar, which means that the People (S2E5) score alone is a strong indicator of the product quality improvement.

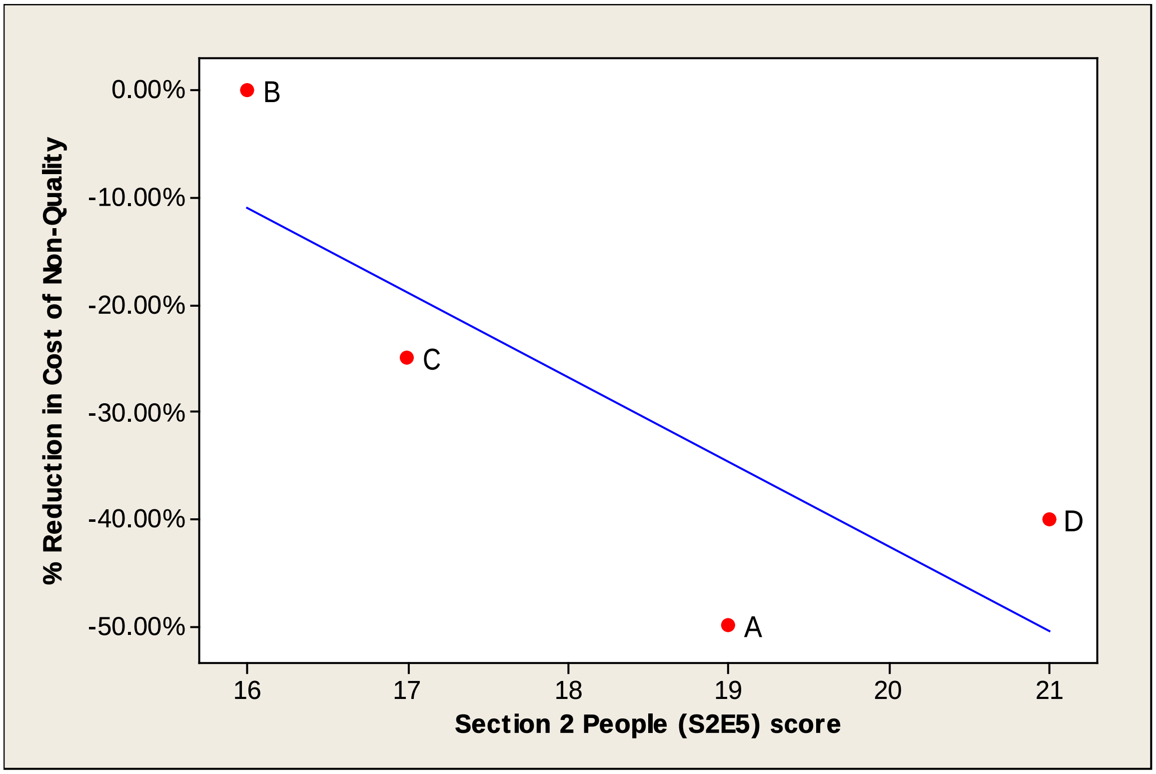

Figure 5.69 Scatter plot of Quality Improvement vs. Section 2 Human score

5.3.4 Cell Complexity vs. Total Questionnaire Scores

In Figure 5.70, the matrix plot illustrates a strong negative relationship between cell complexity and the Lean Practices (Section 3) scores. In addition, a moderate negative relationship exists between cell complexity and the combined Cell Specific System Variables (Section 2) plus Lean Practices (Section 3) score which is more heavily influenced by the larger number of items in

Lean Practices (Section 3). A weak positive relationship appears to exist between cell complexity and the Cell Specific System Variables (Section 2) score.

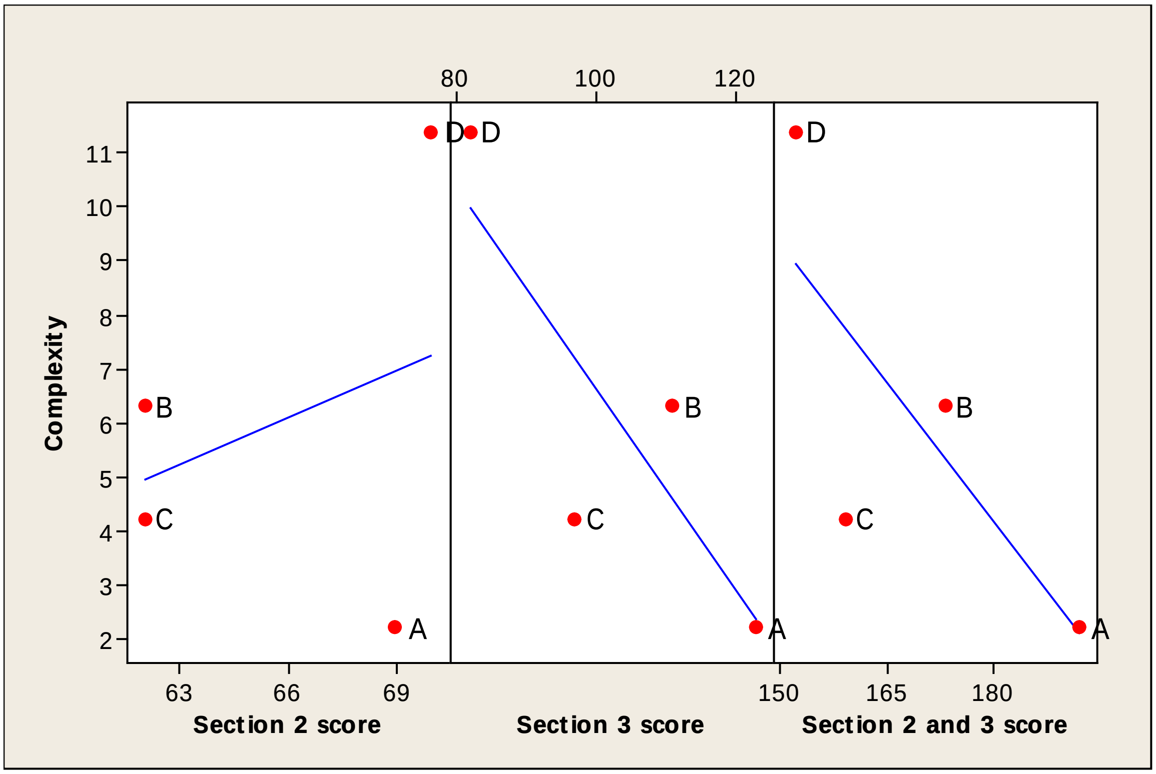

Figure 5.70 Matrix Plot of Cell Complexity vs. Questionnaire Section Scores

In addition to a graphical view of the relationships between these variables, a mathematical understanding can be established through the use of the Pearson product moment correlation coefficient (Galton 1890, Pearson 1900, Stigler 1989). The correlation table in Figure 5.71 provides Pearson product moment correlation coefficient between the cell complexity, the individual questionnaire section scores, and the overall questionnaire score for the four manufacturing cells. The correlation coefficient between cell complexity and Cell Specific System Variables (Section 2) is 0.314, indicating a weak relationship exists between these variables. In practical terms, all cells achieved about the same level of implementation on Cell Specific System Variables (Section 2), regardless of cell complexity.

Meanwhile, the correlation coefficient between cell complexity and Lean Practices (Section 3) is -0.839. In addition, the correlation coefficient between cell complexity and the combined Cell Specific System Variables (Section 2) plus Lean Practices (Section 3) score is -0.764. A Pearson correlation coefficient above 0.7 is generally accepted as a strong positive relationship (Groebner *et al.* 2011). A value between 0.4 and 0.7 is considered to be a moderate relationship. Therefore, the relationship between cell complexity and Lean Practices (Section 3) is viewed as strong negative linear relationship. The relationship between cell complexity and the combined Cell Specific System Variables (Section 2) plus Lean Practices (Section 3) score is also viewed as a strong negative relationship. From a practical standpoint, the cells that achieved lower implementation scores on the Lean Practices (Section 3) portion of the questionnaire were more complex in nature. This is intuitive as the more complex cells would have to spend more time and effort implementing the Cell Specific System Variables (Section 2).

	Complexity	Sect 2 score	Sect 3 score
Section 2 score	0.314		
Section 3 score	-0.839	-0.137	
Section 2 and 3	-0.764	0.109	0.970

Figure 5.71 Correlation Study of Cell Complexity vs. Section Scores

6.0 CONCLUSIONS AND FUTURE RESEARCH

Lean manufacturing is one of the most popular improvement approaches that has emerged in manufacturing and business publications in recent years. There is an immense interest from industry regarding the tenants behind lean manufacturing and the majority of companies are working to implement lean principles in one form or another. However, as discussed in Chapter 1.0, although some companies succeed, a much higher proportion fail to achieve the full benefits of lean manufacturing (Dale 1999, Wemmerlov and Hyer 1989). Further, while companies may achieve robust technical process flows and manufacturing cell designs, many do not fully consider the human element and its importance in achieving the full benefits of lean manufacturing in terms of performance measures such as delivery, quality and cost.

The primary objective of this research is to provide an approach to measure, evaluate and improve the performance of manufacturing cells considering technical and human elements, including the supporting lean practices. In this dissertation, a simple and systematic approach is employed to study the technical, human, and lean practices variables and understand the relationships between these variables and the performance measures within a cellular manufacturing system. Additionally, structured guidance is provided to direct an organization in which areas to focus in a prioritized manner to most expeditiously achieve the anticipated benefits of lean.

More specifically, the research aim was is to 1) explore and examine differences in performance measures during the three discrete phases of cell implementation and maturity, 2) examine relationships between the cell specific system variables and performance measures, 3) examine relationships between supporting lean practices and performance measures, and 4) evaluate factors that relate to differences between cells in regard to importance and implementation levels of cell specific system variable and supporting lean practices.

In order to develop an appropriate assessment tool, the Cell Specific System variables and the cell performance measures were identified via a research site focus group and from various sources the literature. Next, the Lean Practices variables were identified by developing a cross-reference of the two lean standards that exist in the automotive and the aerospace industry. Within the questionnaire, one of the six elements under the Cell Specific System Variables (Section 2) and two of the six elements under the Lean Practices (Section 3) variables were considered to be classified as the human element. Varying numbers of items were developed under each of the element headings to ensure that every identified variable in each section was measured.

The questionnaire was used to collect demographic information on the respondents and employee perceptions of two different types of information for the variables listed above. Implementation level was measured on a scale from 0 to 3 and perceived importance was measured on a scale of 1 to 5 for every item in the questionnaire. A field study was conducted in four manufacturing cells of an aero engine manufacturing, assembly and test company. The performance measure data was collected over a 45 month period and the questionnaire was administered at the end of the study.

6.1 SUMMARY OF THE FINDINGS

This research provides a rich case study which employs real manufacturing cells to pilot an approach to measure, evaluate and improve the performance of manufacturing cells. Through literature review and a field study site focus group, a consolidated view is established of the Cell Specific System variables that need to be addressed when implementing manufacturing cells, along with the related cell performance measures and their clear operational definitions. In addition, a cross-reference of the two major sources of lean best practices in the automotive and aerospace industries is developed to create a consolidated view of the Lean Practices variables that must be considered when implementing lean manufacturing within an organization. These variables are then grouped under element headings and categorizing as technical or human in nature. A straight-forward assessment questionnaire is developed that can be readily used by companies to measure both perceived importance and implementation level of the Cell Specific System variables and Lean Practices within their operations. Note that the questionnaire is written in a manner that does not restrict its use to automotive or aerospace industries, resulting in generalizability.

Three phases of cell implementation and maturity are presented and the performance measure throughput is studied over these three phases. This provides companies with a view of what they might expect in terms of performance via an understanding of staged implementation and also provides an analysis approach a company could mirror to illustrate and confirm achievement of planned performance improvements. In addition, this work provides guidance on how to analyze the questionnaire and to interpret the results utilizing both mathematical and visual tools which could be easily employed by a corporation that is on a lean journey.

In terms of results from the field study, this work demonstrates that cells which achieved higher scores on the Lean Practices (Section 3), coupled with high scores on Cell Specific System Variables (Section 2) achieved higher percentage throughput improvements. This is evidenced by a correlation coefficient of 0.720 which indicates a strong positive relationship. In addition, the cells that achieved the highest scores on Cell Specific System Variables (Section 2) coupled with the highest scores on People (Element S2E5) achieved the highest percentage improvements in product quality. Companies should clearly consider the implications of these finding as they move forward with the implementation of lean within their operations.

The study demonstrates that the elements related to machines, materials and methods are viewed as highly important by the respondents from the four manufacturing cells, and Cell Specific System Variables (Section 2) are generally viewed as more important than Lean Practices (Section 3) variables. However, it is quite encouraging that People (Element S2E5) is viewed as the third highest implemented element of the twelve elements that comprise Cell Specific System Variables (Section 2) and Lean Practices (Section 3) of the questionnaire. Another, key finding is the fact that hourly employees, or workers, generally rate the implementation level of the Cell Specific System Variables (Section 2) lower than their salaried counterparts, validating the idea that demographic factors such as employee type may impact ratings. Finally, through the use of implementation level vs. perceived importance scatter plots, structured guidance is provided to direct an organization in which areas to focus in a prioritized manner to most expeditiously achieve the anticipated benefits of lean.

The key findings from the research can be summarized as follows:

- When examining the performance measures, an improvement in throughput was strongly negative correlated to both lead-time and inventory reduction, which is consistent with the literature. (Throughput improvements ranged from 43% to 87% for the four manufacturing cells, while lead-time reductions ranged from -69% to -78% and inventory reductions ranged from -45% to -80%.)

- Three phases of cell implementation and maturity have been defined as part of the research field study. In only one of the four cells, was a statistically significant throughput improvement observed between phases 1 and 2. However, in all cells, a statistically significant throughput improvement was observed between phases 2 and 3. Employee engagement in the lean improvement activities has been found to be a primary driver of this result. (In the study the one cell that saw significant improvement between phases 1 and 2 had 50% of the respondents involved in the phase 1 cell implementation vs. 20% to 33% for the other cells. Between phases 2 and 3, the cells had 70% to 100% of the respondents participate in the follow-on improvement activities.)
- When the questionnaire data for Cell Specific System Variables (Section 2) was analyzed considering the implementation level achievement, two cells scored higher than the other two – both from an overall standpoint and specifically on People (Element S2E5) which comprised 33% of the items in Section 2. (In addition, although quality was a secondary performance measure, these same two high scoring cells achieved the largest percentage improvement in product quality which is highly attributable to correct staffing and employee engagement.)
- The bar charts and scatter plots illustrate that the cells appeared to invest more of their time and resources into Cell Specific System Variables (Section 2) elements, as most of the elements appear above the midline average of 1.5 on the graphs in comparison with the Lean Practices (Section 3) elements. This is completely intuitive as the cells have to

be physically implemented and staffed as a priority to achieve the business goals associated with the lean transformation.

- People (Element S2E5) had an average implementation score that was the third highest of the 12 elements from the combined Cell Specific System Variables (Section 2) and Lean Practices (Section 3) portions of the questionnaire. This is intuitive and implies that the cells focused obvious effort on items such as staffing the cell, developing and executing training plans, managing attendance and coverage, communication between shifts, and the other human variables captured under this heading to achieve the targeted performance objectives.
- Hourly employees perceived implementation levels lower than salaried employees for Cell Specific System Variables (Section 2). This is to be expected as the workers may not have as holistic a view as their management counterparts and are more focused on their specific job role than the overall management of the cells and related issues.
- When the questionnaire data for Cell Specific System Variables (Section 2) was analyzed considering the perceived importance, two cells rated overall importance higher than the other two cells. (This is most likely due to the fact that cells C and D were implemented later than cells A and B, making the importance appear to be more critical for the Cell Specific System Variables (Section 2) variables as the task was more challenging for cells C and D to accomplish in the time period considered.)
- One cell, B, exhibited markedly lower importance scores on all elements in Cell Specific System Variables (Section 2), which may be attributable to that cell already achieving the highest throughput improvement at the time of the survey.

- All four cells rated Machines (Element 1), Materials (Element 2) and Methods (Element 4) in their top three of the six elements from an importance standpoint for Cell Specific System Variables (Section 2) alone, and in the top three of the twelve elements that comprise Cell Specific System Variables (Section 2) and Lean Practices (Section 3). This is completely intuitive, as the cells must establish the technical process flow in order to operate as manufacturing cells as a foundation for implementation of the other elements.
- In practical terms, hourly and salaried employees viewed importance in the same manner for Cell Specific System Variables (Section 2). Although the hourly and salaried employees view implementation levels differently, it makes sense that these same employees view importance in much the same manner from a logic standpoint.
- When the questionnaire data for Lean Practices (Section 3) was analyzed considering the implementation level achieved, two cells, A and B, achieved higher implementation levels on the Lean Practices (Section 3) than the other two cells. (One possible reason is that since cell D was more complex and scored the highest on the Cell Specific System Variables (Section 2), the employees may not have been able to focus on the Lean Practices (Section 3) part of the implementation. This is further complicated by the fact that cells C and D were the last to be implemented of the four manufacturing cells, giving the cell teams less time than their counterparts to achieve successful implementation on Lean Practices (Section 3)).
- When the questionnaire data for Lean Practices (Section 3) was analyzed considering the perceived importance, cell D rated overall importance the highest and cell A rated overall importance the lowest in comparison with the other cells. Additionally, when all cells

were considered, cells C and D rated overall importance higher than cells A and B for Lean Practices (Section 3). One possible reason is that cells A and B perceived Lean Practices (Section 3) items as less important because they had achieved the highest scores in Lean Practices (Section 3), and that the converse may be true for cells C and D.

- The cells that achieved higher implementation scores on the Lean Practices (Section 3) portion of the questionnaire achieved higher percentage improvements in throughput. However, a high implementation score alone on Cell Specific System Variables (Section 2) did not result in any discernable increase in percentage throughput improvement.
- There is a strong positive linear relationship between the human elements of Management / Trust (S3E1), and People (S3E2) from the Lean Practices (Section 3) and throughput improvement, which is evidenced by a correlation coefficient value of 0.873. This is quite encouraging as the correlation coefficient for the human element of Lean Practices (Section 3) is higher than the overall correlation coefficient for all elements of that section when considered in relation to throughput improvement.
- The cells that achieved lower implementation level scores on the Lean Practices (Section 3) portion of the questionnaire were more complex in nature. This is intuitive as the more complex cells would have to spend more time and effort implementing the Cell Specific System Variables (Section 2). However, no relationship was observed between cell complexity and the implementation level score for Cell Specific System Variables (Section 2).
- Finally, as a next step toward improving performance, two of the four cells needed to focus on elements that were categorized as human. This was based on these elements

having high perceived importance and low implementation level (below the midline of 1.5) for the respective manufacturing cells.

Ultimately, achieving the full benefits of lean manufacturing is based on solid implementation of the Cell Specific System Variables (Section 2) coupled with a prioritized implementation of the Lean Practices (Section 3) variables, which are made up of 33% and 43% human aspects, respectively.

It is worth noting that the field study site developed a proprietary assessment tool comprised of four major building blocks that is quite congruent with the Cell Specific System Variables (Section 2) and Lean Practices (Section 3) portion of the questionnaire. The building blocks are then comprised of elements, similar to the other two industry standards. This asssessment tool has been deployed company wide to all functions and sectors and is based on achievement of implementation levels from 0 to 4. For each element, very specific definitions exist to determine the requirements for achievement of each of the levels. The deployment goes beyond the traditional operartions arena to include the transactional areas of the business. Year on year improvement goals are set for each business to drive continuous improvement.

6.2 LIMITATIONS

Key limitations to this research include the size and nature of the sample, the staggered implementation of the four manufacturing cells, and the administration of the questionnaire only at the end of the study. Although the study employed 45 months of data, the sample was limited to four manufacturing cells within one corporation, and there were thirty-four respondents to the questionnaire. As evidenced by the cell characteristics in Table 4.4., the cells were larger than most of those considered in the literature with the number of machines ranging from 10 to 22, the number of operations ranging from 13 to 34 and the number of workers ranging from 11 to 27. However, the small sample size limits some of the analysis techniques that could be employed with a larger number of cells and a higher number of respondents. Two such methods are factor analysis and linear regression, and these opportunities will be discussed further in the next section. The sample was also limited to only one company. The cells in the study were implemented over a seven month time period and the phases of implementation varied over the time horizon. Although this situation was due to limited resources to move all of the equipment into formation for these large cells, it would have been preferable to study a company that was able to simultaneously implement a large number of cells to enable less variation due to time. From a data collection standpoint, the questionnaire was administered only at the end of the study. Had the questionnaire been developed sooner, it would have been preferable to administer prior to cell implementation and at the end of each phase. Implications will be discussed in the next section.

6.3 RECOMMENDATIONS FOR FUTURE STUDY

The work presented in this document provided a solid foundation for several areas of future study. First, additional validation of the Cell Specific System variables and the Lean Practices variables could be achieved by administering the questionnaire within another company or multiple companies within varying industries and geographical locations. Further research is necessary to refine the questionnaire to make it as concise and user-friendly as possible, in addition to the efforts taken in this work. This leads to the opportunity for standardization which will be covered in the next paragraph. Once the questionnaire is refined, it could be employed at additional companies as mentioned above to obtain much larger sample sizes, both in terms of participating cells and the number of respondents. Larger samples sizes would enable the use of exploratory factor analysis to understand the inter-correlations between individual questionnaire items and to determine which of the individual questionnaire items have the highest factor loadings. In this way, the assumption of equal weighting of each of the questionnaire items could be challenged and potentially revised. In addition, the larger sample sizes may facilitate the use of linear regression to develop a predictive model that relates implementation level of the questionnaire items, elements, and sections to the cell performance measures. If a large enough sample could be obtained, then a portion of the data could be held back for validation of the regression model. Additional insight could be gained if the questionnaire was administered prior to cell implementation and at the end of each of the three identified phases, which is similar in nature to the work of Glover *et al.* (2011). Progress on the lean journey could be gauged at each of these key points for an organization, and with enough data, factor analysis and regression could be employed to determine if the relationships between questionnaire implementation levels and performance measure change over the three phases.

From a standardization viewpoint, there are currently lean standards in the automotive and aero industries, and there is a lean certification that is jointly offered from the Society of Manufacturing Engineers, the Association for Manufacturing Excellence, the Shingo Prize for Operational Excellence, and the American Society for Quality which is based on a lean body of knowledge. An opportunity exists for all of these organizations to work together to jointly develop a simple, straight-forward, standard lean assessment tool with strong consideration of the human element. MIT has started down the path with the development of the Lean Enterprise Transformation Maturity Model (Nightingale and Mize 2002). However, the model and tool appear to be focused on members of the MIT Lean Advancement Institute and has not been widely disseminated outside of that circle. As mentioned previously, SAE has struggled with dissemination and acceptance of the J4000 lean standard (SAE 1999a) and that same challenge holds true for any type of lean assessment tool.

The research provides insight to the relationships between the technical, human and lean elements of manufacturing cells and the related performance measures. It did not attempt to study every variable related to successful lean implementation, but those that are viewed as dominant, common, and most clearly definable. Undoubtedly, the human element is key to achieving the full benefits of lean, and further study is required to supplement and refine the approach presented in this work and its consideration of the human element. This dissertation provides direction for future research that is based on larger samples, focuses on refinement of the assessment questionnaire, considers other industries, and employs statistical techniques such as factor analysis and linear regression.

APPENDIX A

CROSS-REFERENCE OF INDUSTRY LEAN STANDARDS

Section 3 : Lean Manufacturing Assessment Cross Referenced with the Corresponding Element Sources			
		Corresponding Element Source Code	
Element 1	***Management / Trust***	**J4000**	**LEM**
1.1	Continuous progress in implementing lean operating methods is the organization's primary tool in pursuing its strategic objectives	1.1	8.3
1.2	Structured policy (business plan) deployment techniques are used to plan the organization's lean deployment actions	1.2	6.5, 8.1
1.3	Lean progress targets are defined and have been effectively communicated	1.3	2.2, 6.5
1.4	Knowledge of the philosophy and mechanics of lean operation has been obtained and effectively communicated	1.4	2.2
1.5	The organization's senior managers are actively leading the deployment of lean practices	1.5	8.1
1.6	Lean progress is reviewed by senior management against planned targets on a regular basis	1.6	8.1
1.7	Meaningful incentives that reward organization lean progress are in place	1.7	6.4
1.8	Individual manager's performance is evaluated and rewarded relative to lean progress	1.8	6.4
1.9	A non-blaming, performance oriented, process-driven organization atmosphere exists	1.9	
1.10	There is a regular, direct personal involvement by senior managers with the operating workforce concerning lean practices	1.10	8.1
1.11	Consistent policy for disposition of individuals made surplus by lean progress in is place and followed	1.11	
1.12	No employee has reason to perceive that their livelihood to be jeopardized by contributing to organization lean progress	1.12	6.4
1.13	Management has chosen to adhere to lean principles in the face of short term operating objectives inconsistent with lean progress	1.13	6.5

Figure A.1 Page 1 of Lean Standard Cross-Reference (SAE 1999a, MIT 1996)

1.14	Stable and cooperative relationships are built both internally and externally		6.2
1.15	Benchmarking studies are performed		10.2
Element 2	***People***		
2.1	Adequate training resources are provided and paid employee training time is made available	2.1	6.3
2.2	The training syllabus includes training in the lean-specific tools and measurables suitable to the organization's needs, at all levels within the organizations	2.2	8.1
2.3	Training is conducted as scheduled, records of training are kept and training effectiveness is regularly evaluated	2.3	
2.4	Organization is structured to correspond to the structure and sequence of the value chain through the enterprise	2.4	9.1
2.5	Each employee participates in the structure as corresponds to his role	2.5	4.1, 8.2
2.6	Labor and employment policies and agreements are in place which allow lean progress within the organization	2.6	6.2, 8.4
2.7	Team authority level and accountability level is clearly defined	2.7	4.1
2.8	Employee development through Quality Circles / Continuous Improvement teams is encouraged and supported at all levels	2.8	9.1
2.9	Team is accountable for continuous improvement in its segment of the value chain	2.9	8.2
2.10	Team decision making authority and authority to act corresponds to the level of accountability	2.10	4.2
2.11	Management does not supersede team decisions and actions when within the team's authority	2.11	4.2
2.12	Career and skill development programs are established for each employee	2.12	4.3
2.13	Maintenance, certification and upgrading of critical skills is ensured		3.1
2.14	Workforce capabilities and needs are analyzed to provide for balance of breadth and depth skills / knowledge		3.2

Figure A.2 Page 2 of Lean Standard Cross-Reference (SAE 1999a, MIT 1996)

2.15	Jobs are broadened to facilitate the development of a flexible workforce		3.3
2.16	Hand offs and approvals within and between line and support activities are minimized		3.4
2.17	The environment and a well-defined processes are provided for expedited decision-making		4.4
2.18	Experience-generated learning is captured, communicated and applied		4.5
2.19	Capture, communicate and apply experience-generated learning		10.1
Element 3	***Information***		
3.1	Adequate and accurate operating data and information is available to members of the organization as needed	3.1	
3.2	Knowledge is shared across the organization	3.2	10.3
3.3	Data collection and its use are the responsibility of the individuals most closely associated with that part of the process	3.3	
3.4	The operating financial system is structured to present correctly the results of lean progress	3.4	9.3
3.5	Databases are linked for key functions throughout the value chain		2.3
3.6	Documentation is minimized while ensuring necessary data traceability and availability		2.4
Element 4	***Supplier / Organization / Customer Chain***		
4.1	Both suppliers and customers participate at the earliest possible stage in the organization's undertaking of a product / process / project	4.1	5.7
4.2	Both suppliers and customers are appropriately represented on the organization's product / process / project teams	4.2	
4.3	Both suppliers and customers participate in regular reviews of product / process / project progress	4.3	6.5
4.4	Effective incentives for supplier, organization and customer are in place that reward shared performance improvements or cost reductions	4.4	6.4

Figure A.3 Page 3 of Lean Standard Cross-Reference (SAE 1999a, MIT 1996)

4.5		The interchange of knowledge from and within the supplier network occurs		10.3
4.6		Multi-year contracting is used wherever possible		12.2
4.7		Programs are structured to absorb changes with minimal impact		12.4
4.8		Continuous information flow and feedback from stakeholders is provided		7.1
4.9		The contract process is optimized to be flexible to learning and changing requirements		7.2
4.10		Relationships are created and maintained with customers in requirements generation, product design, development and solution-based problem solving		7.3
Element 5		***Product***		
5.1		Product and process design is conducted by fully integrated teams with team representation by all stakeholders	5.1	5.6, 5.7
5.2		Cost, performance and attribute specifications for product and process are unambiguous, measurable and agreed to by all stakeholders	5.2	5.2, 5.9
5.3		Product and process design is conducted from a life-cycle systems approach, fully adhering to DFM/DFA principles and consistent with lean principles	5.3	5.1, 5.4
5.4		Product design and process capability parameters are set to be as robust as possible, consistent with good business practice	5.4	5.5
5.5		Provision is made for continuity of team knowledge for duration of product / process launch	5.5	5.10
5.6		Lead times for product and process design are measured and being continually shortened	5.6	
5.7		Risk management is defined and mitigated		5.3
5.8		Jointly-established targets are set for continuous improvement at all levels and in all phases of the product life cycle		9.4
5.9		Incentives are in place for initiatives that provide beneficial, innovative practices		9.5

Figure A.4 Page 4 of Lean Standard Cross-Reference (SAE 1999a, MIT 1996)

5.10		Incremental product performance objectives are established where possible		12.5
5.11		High risk developments are program managed off critical paths and / or alternatives are provided		12.6
Element 6		***Process / Flow***		
6.1		The work environment is clean, well organized and audited regularly against standard 5S practices	6.1	
6.2		An effective planned preventive maintenance system is in place with the appropriate maintenance conducted at the prescribed frequencies for the all equipment	6.2	1.9
6.3		Bills of material are accurately catalogued and standard operations are accurately routed, timed, and have been value engineered	6.3	12.3
6.4		Value stream is fully mapped and products are physically segregated into like-process streams	6.4	1.8
6.5		Production sequence is load-smoothed to customer pull, and demand is leveled over the manufacturing planning period	6.5	1.8, 12.1
6.6		Process flow is controlled by visual means, internal to the process	6.6	2.1
6.7		Process is in statistical control with capability requirements being met and process variability continually reduced	6.7	11.1, 11.2
6.8		Preventive action, using a disciplined problem solving method is taken and documented in each instance of product or process nonconformance	6.8	6.8
6.9		Production flow commences only upon receipt of shipment order. Process flows at takt time rate, in single unit quantities, to point of customer receipt	6.9	1.6
6.10		Procedures are in place and being followed that result in continually shorted changeover times and smaller lot sizes	6.10	1.4
6.11		Factory layout requires continuous synchronous flow of material and in-factory product travel distance is continually reduced as flow path is improved	6.11	1.7

Figure A.5 Page 5 of Lean Standard Cross-Reference (SAE 1999a, MIT 1996)

6.12		Documented standard work methods are in use that distribute and balance worker loads to eliminate waste throughout the range of expected takt times	6.12	
6.13		The value stream undergoes examination for continuous improvement on a regularly scheduled basis	6.13	12.3
6.14		Models and or simulations are established to permit understanding and evaluation of the flow process		1.1
6.15		The number of flow paths are being reduced		1.2
6.16		Inventory is being minimized through all tiers of the value chain		1.3
6.17		Process owner inspection is being implemented throughout the value chain		1.5
6.18		Make/buy decisions are evaluated as a strategic decision		11.3

Figure A.6 Page 6 of Lean Standard Cross-Reference (SAE 1999a, MIT 1996)

APPENDIX B

QUESTIONNAIRE

University of Pittsburgh School of Engineering
Department of Industrial Engineering

Cell Implementation and Lean Manufacturing Assessment Questionnaire

Background:

The University of Pittsburgh is conducting research in the area of lean manufacturing cell implementation. Quantitative (numerical) data will be collected regarding cell performance within your company. The research also requires the collection of qualitative (subjective) information to fully understand the implementation of lean manufacturing cells within your company. This questionnaire is the method to collect the required information on your experiences with the implementation of lean manufacturing cells. Please provide feedback to every section of the questionnaire. Your responses to the questions will be kept completely confidential and used only in tabulation with others.

Directions:

The questionnaire has three sections. Please follow the directions provided with each section. The first section captures demographic information which will assist in understanding the background of the people that operate the cells. The second section is comprised of cell specific questions with ratings for the importance level and degree of implementation. The third section is comprised of elements of lean best practice with ratings for the importance level and degree of implementation.

Figure B.1 Cover Page of Questionnaire

Section 1: Background Information

Amount of time you've been with the company:	____ years ____ months	
Amount of time you've been with the cell:	____ years ____ months	
Your current role: (circle one)	Capacity Owner	MRP Controller
	Process Improvement	Cell Supervisor
	Technical Lead / ME	Design Engineer
	Operator	Inspector
	Other ______________________	
Your current classification (operators):	__________________________	
Amount of time in classification:	____ years ____ months	

Educational background: (check one)

- ☐ Vocational Technical Coursework
- ☐ GED / High School Diploma
- ☐ Apprentice
- ☐ Journeyman Machinist
- ☐ Some College Coursework
- ☐ Associates Degree
- ☐ Bachelors Degree
- ☐ Masters Degree
- ☐ Other ______________________

	Please circle one	
Were you a member of the initial cell design team (MSE or Blitz Kaizen)?	yes	no
Have additional improvement events been run since the cell was implemented?	yes	no
If there were additional events, have you been involved in those improvement events?	yes	no
Do you understand what the cell needs to produce to satisfy the customer on a monthly basis?	yes	no
Do you understand what the cell needs to produce to satisfy the customer on a weekly basis?	yes	no
Do you understand what the cell needs to produce to satisfy the customer on a daily basis?	yes	no

Figure B.2 Page 1 of Questionnaire

Section 2: Cell Specific Questions

Please rate each element listed in this section in two ways. First, on a scale from 1 (not important) to 5 (most important), rate the importance of the element in achieving the business goals (delivering a quality product on time and at the right cost for the customer). Second, on a scale from 0 (not in place at all or major inconsistencies in implementation) to 3 (fully in place, effectively implemented, and improvements over past 12 months), rate the level of implementation of the element within the cell that you are associated.

		Importance in achieving the business goals					Implementation level within the cell			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
Element 1	***Machines, Equipment, and Outside Services***									
1.1	Machines (especially bottlenecks) are available when required	1	2	3	4	5	0	1	2	3
1.2	Fixtures are available when required	1	2	3	4	5	0	1	2	3
1.3	Tooling and tool holders are available when required	1	2	3	4	5	0	1	2	3
1.4	Consumables (grinding wheels, etc.) are available when required	1	2	3	4	5	0	1	2	3
1.5	Gages and other inspection equipment are available when required	1	2	3	4	5	0	1	2	3
1.6	Gages are calibrated per the calibration schedule and returned to the cell in a timely manner	1	2	3	4	5	0	1	2	3
1.7	Out of cell services (FPI, X-Ray, Heat Treat, etc.) are provided in an agreed turn around time	1	2	3	4	5	0	1	2	3
1.8	Machine and equipment breakdowns are resolved in an expeditious manner	1	2	3	4	5	0	1	2	3

Figure B.3 Page 2 of Questionnaire

		Importance in achieving the business goals					Implementation level within the cell			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
Element 2	***Materials***									
2.1	Raw material is available when required	1	2	3	4	5	0	1	2	3
2.2	Raw material quality is of an acceptable level	1	2	3	4	5	0	1	2	3
2.3	All details for subassembly and / or assembly are available when required	1	2	3	4	5	0	1	2	3
2.4	Containers are provided to minimize metal to metal contact and other quality issues related to part handling	1	2	3	4	5	0	1	2	3
Element 3	***Environment***									
3.1	Lighting is provided at an appropriate level	1	2	3	4	5	0	1	2	3
3.2	Humidity is controlled to minimize the effect on equipment function	1	2	3	4	5	0	1	2	3
3.3	Temperature is is controlled to minimize the effect on equipment function	1	2	3	4	5	0	1	2	3
3.4	The workplace is clean, safe and organized	1	2	3	4	5	0	1	2	3
Element 4	***Methods***									
4.1	Customer demand is placed on the cell via a level schedule	1	2	3	4	5	0	1	2	3
4.2	CNC programs are readily available	1	2	3	4	5	0	1	2	3

Figure B.4 Page 3 of Questionnaire

		Importance in achieving the business goals					Implementation level within the cell			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
4.3	Manufacturing routings are readily available	1	2	3	4	5	0	1	2	3
4.4	Manufacturing routings provide the appropriate level and amount of information	1	2	3	4	5	0	1	2	3
4.5	Inspection routings are readily available	1	2	3	4	5	0	1	2	3
4.6	Inspection routings provide the appropriate level and amount of information	1	2	3	4	5	0	1	2	3
4.7	Setup procedures are readily available	1	2	3	4	5	0	1	2	3
4.8	All nonconformances are addressed in an expeditious manner	1	2	3	4	5	0	1	2	3
4.9	Design changes are communicated to the cell via a process which allows for feedback to ensure design for manufacturability	1	2	3	4	5	0	1	2	3
Element 5	***People***									
5.1	Appropriate level of cell support staffing is in place including a Cell Supervisor, Manufacturing Engineer, Design Engineer, MRP Controller, Capacity Owner, etc.	1	2	3	4	5	0	1	2	3
5.2	Appropriate number, classifications and shift patterns of operators are in place	1	2	3	4	5	0	1	2	3
5.3	Appropriate number, classifications and shift patterns of inspectors are in place	1	2	3	4	5	0	1	2	3

Figure B.5 Page 4 of Questionnaire

		Importance in achieving the business goals					Implementation level within the cell			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
5.4	Outside Operations (FPI, X-Ray, Heat Treat, etc.) are staffed to support cell service requirements	1	2	3	4	5	0	1	2	3
5.5	All salaried personnel associated with the cell have been through the appropriate ERP / SAP training	1	2	3	4	5	0	1	2	3
5.6	A training needs analysis has been carried out for the cell	1	2	3	4	5	0	1	2	3
5.7	A training matrix has been developed for the cell	1	2	3	4	5	0	1	2	3
5.8	Operators and inspectors are permitted to attend training (classroom or on the job) when scheduled per the training plan	1	2	3	4	5	0	1	2	3
5.9	Cell personnel attend work on a regular basis, vacations and sick days are coordinated to ensure coverage	1	2	3	4	5	0	1	2	3
5.10	There is clear communication between shifts (regarding priorities and general coordination)	1	2	3	4	5	0	1	2	3
5.11	The cell personnel operate as a team	1	2	3	4	5	0	1	2	3
5.12	Cell personnel celebrate successes as they are achieved	1	2	3	4	5	0	1	2	3

Figure B.6 Page 5 of Questionnaire

		Importance in achieving the business goals					Implementation level within the cell			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
Element 6	***Cell Measurement and Improvement***									
6.1	Cell personnel monitor part flow via a visual control board or other visual means	1	2	3	4	5	0	1	2	3
6.2	Cell personnel meet regularly (around the control board) to understand customer demand, part flow and address issues that impede flow	1	2	3	4	5	0	1	2	3
6.3	A measurement board is posted within the cell, reflecting key cell business measures (delivery, quality, cost, etc.)	1	2	3	4	5	0	1	2	3
6.4	A cell improvement plan with documented issues, actions, and due dates has been developed via value stream mapping	1	2	3	4	5	0	1	2	3
6.5	The cell team meets regularly to review progress on implementation of improvement plans	1	2	3	4	5	0	1	2	3
6.6	Cell personnel understand what the cell needs to produce to satisfy the customer on a daily basis	1	2	3	4	5	0	1	2	3

Figure B.7 Page 6 of Questionnaire

Section 3: Lean Manufacturing Assessment

Please rate each element listed in this section in two ways. First, on a scale from 1 (not important) to 5 (most important), rate the importance of the element in achieving the business goals (delivering a quality product on time and at the right cost for the customer). Second, on a scale from 0 (not in place at all or major inconsistencies in implementation) to 3 (fully in place, effectively implemented, and improvements over past 12 months), rate the level of implementation of the element within the business unit that you are associated.

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
Element 1	***Management / Trust***									
1.1	Continuous progress in implementing lean operating methods is the organization's primary tool in pursuing its strategic objectives	1	2	3	4	5	0	1	2	3
1.2	Structured policy (business plan) deployment techniques are used to plan the organization's lean deployment actions	1	2	3	4	5	0	1	2	3
1.3	Lean progress targets are defined and have been effectively communicated	1	2	3	4	5	0	1	2	3
1.4	Knowledge of the philosophy and mechanics of lean operation has been obtained and effectively communicated	1	2	3	4	5	0	1	2	3
1.5	The organization's senior managers are actively leading the deployment of lean practices	1	2	3	4	5	0	1	2	3
1.6	Lean progress is reviewed by senior management against planned targets on a regular basis	1	2	3	4	5	0	1	2	3
1.7	Meaningful incentives that reward organization lean progress are in place	1	2	3	4	5	0	1	2	3

Figure B.8 Page 7 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
1.8	Individual manager's performance is evaluated and rewarded relative to lean progress	1	2	3	4	5	0	1	2	3
1.9	A non-blaming, performance oriented, process-driven organization atmosphere exists	1	2	3	4	5	0	1	2	3
1.10	There is a regular, direct personal involvement by senior managers with the operating workforce concerning lean practices	1	2	3	4	5	0	1	2	3
1.11	Consistent policy for disposition of individuals made surplus by lean progress in is place and followed	1	2	3	4	5	0	1	2	3
1.12	No employee has reason to perceive their livelihood to be jeopardized by contributing to organization lean progress	1	2	3	4	5	0	1	2	3
1.13	Management has chosen to adhere to lean principles in the face of short term operating objectives inconsistent with lean progress	1	2	3	4	5	0	1	2	3
1.14	Stable and cooperative relationships are built both internally and externally	1	2	3	4	5	0	1	2	3
1.15	Benchmarking studies are performed	1	2	3	4	5	0	1	2	3
Element 2	***People***									
2.1	Adequate training resources are provided and paid employee training time is made available	1	2	3	4	5	0	1	2	3

Figure B.9 Page 8 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
2.2	The training syllabus includes training in the lean-specific tools and measurables suitable to the organization's needs, at all levels within the organization	1	2	3	4	5	0	1	2	3
2.3	Training is conducted as scheduled, records of training are kept and training effectiveness is regularly evaluated	1	2	3	4	5	0	1	2	3
2.4	Organization is structured to correspond to the structure and sequence of the value chain through the enterprise	1	2	3	4	5	0	1	2	3
2.5	Each employee participates in the structure as corresponds to his role	1	2	3	4	5	0	1	2	3
2.6	Labor and employment policies and agreements are in place which allow lean progress within the organization	1	2	3	4	5	0	1	2	3
2.7	Team authority level and accountability level is clearly defined	1	2	3	4	5	0	1	2	3
2.8	Employee development through Quality Circles / Continuous Improvement teams is encouraged and supported at all levels	1	2	3	4	5	0	1	2	3
2.9	Team is accountable for continuous improvement in its segment of the value chain	1	2	3	4	5	0	1	2	3
2.10	Team decision making authority and authority to act corresponds to the level of accountability	1	2	3	4	5	0	1	2	3
2.11	Management does not supersede team decisions and actions when within the team's authority	1	2	3	4	5	0	1	2	3

Figure B.10 Page 9 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
2.12	Management supports team decisions and actions with required resources, consistent with good business practices	1	2	3	4	5	0	1	2	3
2.13	Career and skill development programs are established for each employee	1	2	3	4	5	0	1	2	3
2.14	Maintenance, certification and upgrading of critical skills is ensured	1	2	3	4	5	0	1	2	3
2.15	Workforce capabilities and needs are analyzed to provide for balance of breadth and depth skills / knowledge	1	2	3	4	5	0	1	2	3
2.16	Jobs are broadened to facilitate the development of a flexible workforce	1	2	3	4	5	0	1	2	3
2.17	Hand offs and approvals within and between line and support activities are minimized	1	2	3	4	5	0	1	2	3
2.18	The environment and a well-defined processes are provided for expedited decision-making	1	2	3	4	5	0	1	2	3
2.19	Experience-generated learning is captured, communicated and applied	1	2	3	4	5	0	1	2	3
Element 3	***Information***									
3.1	Adequate and accurate operating data and information is available to members of the organization as needed	1	2	3	4	5	0	1	2	3
3.2	Knowledge is shared across the organization	1	2	3	4	5	0	1	2	3

Figure B.11 Page 10 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
3.3	Data collection and its use are the responsibility of the individuals most closely associated with that part of the process	1	2	3	4	5	0	1	2	3
3.4	The operating financial system is structured to present correctly the results of lean progress	1	2	3	4	5	0	1	2	3
3.5	Databases are linked for key functions throughout the value chain	1	2	3	4	5	0	1	2	3
3.6	Documentation is minimized while ensuring necessary data traceability and availability	1	2	3	4	5	0	1	2	3
Element 4	***Supplier / Organization / Customer Chain***									
4.1	Both suppliers and customers participate at the earliest possible stage in the organization's undertaking of a product / process / project	1	2	3	4	5	0	1	2	3
4.2	Both suppliers and customers are appropriately represented on the organization's product / process / project teams	1	2	3	4	5	0	1	2	3
4.3	Both suppliers and customers participate in regular reviews of product / process / project progress	1	2	3	4	5	0	1	2	3
4.4	Effective incentives for supplier, organization and customer are in place that reward shared performance improvements or cost reductions	1	2	3	4	5	0	1	2	3
4.5	The interchange of knowledge from and within the supplier network occurs	1	2	3	4	5	0	1	2	3

Figure B.12 Page 11 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
4.6	Multi-year contracting is used wherever possible	1	2	3	4	5	0	1	2	3
4.7	Programs are structured to absorb changes with minimal impact	1	2	3	4	5	0	1	2	3
4.8	Continuous information flow and feedback from stakeholders is provided	1	2	3	4	5	0	1	2	3
4.9	The contract process is optimized to be flexible to learning and changing requirements	1	2	3	4	5	0	1	2	3
4.10	Relationships are created and maintained with customers in requirements generation, product design, development and solution-based problem solving	1	2	3	4	5	0	1	2	3
Element 5	***Product***									
5.1	Product and process design is conducted by fully integrated teams with team representation by all stakeholders	1	2	3	4	5	0	1	2	3
5.2	Cost, performance and attribute specifications for product and process are unambiguous, measurable and agreed to by all stakeholders	1	2	3	4	5	0	1	2	3
5.3	Product and process design is conducted from a life-cycle systems approach, fully adhering to Design for Manufacturability (DFM)/Design for Assembly (DFA) principles and consistent with lean principles	1	2	3	4	5	0	1	2	3
5.4	Product design and process capability parameters are set to be as robust as possible, consistent with good business practice	1	2	3	4	5	0	1	2	3

Figure B.13 Page 12 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
5.5	Provision is made for continuity of team knowledge for duration of product / process launch	1	2	3	4	5	0	1	2	3
5.6	Lead times for product and process design are measured and being continually shortened	1	2	3	4	5	0	1	2	3
5.7	Risk management is defined and mitigated	1	2	3	4	5	0	1	2	3
5.8	Jointly-established targets are set for continuous improvement at all levels and in all phases of the product life cycle	1	2	3	4	5	0	1	2	3
5.9	Incentives are in place for initiatives that provide beneficial, innovative practices	1	2	3	4	5	0	1	2	3
5.10	Incremental product performance objectives are established where possible	1	2	3	4	5	0	1	2	3
5.11	High risk developments are program managed off critical paths and / or alternatives are provided	1	2	3	4	5	0	1	2	3
Element 6	***Process / Flow***									
6.1	The work environment is clean, well organized and audited regularly against standard 5S practices	1	2	3	4	5	0	1	2	3
6.2	An effective planned preventive maintenance system is in place with the appropriate maintenance conducted at the prescribed frequencies for the all equipment	1	2	3	4	5	0	1	2	3

Figure B.14 Page 13 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
6.3	Bills of material are accurately catalogued and standard operations are accurately routed, timed, and have been value engineered	1	2	3	4	5	0	1	2	3
6.4	Value stream is fully mapped and products are physically segregated into like-process streams	1	2	3	4	5	0	1	2	3
6.5	Production sequence is load-smoothed to customer pull, and demand is leveled over the manufacturing planning period	1	2	3	4	5	0	1	2	3
6.6	Process flow is controlled by visual means, internal to the process	1	2	3	4	5	0	1	2	3
6.7	Process is in statistical control with capability requirements being met and process variability continually reduced	1	2	3	4	5	0	1	2	3
6.8	Preventive action, using a disciplined problem solving method is taken and documented in each instance of product or process nonconformance	1	2	3	4	5	0	1	2	3
6.9	Production flow commences only upon receipt of shipment order. Process flows at takt time rate, in single unit quantities, to point of customer receipt	1	2	3	4	5	0	1	2	3
6.10	Procedures are in place and being followed that result in continually shorted changeover times and smaller lot sizes	1	2	3	4	5	0	1	2	3

Figure B.15 Page 14 of Questionnaire (SAE 1999a, MIT 1996)

		Importance in achieving the business goals					Implementation level			
		not important	somewhat important	important	very important	most important	not in place or major inconsistencies in implementation	in place with minor inconsistencies	fully in place and effectively implemented	fully in place with improvement over past 12 mos
6.11	Factory layout requires continuous synchronous flow of material and in-factory product travel distance is continually reduced as flow path is improved	1	2	3	4	5	0	1	2	3
6.12	Documented standard work methods are in use that distribute and balance worker loads to eliminate waste throughout the range of expected takt times	1	2	3	4	5	0	1	2	3
6.13	The value stream undergoes examination for continuous improvement on a regularly scheduled basis	1	2	3	4	5	0	1	2	3
6.14	Models and or simulations are established to permit understanding and evaluation of the flow process	1	2	3	4	5	0	1	2	3
6.15	The number of flow paths are being reduced	1	2	3	4	5	0	1	2	3
6.16	Inventory is being minimized through all tiers of the value chain	1	2	3	4	5	0	1	2	3
6.17	Process owner inspection is being implemented throughout the value chain	1	2	3	4	5	0	1	2	3
6.18	Make/buy decisions are evaluated as a strategic decision	1	2	3	4	5	0	1	2	3

Figure B.16 Page 15 of Questionnaire (SAE 1999a, MIT 1996)

Is there anything else you would like to tell us about your experience in the design, implementation or operation of lean manufacturing cells within your company? Please use this space for that purpose.

Thank you!

Your contribution to this research effort is greatly appreciated. If you would like a summary of the results of the research, please print your name and address on the back of the return envelope (NOT on the questionnaire). We will see that you get the information.

Please check to see that you have answered all the questions and return the questionnaire in the envelope provided.

This form is coded only to avoid sending you reminders once you have returned the completed questionnaire. Your answers will be kept confidential and used only in tabulation with others.

form # ________

University of Pittsburgh, School of Engineering, Department of Industrial Engineering
1048 Benedum Hall, Pittsburgh, PA 15261 (412) 624-9830

Figure B.17 Page 16 of Questionnaire (SAE 1999a, MIT 1996)

APPENDIX C

COMPANY PARTICIPATION LETTER

[redacted]

[redacted]

July 12, 20[redacted]

Dr. Kim LaScola Needy
University of Pittsburgh
Department of Industrial Engineering
1041 Benedum Hall
Pittsburgh, PA 15261

Dear Dr. Needy:

This letter is written to indicate [redacted] interest in the research project entitled "A Systematic Consideration of the Human Element in the Implementation of Lean Manufacturing Cells" sponsored by the University of Pittsburgh Industrial Engineering Department.

[redacted] operates as a stand-alone member of the [redacted] designs, manufactures, markets and supports gas turbine engines and components for aviation, marine and industrial applications. To support our mission and align with our parent company [redacted] has embarked on the process of transitioning our manufacturing and assembly facilities from functional to lean manufacturing cellular layouts over the past few years. As with all improvement initiatives, this process in ongoing.

Like many manufacturers that compete in the global marketplace, we are finding that our employees, and more specifically their technical and "human" skills are one of the most flexible and least understood factors in the process. Your research will provide us with a new perspective and understanding of these factors.

We will consider providing coded data from our manufacturing operation to validate the research models as well as offer to ask employees to fill out questionnaires on a voluntary basis. Of course, we would also request that the source of data not be disclosed, in order to protect our competitive advantage in the market along with our anonymity.

In closing, it is refreshing to support research that is relevant, current, and very much needed in the field of lean manufacturing. If I can be of assistance, please do not hesitate to contact me at [redacted]

Sincerely,

[redacted]
General Manager
Manufacturing Operations and Assembly

[redacted]
HR Generalist Director
Operations

Figure C.1 Letter Agreeing Participation in Study from Field Study Company

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