Analysis of Worker Assignment Policies on Production Line Performance Utilizing a Multi-skilled Workforce

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(ABSTRACT)

Lean production prescribes training workers on all tasks within the cell to adapt to changes in customer demand. Multi-skilling of workers can be achieved by cross-training. Cross-training can be improved and reinforced by implementing job rotation. Lean production also prescribes using job rotation to improve worker flexibility, worker satisfaction, and to increase worker knowledge in how their work affects the rest of the cell. Currently, there is minimal research on how to assign multi-skilled workers to tasks within a lean production cell while considering multi-skilling and job rotation.

In this research, a new mathematical model was developed that assigns workers to tasks, while ensuring job rotation, and determines the levels of skill, and thus training, necessary to meet customer demand, quality requirements, and training objectives. The model is solved using sequential goal programming to incorporate three objectives: overproduction, cost of poor quality, and cost of training. The results of the model include an assignment of workers to tasks, a determination of the training necessary for the workers, and a job rotation schedule. To evaluate the results on a cost basis, the costs associated with overproduction, defects, and training were used to calculate the net present cost for one year. The solutions from the model were further analyzed using a simulation model of the cell to determine the impact of job rotation and multi-skilling levels on production line performance. The measures of performance include average flowtime, work-in-process (WIP) level, and monthly shipments (number produced).

Using the model, the impact of alternative levels of multi-skilling and job rotation on the performance of cellular manufacturing systems is investigated. Understanding the effect of multi-skilling and job rotation can aid both production managers and human resources managers in determining which workers need training and how often workers should be rotated to improve the performance of the cell. The lean production literature prescribes training workers on all tasks within a cell and developing a rotation schedule to reinforce the cross-training. Four levels of multi-skilling and three levels of job rotation frequency are evaluated for both a hypothetical cell and a case application in a relatively mature actual production cell. The results of this investigation provide insight on how multi-skilling and job rotation frequency influence production line performance and provide guidance on training policies.

The results show that there is an interaction effect between multi-skilling and job rotation for flowtime, work-in-process, in both the hypothetical cell and the case application and monthly shipments in the case application. Therefore, the effect of job rotation on performance measures is not the same at all levels of multi-skilling thus indicating that inferences about the effect of changing multi-skilling, for example, should not be made without considering the job rotation level. The results also indicate that the net present cost is heavily influenced by the cost of poor quality. The results for the case application indicated that the maturity level of the cell influences the benefits derived from increased multi-skilling and affects several key

characteristics of the cell. As a cell becomes more mature, it is expected that the quality levels increase and that the skill levels on tasks normally performed increase. Because workers in the case application already have a high skill level on some tasks, the return on training is not as significant. Additionally, the mature cell has relatively high quality levels from the beginning and any improvements in quality would be in small increments rather than in large breakthroughs.

The primary contribution of this research is the development of a sequential goal programming worker assignment model that addresses overproduction, poor quality, cross-training, and job rotation in order to meet the prescription in the lean production literature of only producing to customer demand while utilizing multi-skilled workers. Further contributions are analysis of how multi-skilling level and job rotation frequency impact the performance of the cell. Lastly, a contribution is the application of optimization and simulation methods for comprehensively analyzing the impact of worker assignment on performance measures.

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Chapter 1 : Introduction and Scope of Research

As market and customer expectations change and increase, organizations and managers require quick responses and more precise information to successfully compete in an ever-evolving environment. These customer expectations have also led to a paradigm shift in that the organization no longer determines the price of the product or service based on their desired profit, but the customer strongly influences the price (Monden, 1998). This forces companies to reduce the cost of providing the product or service in order to make a profit.

Large-scale organizational change initiatives have helped some organizations adapt to changes in their environments and improve competitive performance and capabilities. Unfortunately, these types of initiatives do not always lead to success, but may lead instead to waste of valuable resources, obstacles in implementing change, and lack of desired results. Pascale, Millemann, and Gioja (1997) propose that such failures occur because organizations have difficulty in identifying, prioritizing, and aligning their resources in order to address factors that contribute to sustainable organization transformations.

Many organizational transformation initiatives or approaches have been proposed and utilized to improve competitive performance in the last fifteen years, including Total Quality Management (TQM), ERP information systems, and Business Process Reengineering (BPR) (Jones, Hines and Rich, 1997). Jones *et al.* (1997) suggest three reasons for the failure of these solutions: 1) they rely on the batch-and-queue processing method, 2) they do not modify the manner through which the organization fundamentally operates, and 3) changes are only made inside an organization when they need to be made by all enterprises along its supply chain. In order to address these problems a broader philosophy and approach is necessary.

Lean production concepts appear to address these problems and organizational needs. Lean production (or lean thinking) is increasingly being implemented as a potential solution for many organizations (Karlsson and Ahlstrom, 1996). Womack *et al.* (1990) stated in 1990 that none of the European automotive industries had adopted lean production, while eight years later, Panizzolo (1998) discussed the lessons learned from 27 lean manufacturers in

Italy. Additional evidence of the growth of lean production is the number of conferences, seminars, and academic programs associated with lean production. Some of these include the University of Michigan's Lean Manufacturing Certificate Program (University of Michigan, 2001), the Lean Enterprise Institute's training series on lean production and value stream mapping (Lean Enterprise Institute, 2001), and the increase in lean production topics at the Institute of Industrial Engineers Annual Conference (Institute of Industrial Engineers, 1999, 2000, 2001, 2002, 2003). One method organizations use to transform to lean production is cellular manufacturing (Needy, Norman, Bidanda, Tharmmaphornphilas, Ariyawongrat and Warner, 2001). The following sections provide background information on lean production. The remainder of this chapter includes the research question, objectives, and strategy; the contributions of this research; and the organization of the rest of the document.

1.1 Lean Production

Womack and Jones (1996) use the term "lean thinking" to refer to the thought process of Taiichi Ohno and to the collection of methods that describe the Toyota Production System, which evolved to lean production. Although a number of principles and tools appear to be derived from just-in-time, group technology, cellular manufacturing, and world class manufacturing, lean production has emerged as an approach that aims to integrate different tools to focus on the elimination of waste and produce products that meet customer expectations (Hines and Taylor, 2000; Womack and Jones, 1996). Womack and Jones (1996) emphasize seven types of waste identified by Taiichi Ohno for the Toyota Production System: 1) overproduction, 2) waiting, 3) excess transportation, 4) inadequate processes, 5) unnecessary inventory, 6) unnecessary motion, and 7) defective products.

James-Moore and Gibbons (1997) define key areas of focus within the lean production approach:

- flexibility,
- waste elimination,
- optimization,
- process control,
- people utilization.

These areas of focus and the underlying principles can be operationalized using specific tools and techniques. Key principles within lean production are process standardization (Monden, 1993; Ohno, 1988; Womack *et al.*, 1990; Womack and Jones, 1996), waste removal (Monden, 1993; Ohno, 1988; Rother and Shook, 1999; Womack *et al.*, 1990; Womack and Jones, 1996), multi-skilled workers (Monden, 1993; Ohno, 1988), and one-piece flow (Emiliani, 1998; Monden, 1993; Sekine, 1992). Practices and tools prescribed within lean production to achieve these principles are 5S (simplify, straighten, scrub, stabilize, sustain) (Emiliani, 1998; Monden, 1993; Rother and Shook, 1999), standard work (Monden, 1993; Womack and Jones, 1996), cellular manufacturing (Black, 1991; Needy *et al.*, 2001; Ohno, 1988), just-in-time (JIT) (Monden, 1993; Ohno, 1988; Womack *et al.*, 1990; Womack and Jones, 1996), single minute exchange of dies (SMED) (Sekine, 1992; Shingo, 1997; Womack and Jones, 1996), and value stream mapping (Hines, Lamming, Jones, Cousins and Rich, 2000; Hines and Taylor, 2000; Rother and Shook, 1999).

Companies transforming to lean production often use cellular manufacturing as a means of transition. The human element of the transition to cellular manufacturing (and then to lean production) however, is often overlooked in the design of the cells (Needy *et al.*, 2001). A commonly cited cause of the failure of advanced manufacturing technologies is insufficient attention to the human element (Chung, 1996). A strategic competitive advantage can be achieved by placing greater importance on the human element in the design and manufacturing process (Jordan, 1997; Norman, Tharmmaphornphilas, Needy, Bidanda and Warner, 2002). Askin and Estrada (1999 as cited in Askin and Fitzpatrick, 2001) found that worker training was a top concern when implementing cells, yet numerous researchers have found that the human element in cellular manufacturing has mostly been ignored (Askin and Fitzpatrick, 2001; Askin and Huang, 1997; Kher, 2000; Norman, Tharmmaphornphilas, Needy, Bidanda and Warner, 2000; Norman *et al.*, 2002; Warner, Needy and Bidanda, 1997).

Needy *et al.* (2001) state that a human-centered philosophy combined with a systematic approach for the selection and training of workers is critical to the success of implementing lean production. James-Moore and Gibbons (1997) identify people utilization and flexibility as two of the key focus areas of lean production. Proper worker assignment and training can improve both the utilization and the flexibility of workers. Two areas within lean production that are addressed in this research are worker assignment and multi-skilling of workers. Specifically this research will develop a systematic approach for assigning multi-skilled workers to tasks while also providing information on which workers need training.

1.2 Cellular Manufacturing

Lean production is often implemented by initially transitioning to cellular manufacturing (Needy *et al.*, 2001). Within cellular manufacturing, a family of parts is processed on a dedicated group of machines or manufacturing processes, often referred to as cells (Singh, 1993). These groups of parts, products, and processes are created using group technology. Group technology is a manufacturing approach that utilizes the similarities in products and activities to group machines, processes, and workers into cells (Selim, Askin and Vakharia, 1998; Singh, 1993). A key feature of cellular manufacturing is flexibility. Flexibility in workers, demand capabilities, and products allows organizations to adapt to changing environments. Training workers to be multi-skilled creates worker flexibility. Multi-skilled workers provide flexibility, not only for worker assignment, but also for demand. As customer demand increases or decreases, multi-skilled workers can be reassigned within the cell or assigned to other areas in the organization that require additional workers (Black, 1991; Monden, 1998; Ohno, 1988; Womack and Jones, 1996).

Lean production cells are typically U-shaped or rectangular and lend themselves to 1) smooth (balanced) work flow across a wide variety of products, 2) elimination of waste, 3) high quality output, 4) flexible operation, and 5) low total unit production costs (Black, 1991; Womack and Jones, 1996). There are numerous studies in the literature for determining how machines should be assigned to the cells. The majority of these research efforts have been developed to improve the grouping of parts and machines into cells (Askin and Vakharia, 1990; e.g., Burbidge, 1975; King and Nakornchi, 1982; Singh, 1993; Suresh, 1991, 1992). A number of researchers argue that the human element in cellular manufacturing has primarily been ignored (Askin and Fitzpatrick, 2001; Askin and Huang, 1997, 2001; Kher, 2000; Norman *et al.*, 2000; Warner *et al.*, 1997). In a survey of industry, worker training was one of the top concerns when implementing cells (Askin & Estrada, 1999 as cited in Askin and Fitzpatrick, 2001). Training, therefore, is an important aspect of transitioning to cellular manufacturing (Askin and Fitzpatrick, 2001).

The following sections discuss issues related to managing human resources in a lean cell. Job rotation reinforces skills on tasks workers are trained on; improves worker flexibility, productivity, and satisfaction; and reduces injuries due to ergonomic concerns (Carnahan, Redfern and Norman, 1999, 2000; Friedrich and Kabst, 1998; Monden, 1993). Worker assignment provides a method for determining which multi-skilled workers should be assigned to what tasks to achieve a set goal (i.e., meet customer demand, reduce lateness, etc.) and is not typically done in a systematic manner (Askin and Huang, 2001; Needy *et al.*, 2001).

1.2.1 Multi-skilling

Multi-skilling allows workers to be more flexible when addressing changes in demand, worker assignment, and absenteeism. Multi-skilling of workers can be achieved by cross-training. Cross-training is a process in which workers are trained on the tasks, duties, and responsibilities of multiple tasks in a specific work cell or work area. Cross-training provides workers with a clear understanding of the entire team function (Volpe, Cannon-Bowers, Salas and Spector, 1996), develops flexibility (Black, 1991; Ohno, 1988; Womack and Jones, 1996), increases employee productivity (Majchrzak and Wang, 1996), and increases worker satisfaction (Foegen, 1993). Lean production and cellular manufacturing prescribe the use of cross-trained workers for these reasons. Cross-training can be improved and reinforced by implementing a job rotation policy (Monden, 1993).

1.2.2 Job Rotation

Job rotation is a method by which workers are systematically transferred between various areas of responsibility during an established time period (Friedrich and Kabst, 1998). The 2001 American Society for Training and Development (ASTD) State of the Industry Report states that 88% of the 365 firms who participated in the study use job rotation as a work practice (Van Buren, 2001). Yet, there has been minimal research on when and how to develop and implement a job rotation schedule. After workers have been trained on the tasks within the cell a job rotation schedule is needed (Monden, 1993). The job rotation schedule is developed based on the number of workers, absenteeism, number of tasks, and how often workers are to be rotated. In some cells, workers may be rotated as often as every hour, whereas others may be rotated on a weekly basis (Monden, 1993).

As with multi-skilling, job rotation has been found to improve worker flexibility and worker satisfaction (Friedrich and Kabst, 1998; Monden, 1993), raise worker productivity (Friedrich and Kabst, 1998), improve worker communication (Monden, 1993), and increase worker knowledge in how their work affects the rest of the organization (Friedrich and Kabst, 1998; Monden, 1993). Additionally, job rotation has been found to reduce injuries due to repetitive lifting (Carnahan *et al.*, 1999, 2000). The lack of research on rotating workers among tasks however, limits the understanding of how job rotation affects productivity measures. That is, there is little understanding in how job rotation affects the operational measures of a lean production cell.

1.2.3 Worker Assignment

The use of cellular manufacturing requires the use of multi-skilled workers who are assigned to perform multiple tasks within the cell (Black, 1991; Min and Shin, 1993; Norman *et al.*, 2000; Singh, 1993). Wemmerlov and Hyer (1989) state that in 75% of the organizations surveyed, operators either volunteered for the job and were later approved by management or were directly assigned by management. Warner *et al.* (1997) state that workers are typically assigned to cells based solely on their knowledge of how to operate the required machines. Askin and Huang (2001) agree that worker groups are generally assembled in an informal manner with emphasis placed on the technological equipment.

Models that include cross-training evaluate the current skill level of the employee and based on other inputs (required skill levels of tasks, training time allowed, training budget, etc.), determine which employees should receive training on which tasks. One benefit of cross-training is that multiple workers have the capability to perform a task, but without utilizing these skills on some regular basis, the skills will degrade (Ginzburg and Dar-El, 2000; Jaber and Bonney, 1998; Kher, Malhotra, Philipoom and Fry, 1999). Workers should perform tasks for which they are trained on a regular basis to prevent skill loss. A worker assignment model that addresses overproduction, poor quality, cross-training, and job rotation needs to be developed in order to meet the prescription in a lean production environment of only producing to customer demand while utilizing multi-skilled workers.

The models that have been developed for worker assignment typically use one of several objective functions. The models attempt either to reduce costs (e.g., training, cost of quality, etc.), meet customer demand, meet customer due date, minimize lack of fit between the worker and the assigned tasks, minimize lack of synergy, or maximize profitability. Current models include constraints for cross-training and skill level for each task to be performed, but do not include a job rotation schedule or penalize a cell for producing more than the customer demands. In a lean production environment, producing to customer demand, and not exceeding it, is a desirable practice.

1.3 Research Questions and Objectives

This research contributes to the understanding of how human resource policies can affect production performance measures in a lean production cell. The overall question for this research is:

How do alternative multi-skilling and job rotation policies impact production performance in a lean production cell?

Three objectives are used to address the research question. The first objective is to formulate a worker assignment model (WAM) that minimizes overproduction, cost of poor quality, cost of training, and includes policies for multi-skilling and job rotation. The second objective of this research is to investigate how the management of human resources, specifically alternative job rotation and worker multi-skilling levels impact production performance in a hypothetical cell. The third objective is to apply the worker assignment model to an actual manufacturing cell and investigate the impact of job rotation and multi-skilling on production performance. These objectives are described in more detail below.

1) Formulate a worker assignment model that includes multi-skilling and job rotation.

Current worker assignment models tend to focus on productivity and training costs. The models do not use other measures of the manufacturing line's performance such as quality, inventory levels, and flowtime. In this research, a worker assignment model is formulated that addresses customer demand by minimizing overproduction. Additionally the use of multi-skilling and job rotation policies are included as constraints. The three primary objectives of the model are minimizing overproduction, cost of poor quality, and cost of training. The output of the model is an assignment of multi-skilled workers to tasks to ensure job rotation and training opportunities.

2) Investigate the impact of alternative multi-skilling and job rotation policies on a hypothetical manufacturing cell's performance.

First, the worker assignment model developed in this research is executed for a hypothetical cell. The output from the worker assignment model is then entered into a simulation model of the hypothetical manufacturing cell to analyze the impact of alternative levels of multi-skilling and job rotation on the manufacturing cell's performance. A simulation model is developed to correspond to the hypothetical cell (number of workers, number of tasks, processing times, and quality levels) used in the worker assignment model. The simulation is used to determine the effects of multi-skilling and job rotation policies on the cell's performance measures. The primary measures of performance are flowtime, work-in-process, and monthly shipments. The output of both the worker assignment model and the simulation model are used to compare high levels of multi-skilling to lower levels, and more frequent job rotation to less frequent. The experimental design used for this analysis is described in Chapter 4.

3) Apply the worker assignment model to a case application.

Most of the research on worker assignment models either gives no example application of the model or applies the model to a theoretical example only. In this research, the worker assignment model developed is applied to an actual manufacturing cell and an existing simulation model of the cell is used to determine how well the worker assignment model succeeds in an actual setting. The simulation developed for the actual production line is used to determine the impact of job rotation and multi-skilling policies on an actual product line's performance.

1.4 Research Strategy

In order to achieve the above objectives, the following research activities are conducted:

1. Survey the literature to determine how current research assigns workers to tasks and to determine how values for the model parameters are set.

2. Develop a worker assignment model that incorporates multi-skilling, job rotation, and customer demand while minimizing overproduction, cost of poor quality, and cost of training.
3. Apply the worker assignment model to a hypothetical cell.
    a. Develop an experimental plan to investigate the impact of multi-skilling and job rotation on a hypothetical cell's performance measures.
    b. Execute the model to develop an assignment of workers to tasks and job rotation schedule.
    c. Simulate the results to explore the effect of multi-skilling and job rotation on flowtime, work-in-process, and monthly shipments.
4. Apply the worker assignment model to an actual manufacturing cell.
    a. Develop an experimental plan to investigate the impact of multi-skilling and job rotation on an actual cell's performance measures.
    b. Execute the model to develop an assignment of workers to tasks and job rotation schedule.
    c. Simulate the results to explore the effect of multi-skilling and job rotation on flowtime, work-in-process, and monthly shipments.
5. Analyze and discuss the results of the hypothetical and case application.
6. Discuss conclusions and areas for future research.

1.5 Contributions of this Research

This research contributes to the body of knowledge for worker assignment models by applying it in a lean production environment. Currently, there is minimal research on how to assign multi-skilled workers to tasks within a lean production cell. Additionally, job rotation has only been included in worker assignment models as a means to reduce the risk of injury due to lifting tasks (Carnahan *et al.*, 1999, 2000) or to reduce exposure to noise (Tharmmaphornaphilas, Green, Carnahan and Norman, 2003) versus for flexibility in production or worker satisfaction. This research results in a worker assignment model that could be run on a periodic basis to determine where workers should be assigned, which workers need additional training, and how often workers should be rotated through the tasks they are trained. Potentially, the performance of the product line could be improved by utilizing the model when inputs to the model (i.e., customer demand, training budget, required training time, etc.) change. Additionally, use of the model could influence the selection of human resource policies concerning training and skill levels.

1.6 Organization of this Document

The remainder of this document is organized as follows. Chapter 2 reviews the literature for evaluating and describing worker assignment models. Chapter 3 describes the worker assignment model formulation. Chapter 4 describes the experimental design, provides operational definitions for the performance measures, describes how the worker assignment model and discrete event simulation can be used in conjunction, provides a description of the generic cell and the simulation model of the actual production line. Chapter 5 presents and discusses the results for the hypothetical cell. Chapter 6 presents and discusses the results for the case application. Chapter 7 provides conclusions and describes future areas for research.

Chapter 2 : Review of the Literature

This research studies the effect of multi-skilling and job rotation on a lean production cell. Although previous worker assignment models have been proposed for cellular manufacturing, they do not include overproduction or job rotation, nor do all of them require multi-skilled workers to perform multiple tasks. Additionally, none of the previous research has included a schedule for worker assignment for a time intervals within a larger time period. That is, the models provide worker assignment schedules but do divide the schedule into smaller time increments (e.g., two-hour periods within a working month). The study of worker assignment and worker multi-skilling within a lean production environment, and the application of this research within an actual lean production cell differentiates this research from previous worker assignment research. In the following sections, the previous research on multi-skilling, worker assignment, and job rotation is discussed.

2.1 Multi-skilling

Cross-training, the process by which workers become multi-skilled, has been recognized as a tool for increasing production flexibility (Park, 1991). Park (1991) uses a simulation model to evaluate the effect of five different cross-training levels on a hypothetical dual resource constrained (DRC) job shop. A DRC job shop has fewer workers than machines and requires both to be available when processing a job. DRC job shops are limited by both machine and worker capabilities. The model assigns workers to five workstations based on varying levels of cross-training. Each of the workstations (cells) has two identical machines with a common queue and one worker and can produce multiple products. The number of workstations a worker is cross-trained for determines the level of cross-training. The number of workstations workers were capable of working at determined the cross-training level (i.e., for Level 2 the worker was trained to work at two workstations, Level 3 was three workstations, etc.). However, the training level on each machine within the workstation is not considered. Five dispatching rules are used to determine the sequence of jobs at each of the five workstations: 1) earliest due date, 2) shortest processing time, 3) first in first served, 4) modified operating due date, and 5) critical ratio. The performance measures for the model are: percentage of jobs late, mean tardiness, variance of tardiness, mean wait time, variance of wait time, and mean number of labor transfers per day. Workers are allowed to move from one workstation to another to improve the performance measures but are not forced to rotate otherwise.

Park (1991) found that cross-training is better than no cross-training (defined as being trained to work at only one workstation) for all of the performance measures across all of the dispatching rules. Park (1991) concludes that the lowest level of cross-training (can work at two workstations) is the best alternative, because the differences between the levels of cross-training are not significant.

Brusco and Johns (1998) propose the development of a model for determining the workforce staffing costs associated with different cross-training policies. The model is formulated as a single objective mathematical model to minimize total workforce staffing costs. The model assumes an eight-hour workday divided into multiple planning periods. Brusco and Johns (1998) evaluate 36 different configurations of cross-training classified into eight structures. The structures are based on three characteristics: the number of secondary skill classes for which an employee is cross-trained, the productivity of cross-trained employees when working in their secondary skill classes, and whether the configuration matrix is symmetric or asymmetric. A primary skill class denotes an employee's skill class for employment purposes, while a secondary skill class denotes other classes for which the employee is cross-trained. A symmetric configuration implies that if employees within a skill class j are cross-trained to work in skill class k at a certain productivity rate, then employees in skill class k are cross-trained to work in skill class j at the same productivity level. Each employee has full competency, or 100% productivity, in one of four skill classes. Employees also have 50% productivity in two of the three secondary skills. The four skill classes are: millwrights, pipefitters, electricians, and instrument mechanics. The findings from Brusco and Johns (1998) are consistent with Park (1991) in that the greatest cost benefit from cross-training was obtained by cross-training on only one additional skill. Additionally, Brusco and Johns (1998) found that cross-training employees at 50% productivity (50% competency) for secondary skills attained 86.9% of the cost savings available from cross-training employees to 100% productivity, or fully competent. The example is for a maintenance service department at a paper mill. The products are the services provided by each of the skill classes. Employees are not forced to rotate to the secondary skill classes for which they have training.

The above models discuss how cross-training levels, and therefore multi-skilling, affect performance measures. Both models find minimal cross-training provides the greatest benefit. However, Park (1991) only considers workstations with two machines each and allows workers to transfer between stations. The following models discuss worker assignment in terms of cells comprised of more than two tasks.

2.2 Worker Assignment

In practice, worker groups are often assembled in an ad hoc manner when cellular manufacturing is implemented. Workers are generally treated as an afterthought with the emphasis placed on the grouping of equipment instead (Askin and Huang, 2001). The research that has been conducted considering human skills can be separated into two categories: assigning workers after cell formation and assigning cells and workers simultaneously.

2.2.1 Post Cell Formation Worker Assignment

After the formation of cells, workers can be assigned to the cells based on several factors, including the following:

- assignment based on productivity (Suer, 1996; Suer and Bera, 1998),
- assignment based on cycle time (Nakade and Ohno, 1999)
- assignment based on technical and human skills (Askin and Huang, 1997; Norman *et al.*, 2000; Norman *et al.*, 2002; Warner *et al.*, 1997)
- assignment based on training needs and job fit (Askin and Fitzpatrick, 2001; Askin and Huang, 2001) and,

The following sections describe the worker assignment models based on productivity, the model based on cycle time, the models based on skills, and lastly the models based on training needs and job fit.

2.2.1.1 Worker Assignment Based on Productivity

Suer (1996) develops a worker assignment algorithm that includes two assignment models to use when cells are labor-intensive rather than machine-intensive. Worker assignment and involvement within a labor-intensive cell is a major role in the performance of the cell (Suer, 1996). The first model assigns multi-skilled workers to existing cells while the second model finds the optimal operator assignment within a cell. The first model determines the alternative cell configurations (the number of operators assigned to each task type) by independently running the model for alternative operator levels (total number of operators to be assigned) of each product and uses mixed-integer programming to maximize the production rate. The model considers multiple products and cells, but each product can only be assigned to a single cell. In the example of an actual production area, the number of workers is set at 15, 20, and 25 with six products being processed on five tasks.

The second model uses integer programming to find the worker assignment and load the cell. The problem is formulated as a single objective mathematical model to maximize the production of the cell utilizing the least number of operators. The model assumes that the number of cells needed has been determined, that alternative worker levels (or number of workers needed in the cell) have been determined, and that a product (multiple products are considered) can only be assigned to a single cell. The time required to produce a product in the cell is calculated by dividing the customer demand by the production rate determined in the first model. Worker assignment within cells is affected by several factors such as the maximum number of operations, maximum number of workers, available space, etc. The maximum number of operators needed is determined by the number of operations in the cell. The maximum number of operators assigned is limited by the available space, operator skill levels, span of control, machine availability, or a combination of these factors (Suer, 1996).

Suer (1996) found that the first model does not require re-solving unless operator levels or processing times change. The second model, however, must be solved whenever there is a change in customer demand.

Suer and Bera’s (1998) models are an expansion of Suer's (1996) models that allows multiple products to be assigned to multiple cells (lot-splitting) in the second algorithm. The first model of the expanded algorithm is identical to the first model proposed by Suer (1996). The expanded second model includes the second model proposed by Suer (1996) plus lot-splitting and set-up times have been included. To allow lot-splitting, the product assignment variable is allowed to take on non-integer values rather than being limited to zero (0) or one (1). Two additional constraints are added to account for setup times. When setup times are negligible lot-splitting is beneficial (Suer and Bera, 1998). The expanded models used the same example of an actual production area as the original models.

While these models address producing to maximize productivity, they fail to address the fact that the cell may be able to produce more than the customer demands. Both models operate under the assumption that the number of operators per cell is known, but fail to address the operators' skill level for each of the tasks within the cell. The models do not include objectives for training workers or for job rotation. Cost of scrap and cost of training are also not included in the models.

2.2.1.2 Worker Assignment Based on Cycle Time

Nakade and Ohno (1999) formulate a model to optimize worker allocation within a single cell in such a manner as to minimize overall cycle time with the minimum number of workers that satisfies customer demand. The model considers a hypothetical U-shaped production cell using J multi-function workers and K machines to produce multiple products. Each multi-skilled worker operates multiple machines and visits each machine once for each unit of production. While the model assigns workers to tasks, neither worker skill level nor the number of tasks the worker is capable of performing is considered. This model assumes workers have all the required skills to do all jobs within the cell, but does not address training, customer demand, or job rotation.

2.2.1.3 Worker Assignment Based on Technical and Human Skills

Askin and Huang (1997) develop and compare two models for determining worker training and assignment for a reconfigured facility. The facility was converted to cellular manufacturing from a process-oriented configuration. Each cell is dedicated to a part family and has an associated set of required skills. Askin and Huang (1997) assume that the employees have the skills required to operate all equipment within the cell. In addition to the skills necessary to operate the cell, Askin and Huang (1997) provide examples of operator, administrative, team, and leadership skills. The objective of both models is to minimize the training costs associated with assigning a pool of workers to multiple cells. The Basic Assignment and Aggregate Training Model determines the cell assignment for each worker, ensures each cell has the necessary amount of skill, and gives an aggregate training schedule. The model does not provide a detailed schedule for each worker or ensure that some workers are not overly relied upon. The Individual Assignment and Training Model determines the cell assignments, the task assignments within the cell, as well as limiting the amount of training each worker can receive. While the models allow worker training and include a cost of training, they do not include a cost of poor quality associated with a lack of training, a method for addressing job rotation, or a method for addressing customer demand.

Warner, Needy, and Bidanda (1997) propose a five-step model to assess workers' skills and then assign workers to cells based on technological and human skills. Each cell is for a part family. The five steps of the model are:

1. Identify technological and human skills required for the cellular manufacturing system.
2. Determine the metrics for each of the skills.
3. Develop a model that results in the assignment of workers to cells with some predictive knowledge of the cell's performance.
4. Compare the performance of the proposed model with the current performance.
5. Use feedback from the model for continuous improvements.

Simply identifying the skills required to operate machines within the cell provides the list of technological skills. Technological skills can be easily measured by hands-on methods or certification. The human skills depend upon the type of work group used by the organization. An appropriate instrument(s) is needed to measure the human skills. Warner *et al.* (1997) state that cells, tasks, skills, and workers have a hierarchical relationship. Each cell has tasks that are required in order to manufacture or assemble the product. Each task has associated skills that are required to complete the task. Tables 2.1 through 2.3 give examples of these relationships.

Financial, worker, and operational measures can be used to determine cell performance. Example measures are performance to cost, worker satisfaction, performance to schedule, throughput, machine utilization, and setup time reduction (Warner *et al.*, 1997). The feedback provided by the measures is then used to determine the training required for each employee. The performance measures can be improved by training workers to have either more skills or more in-depth training of a particular skill. This model uses matrices and performance measures to determine what worker skills need to be improved. There is no mathematical basis behind the assignment of the workers. The model does, however, allow leeway in what performance measures can be chosen, so that it can be generalized across all types of organizations. Job rotation is not explicitly addressed in the research.

Table 2.1: Example Cell to Task Matrix[1] (adapted from Warner *et al.*, 1997)

	Cell		
Task	Cell 1	Cell 2	Cell 3
Turning			
Broaching			
Testing			

Table 2.2: Example Task to Skill Matrix[2] (adapted from Warner *et al.*, 1997)

	Task		
Skill	Turning	Broaching	Testing
Technical			
Verbal			
Teamwork			

Table 2.3: Example Skill to Worker Matrix[3] (adapted from Warner *et al.*, 1997)

	Skill		
Worker	Technical	Verbal	Teamwork
Worker A			
Worker B			
Worker C			

Norman *et al.* (2000; 2002) propose a mathematical model to determine the assignment of multi-skilled workers within a single cell based on technical and human skills. The example skills provided by Norman *et al.* (2000; 2002) are similar to the skills given by Warner *et al.* (1997). The objective of the model is to maximize profit, where profit is based on productivity, quality costs, and training costs. Productivity is based on the throughput a worker of a given skill level can produce. Quality costs include costs due to rework and scrap. Training costs are incurred for any additional training necessary to improve worker

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skills in order to increase productivity or reduce quality costs. Each cell is dedicated to a part family. Hypothetical cells with varying numbers of workers and tasks were evaluated. While this model includes productivity, cost of poor quality, and cost of training, it does not prevent overproducing or force workers to rotate to all tasks they are trained to perform.

2.2.1.4 Worker Assignment Based on Training Needs and Job Fit

Askin and Huang (2001) propose a mathematical model that assigns multi-skilled workers to multiple cells based on the workers' current skill levels and the training requirement necessary to operate all the tasks within the cells. The model is a single-objective model that combines the cost of worker training; loss due to lack of fit between individual's conative, cognitive, and physical abilities and the tasks to which they are assigned; and deviation from the ideal team synergy (Askin and Huang, 2001). The model does not assign workers to tasks within the cell. Askin and Huang (2001) evaluated multiple hypothetical cells with a varying number of workers and tasks in the cell.

Askin and Fitzpatrick (2001) extend the model proposed by Askin and Huang (2001). The first extension by Askin and Fitzpatrick (2001) limits the amount of time a worker spends in training. The second extension of the model forms a single team from a pool of qualified workers (Askin and Fitzpatrick, 2001). This Labor Pool Extraction Model assumes that the part-machinery cell has already been formed. The model also assumes that the set of necessary employee skills has been determined and the workers with those skills are available. The model then selects which employees should be assigned to the cell, but does not assign the workers to tasks within the cell.

The models developed by Askin and Huang (2001) and Askin and Fitzpatrick (2001) address worker training and its associated cost, but do not address how to rotate the workers through the tasks for which they have been cross-trained in order to prevent loss of skill. The models also do not address customer demand or cost of quality. Both models assume that a cell is dedicated to a part family. Askin and Huang (2001) and Askin and Fitzpatrick (2001) investigated the performance of the solution method (e.g., CPLEX, greedy heuristic, beam search, etc.) rather than the performance of the cell.

2.2.2 Simultaneous Formation of Cells and Worker Assignment

Min and Shin (1993) state that cellular manufacturing will not be successful unless human and machine cells are formed simultaneously. They also state that a new approach is required to handle multiple objectives instead of single objectives such as maximization of part similarities, maximization of total productivity, minimization of total bottleneck cost, minimization of intercellular handling costs, etc.

The model Min and Shin (1993) developed assumes that multi-skilled workers with different levels of job skills are available for assignment. The objectives of the model are to maximize part similarities, match operator skills to parts, minimize total machine processing times, and minimize total labor costs. The model considers multiple products assigned to multiple cells. The hypothetical example consisted of two part families with a total of three workers to be assigned to tasks within each cell.

Due to the computational difficulty in solving the model, Min and Shin (1993) propose a sequential heuristic that decomposes the model into two smaller problems: formation of the machine cells and assignment of workers to cells to form the corresponding human cell. The first step of the model is to solve the reduced goal programming formulation for the cell formation. The second step of the model is to assign appropriate part-machine values and solve the reduced formulation for worker assignment. The model developed by Min and Shin (1993) does not address cost of training, worker training, or job rotation. Worker skill levels, therefore, cannot be improved to see if a better solution could be obtained from increased training.

2.3 Job Rotation

Monden (1993) states than after workers have been trained on the tasks within the cell a job rotation schedule is needed. The assignment models in the literature that include job rotation rotate workers for ergonomic issues. Carnahan *et al.* (1999; 2000) rotates workers to reduce the injuries due to lifting tasks, while Tharmmaphornphilas *et al.* (2003) rotate workers to reduce exposure to occupational noise.

Carnahan *et al.* (1999; 2000) develop and compare an integer programming model and a genetic algorithm approach that minimizes the Job Severity Index (JSI) (Liles, 1986). The JSI assesses the potential for back injury. The model minimizes the JSI for four gender capacity groups, across four lift tasks, and over eight time periods. Carnahan *et al.* (1999; Carnahan *et al.*, 2000) found that the genetic algorithm provided more solutions in a shorter amount of computational time than the integer programming model.

Tharmmaphornphilas *et al.* (2003) develop a mathematical programming model to minimize the maximum daily noise dose among all workers. The data for the model were collected from a sawmill operation at a cabinet manufacturer. The sawmill operation consisted of eleven workers performing eleven tasks. The sawmill operation had been operating on a three-job rotation policy. That is, only three of the tasks were considered for job rotation. Tharmmaphornphilas *et al.* (2003) propose including all eleven tasks in the rotation schedule. The eleven-job rotation schedule reduced the maximum daily noise dose by 58.8% and the time-weighted average noise exposure level by 3.8 dB. The next section provides a summary of the worker assignment models and summarizes the contributions of this research.

2.4 Summary and Contributions of this Research to Worker Assignment Model Research

Suer (1996) and Suer and Bera (1998) propose mixed integer and integer programming models to achieve optimal operator and product assignment to labor-intensive cells. The models only maximize productivity, while not addressing issues such as job rotation or cross-training. Askin and Huang (1997) formulated an integer model for minimizing the total training cost when converting a functionally organized environment to a cellular manufacturing environment. While the model includes cross-training, it does not address job rotation or customer demand. Warner *et al.* (1997) researched relevant factors (both technological and human interaction) for assigning workers to manufacturing cells. The model uses matrices to determine which workers have the required skills to perform the tasks within the cell. The model does not address other issues such as customer demand, training, or job rotation. Norman *et al.* (2000; 2002) expand these technological and human factors proposed in Warner *et al.* (1997) into a mixed integer model that optimizes the effectiveness of the organization. Organizational effectiveness is comprised of the productivity, output quality, and training costs associated with a worker assignment schedule (Norman *et al.*, 2000; Norman *et al.*, 2002). These models do not address the issues of meeting customer demand or job rotation. Askin and Huang (2001) and Askin and Fitzpatrick (2001) formulate single objective models for assigning workers to cells and then tasks within the cell. While the models address worker training and its associated cost, they do not address how to rotate the workers, customer demand, or cost of quality. Min and Shin (1993) formulate a multi-objective model for grouping both machines and workers to a cell, but training, customer demand, nor job rotation are considered in their model.

Lean production advocates producing to customer demand (Monden, 1993; Monden, 1998; Rother and Shook, 1999; Womack and Jones, 1994). The above models do not address the fact that cells may be able to produce more than customer demand. Current models include constraints for cross-training and skill level for each task to be performed, but they do not include a penalty for overproduction, nor do they provide a worker assignment and job rotation schedule. Models that include minimizing customer demand while utilizing multi-skilled workers need to be developed in order to meet lean production's prescribed practice of only producing to customer demand.

The worker assignment model proposed in this research attempts to extend the previous work performed in worker assignment by addressing some of these shortcomings. The objectives of the model are to 1) minimize overproduction, 2) minimize the cost of poor quality, and 3) minimize the cost of training. The model also extends the worker assignment research into lean production by using multi-skilled workers to produce to customer demand while minimizing overproduction in both a hypothetical cell and in an actual cell. Additionally, the model provides a worker assignment and job rotation schedule. Finally, the model is solved using sequential goal programming to prioritize the three objectives.

Chapter 3 : Model Formulation

This chapter presents a mathematical model for determining worker assignment to tasks while considering multi-skilling and job rotation in a lean production environment. The model is an extension of various models from the current literature. The objectives of the model are to:

1) minimize overproduction,

2) minimize the cost of poor quality, and

3) minimize the cost of training.

Overproduction is producing more product than the customer demands. Cost of poor quality is the cost of producing defects or scrap. Training costs are incurred when additional training is needed to enhance worker skills to reach productivity and quality levels necessary to meet customer demand. Productivity is defined as the throughput that a worker of a given skill level produces when assigned to a particular task. The objective of the model is to minimize the deviation from each of the three goals. The model determines which workers need additional training in each of the tasks and where workers should be assigned, given the cross-training level, job rotation level, and current levels of worker training. The following sections describe the assumptions associated with the model, define the model notation, and provide the math programming formulation.

3.1 Assumptions

Several assumptions require additional explanation. The assumptions requiring more explanation include the corresponding section number. The following assumptions are made for the worker assignment and simulation models:

1. Decisions are made for a single production cell.
2. The production cell is dedicated to a single product family.
3. Machines have been previously assigned to the production cell.
4. The capabilities and capacity of each machine type are known and are considered constant.

5. The processing times for all part types on different machine types are known for all operators.
6. Any set-up times are included in the processing times.
7. Machine breakdowns are not considered.
8. Absenteeism is not considered.
9. A worker can only train up one skill level per task per working month.
10. Production is maintained when a worker is in training by either a replacement worker or by the worker if on-the-job training is being used.
11. Only final product is considered as overproduction; work-in-process is not included as overproduction in the model.

The following section describes the model parameters, decision variables, and objectives:

3.2 Model Parameters

The following parameters are used in the worker assignment model.

i	Index of workers	$i = 1, 2, ..., I$
j	Index of tasks	$j = 1, 2, ..., J$
l	Index of skill levels	$l = 1, 2, ..., L$
t	Index of time periods	$t = 1, 2, \ldots, T$
C_{Budget}	Maximum permissible total training costs;	
C_{ijl}	Cost to train worker i from skill level $l\text{-}1$ to a skill level of l for task j;	
CQ_j	Per unit cost poor quality at task j;	
D	Customer demand;	
MSL_i	Multi-skilling level for worker i (the number of tasks for which worker i is trained);	
NS_j	Necessary skill level for task j. That is, in order to perform task j it is necessary for the worker to have at least this skill level value;	
P_{jl}	Productivity if task j is performed with skill level l;	
pr_{ijt}	Proportion of *takt* time required by worker i to perform task j during time period t;	
q_{jl}	Quality level associated with performing task j with skill level l;	

s_{jl} Skill level for task j at level l (If task j has three levels (1, 2, 3), then $s_{j1} = 1$; $s_{j2} = 2$; $s_{j3} = 3$);

TA_i Maximum allowable time that worker i can spend in training;

tr_{ijl} Time required to train worker i from skill level l-1 to skill level l for task j;

T_{total} Total available training time for all of the workers in the cell;

w_{ij} Initial skill level that worker i has for task j; and

u_{ij} $\begin{cases} 1 \text{ if worker } i \text{ has the required skill for task } j \text{ (such that } w_{ij} > NS_j) \\ 0 \text{ Otherwise} \end{cases}$

3.3 Decision Variables

The following decision variables are used in the worker assignment model:

$$z_{ijlt} = \begin{cases} 1 & \text{if worker } i \text{ is assigned to task } j \text{ at skill level } l \text{ during assignment period } t, \\ 0 & \text{Otherwise} \end{cases}$$

$$y_{ijt} = \begin{cases} 1 & \text{if worker } i \text{ is assigned to task } j \text{ during assignment period } t \text{ at any skill level}, \\ 0 & \text{Otherwise} \end{cases}$$

$$v_{ijl} = \begin{cases} 1 & \text{if worker } i \text{ assigned to task } j \text{ at skill level } l \text{ during any assignment period}, \\ 0 & \text{Otherwise} \end{cases}$$

3.4 Model Objective Function and Constraints

The three goals of the model include:

1 Minimize overproduction

2 Minimize cost of poor quality

3 Minimize cost training

The objective function is:

$$Min \quad z = d_1^+; d_2^+; d_3^+ \tag{3.1}$$

Where d_1^+ is the positive deviation from minimizing overproduction; d_2^+ is the positive deviation from minimizing the cost of poor quality goal, and d_3^+ is the positive deviation from minimizing the cost of incremental training. The objective is to minimize the deviations from each goal.

Five types of constraints are included in the model:

- Goal constraints;
- Constraints to ensure each task is performed and each worker performs at least one task;
- Constraints to ensure customer demand and minimum skill levels are met;
- Constraints to address training issues; and
- A constraint to ensure workers are rotated between tasks.

These constraints are described in more detail in this section.

The following three goal constraints are associated with the deviation variables

$$\left(\left(\sum_i \sum_l \sum_t \left(P_{Nl} \bullet z_{iNlt} - P_{Nl} \bullet z_{iNlt}\left(1 - q_{Nl}\right)\right)\right) - D\right) - d_1^+ = 0 \tag{3.2}$$

$$\sum_i \sum_j \sum_l \sum_t \left(z_{ijlt} \bullet P_{jl} \bullet \left(1 - q_{jl}\right) \bullet CQ_j\right) - d_2^+ = 0 \tag{3.3}$$

$$\left(\sum_i \sum_j \sum_l v_{ijl} \bullet C_{ijl}\right) - d_3^+ = 0 \tag{3.4}$$

Equation (3.2) minimizes producing more units than the customer demands. The number of units produced is only counted at the last station. All other stations produce work-in-process that is not considered when calculating the number of complete units produced. Units lost due to poor quality reduce the total number of units produced. Equation (3.3) reflects the number of units lost due to poor quality and calculates the associated cost for producing a defective unit. For Equations (3.2) and (3.3), the skill index (*l*) for (q_{jl}) is determined by the maximum value of the initial skill level the worker has for a task or the skill level parameter that results in a non-zero answer for the worker assignment decision variable. For example, if Worker 1 has an initial skill level of 3 on Task 6 (w_{16} = 3) and the worker assignment model assigns Worker 1 to perform Task 6 at a skill level of 2 (z_{162t} = 1), then the quality level (q_{jl}) used is that for skill level 3. Equation **Error! Reference source not found.** reflects the cost of training workers to enhance their skill levels and minimizes the cost of training throughout the working month.

A set of constraints are included to ensure that each task in the cell is performed and that each worker performs at least one task but not more than their multi-skilling level (MSL) as follows:

.
$$\sum_{l} z_{ijlt} \le y_{ijt} \quad \forall i \in I, \forall j \in J, \forall t \in T \tag{3.5}$$

$$\sum_{i} y_{ijt} = 1 \quad \forall j \in J, \forall t \in T \tag{3.6}$$

$$\sum_{j} y_{ijt} \ge 1 \quad \forall i \in I, \forall t \in T \tag{3.7}$$

$$\sum_{j} y_{ijt} \le MSL_i \quad \forall i \in I, \forall t \in T \tag{3.8}$$

$$\sum_{j} pr_{ijt} \bullet y_{ijt} \le 1 \quad \forall i \in I, \forall t \in T \tag{3.9}$$

Equation (3.5) ensures that if worker i is assigned to task j during time t, then the assignment only occurs at one skill level. Equation (3.6) ensures that each task j is assigned to a single worker i during each time period t. Equation (3.7) ensures that each worker i will be assigned to at least one task j during each time period t. Equation (3.8) limits the number of tasks j a worker i can be assigned during each time period t, to be no greater than the multi-skilling level (e.g., MSL = 3 then the worker can do at most three tasks). Equation (3.9) ensures that worker i will not be assigned to more than full-time duties during each time period t. Within a lean production cell the total processing time for a worker to cycle through all assigned task(s) must be less than the *takt* time. *Takt* time is the unit production pace that must be met to match customer requirements (Rother and Shook, 1999). Therefore, the proportion of time a worker spends on a task is determined by dividing the processing time by the *takt* time. The total cycle time for a worker cannot be greater than 100% of *takt* time.

The following constraints are included to ensure that minimum skill levels for tasks and customer demand are met:

$$\sum_{i} \sum_{l} z_{ijlt} \bullet s_{jl} \ge NS_j \quad \forall j \in J, \forall t \in T \tag{3.10}$$

$$\left(\sum_{i} \sum_{l} \sum_{t} P_{jl} \bullet z_{ijlt} - P_{jl} \bullet z_{ijlt} \left(1 - q_{jl} \right) \right) \ge D \quad \forall j \in J \tag{3.11}$$

Equation (3.10) ensures that the worker i assigned to task j during time period t meets the minimum skill level requirement for that task. The skill index (l) for (s_{jl}) is determined by the maximum value of the initial skill level the worker has for a task (w_{ij}) and the current skill index (l) value. Equation (3.11) ensures that customer demand is met at each task. As with equations (3.2) and (3.3), the skill index (l) for (q_{jl}) is determined by the maximum value of the initial skill level the worker has for a task (w_{ij}) or the skill level parameter that results in a non-zero answer for the worker assignment.

A set of constraints limits the amount of time any given worker can spend in training, both individually and totally for the cell, as well as controlling the training budget and the number of levels a worker can train on a task as follows:

$$\sum_t z_{ijlt} \le v_{ijl} * T \quad \forall i \in I, \forall j \in J, \forall l \in L \tag{3.12}$$

$$\sum_t z_{ijlt} \ge v_{ijl} \quad \forall i \in I, \forall j \in J, \forall l \in L \tag{3.13}$$

$$\sum_j \sum_l tr_{ijl} \bullet v_{ijl} \le TA_i \quad \forall i \in I \tag{3.14}$$

$$\sum_i \sum_j \sum_l tr_{ijl} \bullet v_{ijl} \le T_{total} \tag{3.15}$$

$$\sum_i \sum_j \sum_l C_{ijl} \bullet v_{ijl} \le C_{Budget} \tag{3.16}$$

$$z_{ijlt} \bullet s_{jl} - 1 \le w_{ij} \quad \forall i \in I, \forall j \in J, \forall l \in L, \forall t \in T \tag{3.17}$$

Equation (3.12) ensures that worker i cannot be in training for task j at any skill level l for more than the total number of time periods T. Equation (3.13) ensures that worker i can not be in training for task j for skill level l if the worker has not been assigned to task j during some time period t. Equation (3.14) ensures that each worker i does not receive more training than their permissible total training days. Equation (3.15) ensures that the total time spent on training by all workers does not exceed the total number of training days permitted. Equation (3.16) ensures that the total amount spent on training workers does not exceed the budget that has been allocated for training. Equation (3.17) prevents workers from being trained more than one level above their current skill level on a task in the time period T.

The following constraint is included to make sure workers perform all tasks for which they are trained;

$$u_{ij} - \sum_{t} y_{ijt} \leq 0 \quad \forall i \in I, \forall j \in J \tag{3.18}$$

Equation (3.18) ensures that if worker i is trained on task j, that worker must perform that task at least once during the total time period T.

The mathematical model described above is unique in that it is a single objective, multiple goal model that minimizes overproduction; addresses training; and includes job rotation. While previous models have addressed training or job rotation, they are single period models and do not include constraints for minimizing or controlling the total amount workers are allowed to produce. This model provides a worker schedule that can be used by a manager to determine where workers should be assigned over the next time period T and who should receive training on what tasks.

Chapter 4 : Solution Approach and Analysis

In the previous chapter, a sequential goal programming model for assigning workers to tasks while considering multi-skilling and job rotation within a cell is developed. To evaluate the impact of alternative levels of multi-skilling and job rotation on the performance of a cell, the model was solved for a hypothetical cell and an existing cell of a research sponsor. For both cells, an experimental design (described in Section 4.3.2 and 4.4.2) was developed using the level of multi-skilling and job rotation as the factors of analysis. The worker assignment model was executed for each combination of the multi-skilling and job rotation levels. The output from the sequential goal programming worker assignment model was then entered into a simulation model of the cell to evaluate the cell's performance for the levels of multi-skilling and job rotation.

The following sections describe the solution approach and how the research questions are analyzed using optimization and simulation. Following these descriptions are a discussion of the hypothetical cell and the values associated with the decision variables and parameters used. Then, the same information is discussed for the case application.

4.1 Solution Approach for Worker Assignment Model

The worker assignment model is solved using sequential goal programming. Sequential goal programming is an extension of goal programming (GP) developed by Ignizio (1985) for solving strictly linear goal programming models. The basic intent of sequential goal programming is to separate the model into a related sequence of single-objective models. Ignizio (1985) provides the following sequence for developing the sequential goal program:

1. Establish the goal programming formulation and set k = 1 (where k = 1, …, K).
2. Establish the mathematical model for priority level 1 alone.
3. Solve the single-objective problem associated with priority level k via any appropriate algorithm. Let the optimal solution be designated as u_k^*.
4. Set k = k + 1. If k = K, go to step 6. Otherwise, proceed to step 5.

5. Establish the equivalent single-objective model for the next priority level. The constraints for this model include constraints that maintain the optimal solution for the previous priority levels. Return to step 3.
6. The solution vector associated with the last single-objective model is the optimal solution to the original goal programming model.

Ignizio (1985, p. 83) states "that this algorithm is applicable to *any* type of GP model (i.e., linear, integer, or nonlinear)." In this research, CPLEX Solver is used to solve and analyze the sequential goal programming model.

The worker assignment schedule from the model was implemented in a simulation model of the cell to further analyze the effect multi-skilling and job rotation have on a cell. The simulation model emulated the worker assignment model in production flow, worker assignments, and quality levels. The performance measures for the simulation model are flowtime, work-in-process, and monthly shipments. Flowtime is the amount of time between the entry of the part into the system and exit from the system, and is only calculated for completed units. Work-in-process is measured as all parts that have been started, but have yet to be finished. This includes any parts currently being processed and any parts in queues waiting to be processed. Monthly shipments are the total number of parts completed in the 20-day time period.

4.2 Analysis of the Research Questions

Using the results of the worker assignment model and the simulation model, the overall research question investigated is:

> *How do alternative multi-skilling and job rotation policies impact production performance in a lean production cell?*

The overall research question is separated into six questions, one for each of the three goals in the optimization model and one for each of the three performance measures in the simulation model. The optimization model attempts to minimize overproduction, cost of poor quality, and cost of training for different levels of multi-skilling and job rotation frequency. The simulation model investigates how levels of multi-skilling and job rotation frequency affect flowtime, WIP, and monthly shipments. The following six research questions are investigated for both the hypothetical cell and case application:

1. How do alternative multi-skilling and job rotation policies impact overproduction in a lean production cell? Overproduction is the production of more product than the customer demands, and is calculated only at the last task of the cell. The number of units produced is calculated after accounting for any defects or scrapped units. Production at all other tasks is considered work-in-process.
2. How do alternative multi-skilling and job rotation policies impact the cost of poor quality in a lean production cell? The cost of poor quality is the cost of producing defects or scrap. The cost of poor quality increases as the unit is processed through subsequent tasks. That is, a unit scrapped at Task 5 would have a higher cost of poor quality than a unit scrapped at Tasks 1, 2, 3, or 4.
3. How do alternative multi-skilling and job rotation policies impact the cost of training in a lean production cell? Training costs are a function of the additional necessary training to enhance worker skills to improve productivity and quality. Productivity is defined as the throughput that a worker of a given skill level produces when assigned to a particular task.
4. How do alternative multi-skilling and job rotation policies impact flowtime in a lean production cell? Flowtime is defined as the time required for a unit to be processed through the cell. Flowtime is calculated only for units that have been completed. Any unit that is scrapped has a replacement unit that starts back at Task 1. Flowtime for a unit that was scrapped and had a replacement unit be completed is the total time both the scrapped unit and the replacement unit were in the cell. That is, if a unit is scrapped at Task 5 and a replacement unit is then completed the flowtime is the time the scrapped unit was in the system before it was scrapped plus the time it took the completed unit to be processed through all tasks.
5. How do alternative multi-skilling and job rotation policies impact work-in-process in a lean production cell? Work-in-process is defined as all units in the system that have not been completed.
6. How do alternative multi-skilling and job rotation policies impact monthly shipments in a lean production cell? Monthly shipments is defined as all units that have been processed through the last task of the cell.

Table 4.1 summarizes the data analysis methods for each of the research questions. For each performance measure from the worker assignment model, the results are tabulated and then grouped by multi-skilling level and job rotation frequency to determine if any patterns emerged. To further analyze the results, the net present cost (NPC) for a one-year period is calculated for each configuration of multi-skilling and job rotation level to evaluate the results on a cost basis. The NPC is comprised of the cost of the current multi-skilling level, the cost of overproduction, the cost of poor quality, and the incremental cost of training workers. The cost of the current multi-skilling level is determined by totaling the cost for workers to reach their current level of training from an unskilled state.

Table 4.1: Summary of Overall Research Questions and Data Analysis Methods

Research Model	Data Analysis Method
Worker Assignment Model (Research Questions 1 – 3)	1. Tabulation by factor to determine patterns across or within each factor. 2. Net present cost analysis considering cost of overproduction, cost of poor quality, and incremental cost of training.
Simulation Model (Research Questions 4 – 6)	1. Lowess plot of data to determine if there is an interaction effect between multi-skilling and job rotation. 2. Levene's test for homogeneity of variances to determine if the variances are equal. 3. Univariate analysis of variance with three dependent variables (Flowtime, WIP, Monthly Shipments) and two factors, Multi-skilling Level and Job Rotation Frequency, having four and three levels, respectively. 4. Tamhane's T2 post-hoc analysis to determine if levels of one factor were significantly different within each level of the other factor. 5. Tamhane's T2 post-hoc analysis to determine if experiments were significantly different.
Both Models (All Research Questions)	Subjective rating to evaluate the overall performance of the models.

For each performance measure from the simulation model, the results are plotted using a Lowess plot. The Lowess plot is a robust locally weighted regression method for smoothing scatterplots. The value of the line fit to the data is calculated using a weighted, least squares method. The weight for each point decreases as the distance from that point to the fitted line increases. That is, points near the fitted line are weighted more heavily than points occurring farther out from the line. This procedure guards against outliers distorting the fitted points (Cleveland, 1979, 1981). After evaluating the Lowess plot, Levene's test for homogeneity of variances was used to evaluate the assumption that the variances of each performance measure were equal. Levene's test for homogeneity of variances conducts "an ANOVA on the *differences* between each case and the mean for that variable, rather than for the *value* of that variable itself" (George and Mallery, 1999 p. 217). Levene's test showed that there are non-homogeneous variances and therefore caution must be taken when interpreting the results from the ANOVA and an appropriate post-hoc test must be selected.

To evaluate the impact of multi-skilling and job rotation on performance measures, the appropriate post-hoc test is used. Tamhane's T2 test is a conservative pairwise comparison based on the Welch solution, the Šidák inequality, and the t-test (SPSS, 2001; Tamhane, 1979). The results were also analyzed using ANOVA and Tamhane's T2 post-hoc analysis to determine whether there are differences in performance measures for varying multi-skilling levels and job rotation frequency.

Finally, the results for all six performance measures are subjectively rated for an overall evaluation. The performance of each measure was rated as "good," "neutral," or "poor." Observations were then made, based on a count of each rating for multi-skilling and job rotation level.

The following sections discuss the hypothetical cell and the experimental design used for the hypothetical cell, and provides detailed information on the values used for the decision variables and parameters. The cell was treated as a start-up cell, with worker skill levels and quality levels that would be expected during the start-up of a cell like this. Following the discussion of the hypothetical cell is a discussion of the case application.

4.3 Overview of the Hypothetical Cell

The hypothetical cell was developed from the current worker assignment literature, the author's personal experience, and from knowledge of actual practices by industrial research partners. The following sections describe the hypothetical cell and provide detailed information about the experimental design for the worker assignment model and the simulation model.

4.3.1 Description of the Hypothetical Cell

The hypothetical cell produces a single product family. The cell consists of six multi-skilled workers initially capable of performing at least 20% of the ten serial tasks. The cell operates eight hours per day with two fifteen minute breaks and has a monthly demand requirement of 900 units. Assuming 20 operating days per month the daily demand is 45 units per day. A daily demand of 45 units and 450 minutes (480 minutes minus 30 minutes for breaks) of production time per day results in a ten (10) minute *takt* time for the cell. As defined earlier, *takt* time is the unit production pace that must be met to match customer requirements (Rother and Shook, 1999).

While workers may perform multiple tasks at a time, each worker's task content should be below *takt* time. For example, Task 6 takes 9.5 minutes to perform, and there are no tasks that take less than 0.5 minutes, therefore, any worker assigned to Task 6 would only perform that task. However, Task 3 requires 7.8 minutes, and there are several other tasks with processing times less than 2.2 minutes (10 – 7.8 = 2.2) that a worker could also perform at the same time as Task 3. Therefore, the proportion of time a worker performs any single task is determined by dividing the task processing time by the *takt* time. A constraint in the worker assignment model prevents workers from being assigned to greater than 100% of *takt* time. There is a sequence the worker follows when performing the assigned tasks. The worker follows this sequence throughout the rotation period (s)he is assigned to those tasks. The hypothetical cell does not require any set-ups for this product family.

Training is classroom training requiring the worker to be removed from the cell. That is, any worker that is in training is not working on the line. A replacement worker, trained to the level the worker is in training for, performs the task while the worker is in training. There are a number of assumptions that affect the hypothetical cell, but are not assumptions of the worker assignment model or the simulation model. First, there are sufficient resources within the overall organization to replace workers in training. Second, the organization determines which replacement workers are transferred into the cell. Third, the evaluation time period is 20 days or a working month. Fourth, suppliers provide parts as planned with continued good quality. Fifth, workers use any time not performing tasks for clean up and other miscellaneous tasks. The following sections provide detailed information about the experimental design factors and parameters.

4.3.2 Experimental Design for the Hypothetical Cell

The purpose of the experimental design is to determine how the worker assignment model performs under different circumstances and to assess how the goals of the worker assignment model and the performance measures from the simulation model are affected by different levels of multi-skilling and job rotation. The set of variables for the design factors are selected from those affecting the cell configuration. The two most important factors for addressing the research question are: 1) the number of tasks a worker can be assigned (level of multi-skilling), and 2) the frequency of job rotation. The multi-skilling level for an individual worker is the number of tasks within the cell the worker has been trained to perform. The frequency of job rotation is how often within a specified time period workers are rotated between jobs they are trained to perform.

This research uses a full factorial design with four levels of multi-skilling and three levels of job rotation frequency for the worker assignment and simulation models. The worker assignment model investigates the impact different levels of multi-skilling and job rotation have on overproduction, cost of poor quality, and cost of training. The multi-skilling levels are interdependent. That is, the second, third, and fourth multi-skilling levels are developed based on the first multi-skilling level. When increasing to the next higher multi-skilling level (e.g., from the first level to the second level), data for two of the workers from the current level are changed such that they are fully trained on all tasks within the cell. This was continued as the level of multi-skilling was increased until all workers were fully trained on a proportion of the tasks. The worker assignment output from each worker assignment schedule is implemented in a simulation model.

While the worker assignment model is a static model of the system, the simulation model provides a dynamic view of the cell to analyze the impact of alternative multi-skilling and job rotation levels on the cell performance. The simulation model is based on the same information used in the worker assignment model, including the number of workers, tasks, worker productivity rates, quality levels, and customer demand.

The simulation model was verified (see Appendix C) to ensure all aspects matched the output from the worker assignment model and to ensure parts flowed through the cell correctly. That is, the model was checked to ensure the correct workers were performing the correct assigned tasks at the specified quality levels during the specified times.

After verification, the model was executed, and Welch's method was used to determine the warm-up period. The warm-up period was determined to be 860 days. Because the worker assignment model was for a 20-day time period, the simulation model was executed for 880 simulated days with data collected for only the last 20 simulated days. To ensure a 95% confidence interval within ±10% of the mean of the performance measure, 80 replications of the model were executed. The levels of multi-skilling, job rotation frequency, and the other model parameters are described in the following sections.

4.3.3 Values for the Design Factors for the Hypothetical Cell

The values for the design factors for this research were determined from the surveyed literature, the author's experience, and from knowledge of actual practices by industrial research partners. Table 4.2 summarizes the values for the levels of multi-skilling, the frequency of job rotation, the number of tasks or skills required within a cell, and the number of workers per cell used in the worker assignment literature. The table also summarizes the lean production prescriptions for the use of multi-skilled workers and job rotation.

In previous research, levels of multi-skilling are only given in terms of performing a single task at a time or multiple tasks (without a numeric value given). In all but one instance, the worker assignment models match the lean prescription that workers must be capable of performing multiple tasks within a cell. Lean production prescribes training workers on all tasks within the cell to meet any changes in customer demand, thus, this research enabled workers to be trained to the highest level for the highest multi-skilling level. The values for the multi-skilling levels used in this research for the hypothetical cell are shown below:

a. Level 1: all workers are trained on at least 20% of all tasks,
b. Level 2: 33% of all workers are fully trained on all tasks,
c. Level 3: 67% of all workers are fully trained on all tasks, and
d. Level 4: all workers are fully trained on all tasks.

The highest level of multi-skilling for a cell is selected such that all workers are fully trained on all tasks in the cell. The lowest level of multi-skilling is selected such that all workers have minimal levels of cross-training, considered to be one-fifth (or 2) of the tasks in the cell to be consistent with the literature and industry practice. The one-third increase in the number of workers trained on all tasks for the middle levels is set between the maximum and minimum. Next, the second design factor, job rotation frequency, is defined.

Table 4.2: Cell Design Factors in Literature

Literature Type	Publication	Level of Multi-skilling	Frequency of Job Rotation	Number of Tasks or Skills in the Cell	Number of Workers/Cell
Worker Assignment Models	(Suer, 1996; Suer and Bera, 1998)	N/A*	N/A	5	15, 20, 25
	(Min and Shin, 1993)	N/A	N/A	4	3
	(Askin and Fitzpatrick, 2001; Askin and Huang, 1997, 2001)	Can do multiple tasks	N/A	2, 4, 8, 16	2, 8
	(Kher, 2000)	Can do multiple tasks	N/A	4	2
	(Norman *et al.*, 2000; Norman *et al.*, 2002)	Can do a single task	N/A	6	6
	(Nakade and Ohno, 1999)	Can do multiple tasks	N/A	20, 40, 60, 80, 100	N/A
	(Brusco and Johns, 1998)	Can do multiple tasks	N/A	2	1
	(Park, 1991)	Can do multiple tasks	N/A	2	1
	(Tharmmaphornaphilas *et al.*, 2003)	Can do multiple tasks	2.5 hours	11	11
	(Carnahan *et al.*, 1999, 2000)	Can do multiple tasks	Hourly	4	N/A
Lean Prescription	(Monden, 1993)	Must be able to perform all tasks	Daily to multiple times daily	N/A	N/A
	(Womack *et al.*, 1990; Womack and Jones, 1996)	Must be multi-skilled	Daily to multiple times daily	N/A	N/A
	(James-Moore and Gibbons, 1997)	Must be multi-skilled	N/A	N/A	N/A

*N/A indicates the author(s) did not address that factor.

From Table 4.2 it can be seen that the literature for lean production addresses job rotation in broad terms. Carnahan *et al.* (1999; 2000) rotates employees on an hourly basis to prevent injury due to heavy lifting tasks and Tharmmaphornphilas *et al.* (2003) rotates workers every 2.5 hours to reduce noise exposure. This research explicitly defines multiple levels of job rotation and analyzes how these levels affect the cell's performance. The job rotation levels used in this research are:

a. Level 1: workers are rotated on a daily basis, (i.e., every eight hours)
b. Level 2: workers are rotated every four hours, and

c. Level 3: workers are rotated every two hours.

The levels of job rotation frequency are selected such that the workers are rotated after usual breaks in a manufacturing cell in the U.S. With eight-hour rotation, workers are rotated at the beginning of a shift. Four-hour rotation occurs after a mid-shift break and two-hour rotation is after a quarter-shift break. Table 4.3 defines the full factorial design and assigns an experiment number. Next, the values for the design parameters are defined.

4.3.4 Values for the Design Parameters for the Hypothetical Cell

The data provided in Table 4.2, the author's experience, and data from industrial research partners were used to determine the values for the design parameters. The main parameters are: number of workers, number tasks, number of assignment periods, skill levels, minimum task required skill level, customer demand, productivity rate, quality level, individual training time, total training time, and training budget. These design parameters are listed below:

1. The number of workers per cell used in the literature varies from 1 to 25 with an average of 8.5, but excluding Suer (1996) and Suer and Bera (1998) as outliers, the average is 4.3. Suer (1996) and Suer and Bera (1998) are considered outliers because the number of workers is two or more times the number of workers used elsewhere in the literature. Six workers per cell is used in this research.
2. The number of tasks in the cell varies in the literature from 2 to 100, with an average of 21.6, but excluding Nakade and Ohno (1999) as outliers, the average is 5.5. Nakade and Ohno (1999) are considered outliers because the number of tasks is six or more times the number of tasks used elsewhere in the literature. Because the average is equal to the number of workers within the cell (defined as six), a larger number of tasks is required so that workers can be assigned to multiple tasks at a time. The number of tasks per cell is set at ten for the purpose of this research.
3. The literature reviewed on worker assignment models does not apparently include multiple time divisions in the evaluation period. While the models in the literature could possibly be used at the beginning of each rotation frequency interval for assigning workers, this research provides a worker assignment schedule based on the job rotation frequency for a full working month, or 20 days.

Table 4.3: Description of the Full Factorial Design of Experiments

Experiment	Multi-skilling Level	Description	Job Rotation Frequency	Description
1	1	All workers are trained on at least 20% of the tasks	1	8-hour rotation
2	1		2	4-hour rotation
3	1		3	2-hour rotation
4	2	33% (2) of all workers are fully trained on all tasks	1	8-hour rotation
5	2		2	4-hour rotation
6	2		3	2-hour rotation
7	3	67% (4) of all workers are fully trained on all tasks	1	8-hour rotation
8	3		2	4-hour rotation
9	3		3	2-hour rotation
10	4	100% (6) of the workers are fully trained on all tasks	1	8-hour rotation
11	4		2	4-hour rotation
12	4		3	2-hour rotation

4. Most of the literature reviewed, as well as the industrial partner for the actual cell, use four levels to characterize employee skill level. Therefore, the number of skill levels is set to four. The categorization of the levels for the hypothetical cell is shown in Table 4.4.

Table 4.4: Description of Skill Level for Hypothetical Cell

Skill Level	Description of Skill Level
1	Can minimally perform the task
2	Can moderately perform the task
3	Can perform the task
4	Can perform the task and train others to do the task

5. The required skill level for the tasks in the hypothetical cell is generated from a discrete uniform distribution between 2 and 3, DU[2-3]. The development of the randomly generated parameters for the hypothetical cell is described in detail in the next section.
6. The literature in this area addresses customer demand either in the objective function or not at all. Using customer demand without a constraint to prevent overproduction allows workers, and therefore the cell, to produce while not considering the impact overproduction may have on inventory costs, space requirements, etc. As discussed

earlier, the customer demand level is set to 900 units per month or 45 units per day, representing a *takt* time of 10 minutes.

7. The productivity rate is the production level for each employee at each of the skill levels. The productivity rate for each skill level at each rotation frequency for the hypothetical cell is shown in Table 4.5. The productivity rate for the lowest skill level is chosen such that workers assigned at the lowest skill level are able to produce to customer demand. The increasing productivity rates at the higher skill levels are developed such that the highest rates could overcome any underproduction due to quality losses. The productivity rates at the four-hour and two-hour rotation frequencies are calculated by dividing the eight-hour rates by two and four, respectively.
8. The quality level associated with each skill level is also shown in Table 4.5. Based on Norman *et al.* (2002), the quality level associated with the highest skill level is set at 100%. Lower levels of quality for lower skill levels are set decrementing from 100%. The lowest level is set at 88% based on the assertion that a lean cell has 45% – 90% fewer defects than a non-lean cell (Liker, 1998; Rother and Shook, 1999) and, therefore, has a high level of quality even at the lowest skill levels. The other two levels are set between the minimum and maximum. The greatest benefit is realized in increasing from skill level two to three, to give the greatest return after some training, but not for training to the highest level.
9. The 2001 ASTD State of the Industry Report (Van Buren, 2001) states that industry leaders for training, on average, provide 62.5 hours (or approximately eight working days) of training per eligible employee per year. Therefore, for this research the number of allowed training days per worker per year is set to eight.

Table 4.5: Productivity Rate and Quality Level associated with Skill Level

Skill Level	Productivity Rate (units/period)			Quality Level
	Eight-hour Period	Four-hour Period	Two-hour Period	
1	45	23	11	0.88
2	49	25	12	0.92
3	54	27	13	0.97
4	57	29	14	1.00

10. The total training time allowed for all workers within the hypothetical cell is set at 48 days (8 days/worker*6 workers).
11. The ASTD report (Van Buren, 2001) states that industry leaders for training, on average, expend $1,655 per year per eligible employee. However, the median training expenditure per eligible employee is $1,225 per year. The median training expenditure for industry leaders is used for this research. Lean production advocates training all workers to be capable of performing all tasks within the cell (Monden, 1993; Womack and Jones, 1994, 1996). Therefore, the training budget is determined by multiplying the median cost per employee by the number of employees or $7,350 (8 workers*$1,225).

The tasks workers are capable of performing, the associated skill level, the minimum required skill level, and training times are all randomly assigned parameters. The next section describes how the values for these parameters are generated.

4.3.5 Development of the Randomly Assigned Parameters for the Hypothetical Cell

Microsoft Excel® was used to randomly assign which workers are trained on each of the tasks. Excel's® RANDBETWEEN function was used to assign either a zero (0) or one (1) to each task for each worker. Workers with a 1 are trained on the task, while workers with a 0 are not trained on the task. The multi-skilling level for each worker was then determined by summing the number of tasks for which the worker was trained.

The required skill level (see Table 4.6) for each task was created using the RANDBETWEEN function to randomly assign a value between two (2) and three (3) for each task. RANDBETWEEN was then used to determine the skill level for each task a worker was trained to perform by assigning a value that is between the required skill level (NS_j) and the highest skill level. If a worker was not trained on a task, then the current skill level for that worker was set to one (1).

The RANDBETWEEN function was used to randomly create the processing times for each task. Processing times are assumed to be between one (1) and ten (10) minutes and are shown in Table 4.6. Each worker schedule generated from the assignment model shows the task(s) for which workers are assigned for the rotation period. The total processing time for a worker to cycle through the assigned task(s) must be less than the *takt* time. Therefore, the proportion of time a worker spends on a task was determined by dividing the processing time by the *takt* time. The total time in a rotation period a worker could be assigned to tasks cannot be greater than 100% of *takt* time.

Table 4.6: Task Required Skill Level and Processing Time

Task	Required Skill Level	Processing Time (minutes)
1	2	4.8
2	3	2.0
3	3	7.8
4	2	3.9
5	2	2.7
6	2	9.5
7	3	7.1
8	3	6.2
9	3	1.4
10	3	5.4

Training costs are based on the number of days required to train a worker to reach the next skill level. Table 4.7 shows the cost of training based on the number of days of training. The number of days required for training are expanded from Norman *et al.* (2002) who required a training time equal to the skill level the worker is training to. Most training seminars today last from one to five days, therefore, training to the next skill level for the hypothetical cell requires from one (1) to five (5) days of training. The time to train was determined by using the RANDBETWEEN function in Excel®. The training costs were based on the advertisements of training seminars. The ASTD Report (Van Buren, 2001) states that participating organizations spent 21% (the largest percentage) of total training expenditures on production employees and that 77% of the training was instructor-led classroom instruction.

To prevent a task from not being performed (a constraint of the mathematical model described in detail in Chapter 3) when a worker is in training, a replacement worker from a different cell is assumed to perform the tasks required of the worker in training. The cost for the replacement worker is based on the average salary plus benefits of an industrial sponsor and is shown in Table 4.7. Table 4.8 shows the training time and training cost to reach the next skill level for each task.

Table 4.7: Cost of Training Based on Number of Days of Training

Time to Train (days)	Cost of Training ($)	Cost of Replacement Employee ($)	Total Cost of Training ($)
1	50	100	150
2	100	200	300
3	200	300	500
4	400	400	800
5	1,000	500	1,500

The initial multi-skilling level has all six workers trained on at least 20% of the ten serial tasks. The skill level for workers capable of performing the highest number of tasks were set to four for all ten tasks when increasing from multi-skilling Level 1 to 2. The same procedure was repeated when increasing from multi-skilling Level 2 to Level 3 and from multi-skilling Level 3 to Level 4.

Table 4.8: Training Time and Training Costs to Advance to the Next Skill Level for the Hypothetical Cell

Task	Skill Level	Time To Train (Days)	Training Cost ($)
1	1	0	0
	2	2	300
	3	3	500
	4	4	800
2	1	0	0
	2	3	500
	3	2	300
	4	3	500
3	1	0	0
	2	4	800
	3	3	500
	4	3	500
4	1	0	0
	2	1	150
	3	3	500
	4	3	500
5	1	0	0
	2	2	300
	3	3	500
	4	5	1,500
6	1	0	0
	2	2	300
	3	3	500
	4	1	150
7	1	0	0
	2	5	1,500
	3	2	300
	4	2	300
8	1	0	0
	2	4	800
	3	1	150
	4	4	800
9	1	0	0
	2	5	1,500
	3	4	800
	4	3	500
10	1	0	0
	2	4	800
	3	5	1,500
	4	3	500

4.4 Overview of the Case Application

To test the applicability of the model for an actual production cell and to assess how the goals of the worker assignment model and the performance measures from the simulation model are affected by different levels of multi-skilling and job rotation, a case application was conducted at an industrial site. Information on customer demand, productivity levels, quality levels, employee skill levels, training times, training budget, and cost of training were collected for an actual production line (cell) at an industrial partner's site. The information was entered into the worker assignment model and a simulation model of the actual production line to investigate the same research questions as in the hypothetical cell (i.e., what was the impact of alternative levels of multi-skilling and job rotation on overproduction, cost of poor quality, cost of incremental training, flowtime, WIP level, and monthly shipments?). A description of the case application is provided in section 4.4.1. Following the case application description, the experimental design was defined, and the values for the design factors and the design parameters are provided.

4.4.1 Description of the Case Application

The case application was conducted in a high-performance motion control products manufacturing plant in the southeast United States. The plant is one of many within a larger global corporation in the motion control industry. The identity of the organization is protected, however, we refer to the plant as Industrial Motors (IM). Motors manufactured in the IM plant are used in applications in the machine tool, medical products, and aerospace and defense industries.

Training at IM is on the job training with an additional resource providing the training. There are a number of assumptions that affect the case application cell, but are not assumptions of the worker assignment or simulation models. As with the hypothetical cell, the time period is 20 days, suppliers provide good quality parts as planned, and workers use any time not performing tasks for cleanup. Set-ups occur only when changing motor types. Set-up times are included in the processing times for the worker assignment model, but included as an actual set-up time in the simulation model.

The manufacturing cell evaluated at IM produces a single product family of motors for a high-demand customer consisting of two sizes of motors, 630 kg and 1,000 kg. The product family is manufactured in a dedicated cell that performs three main assembly processes: 1) stator subassembly, 2) rotor subassembly, and 3) final assembly. The stator and rotor subassemblies are sent to final assembly where they are matched based on the motor size before being assembled and tested prior to shipment. IM has conducted time studies to determine the processing times for each of the tasks. Since all processes have a processing time less than the *takt* time, they are capable of meeting the customer's demand assuming the suppliers provide parts as planned and the production equipment performs as expected.

The manufacturing cell at IM is a mature cell that has high current quality levels due to previous kaizen and process improvement "events" targeted at improving quality. In addition, the cell is dedicated to a single customer, which is one of the most important customers for the plant. Therefore, there has historically been a strong emphasis on achieving and sustaining high quality since the startup of the line.

The cell consists of 13 workers performing 25 tasks. Eleven of the tasks are in the stator subassembly, seven tasks are in the rotor subassembly, and seven tasks are in the final assembly. The task name, number, minimum required skill level, and task processing times are shown in Table 4.9. In each of the assembly processes, the tasks are performed serially. Assuming 20 operating days per month and 5 operating days per week, a monthly demand of 560 units results in a daily demand of 28 units and a weekly demand of 140 units. A daily demand of 28 units and 450 minutes of production time per day results in a 16.07 minute *takt* time for the cell. As defined earlier, *takt* time is the unit production pace that must be met to match customer requirements (Rother and Shook, 1999).

As with the hypothetical cell, workers may perform multiple tasks, but each worker's task content should be below *takt* time. For example, Encapsulation takes 12.79 minutes to perform and there are several other tasks with processing times less than 3.28 minutes that a worker could also perform at the same time as Encapsulation. Therefore, the proportion of time a worker performs any single task, (pr_{ijt}), is determined by dividing the task processing time by the *takt* time, and a constraint (equation 3.9) was included in the worker assignment model to prevent workers from being assigned to greater than 100% of *takt* time. There is a sequence the worker will follow when performing the assigned tasks. The worker will repeat this sequence throughout the rotation period (s)he is assigned to those tasks.

Table 4.9: Task Name, Task Number, Required Skill Level, and Processing Time for the Case Application

Task	Task Number	Required Skill Level	Processing Time (minutes)
Encapsulation	394	3	12.79
Post Connect Test	395	2	5.00
Post Encapsulation Test	396	2	1.00
Skew/Shrink Housing	397	3	4.00
Assemble Connector	400	3	12.46
Connect	401	3	6.00
Stack Lams	403	2	2.50
Final Test	404	3	1.50
Inspect Machining	405	2	3.10
Machine	406	3	8.07
Assemble Rotor Field	407	3	6.50
Install Bearings	408	2	2.50
Assemble Shaft/Frame	409	3	7.50
Rotor/Spacer/Shaft	410	3	1.00
Assemble. Stator/Frame	411	3	5.67
Install Brake	412	3	6.50
Balance	413	2	7.50
Shape and Lace Lead End	414A	3	12.85
Shape and Lace Non-lead End	414B	3	12.85
Pack & Ship	416	3	9.75
Magnetize	417	2	2.50
Primary Encoder	418	3	1.00
Install End Bell	419	3	0.75
Rescue Encoder	420	3	0.25
Machine Wind	426	3	14.21
Vibration Test	427	2	2.50

Industrial Motors produces every part every week (EPE = weekly). That is, both the 630 kg model and the 1,000 kg model are produced once a week. Changing over from a 630 kg motor to a 1,000 kg motor requires a setup. An assumption of the optimization model is that set-up times are included in the processing time. The procedure used for including the set-up time in the processing time is described below.

For two tasks, set-up times are distributed across processing times. The Machine Wind and Machine tasks have setup times of fifteen and five minutes, respectively, changing from 630 kg motors to 1,000 kg motors and vice versa. The line processes all 630 kg motors for the week before switching over to the 1,000 kg motors. Therefore, there are two setups per week – one at the beginning of the week to changeover from 1,000 kg motors to 630 kg motors and one towards the end of the week to changeover from the 630 kg motors to the 1,000 kg motors.

As stated previously, for every motor produced, there is a *takt* time. To determine the proportion of time spent on setups, the following procedure was conducted. The total time per week used for setups was divided by the number of *takt* times per week to find the amount of time the two setups would increase each of the *takt* times. The result was divided by the required *takt* time to determine the proportion of time that would be spent on setups during each *takt* time. That is, for the Machine Wind task, there are two setups per week at fifteen minutes each. There are a total of 140 *takt* times per week (28/day*5 days/week). Dividing the total setup time for the week (30 minutes) by the total number of *takt* times per week (140) gives the amount of time per *takt* time attributed to the setups (0.21 minutes). The time per *takt* time (0.21 minutes) was divided by the *takt* time of the cell (16.07 minutes) to calculate the proportion of *takt* time attributed to the setup time (0.013). That is,

$$\text{Setup time per } \textit{takt} \text{ time} = \frac{(2\ \ setups/week * 15 \min utes/setup)}{(28\, takt\, times/day * 5\, days/week)} = 0.21 \min/takt\, time$$

$$\text{Proportion of } \textit{takt} \text{ time for setups} = \frac{0.21 \min/takt\, time}{16.07 \min/takt\, time} = 0.013.$$

The proportion (pr_{ijt}) of time a used in the optimization model for Machine Wind was the sum of the proportion of time a worker uses Machine Wind plus the proportion of time needed for set-up at Machine Wind. The proportion of time needed at Machine Wind is (14 minutes/16.07 minutes = 0.8711). Therefore, the total proportion of time spent at Machine Wind (pr_{ijt} for Machine Wind) is 0.8841 (0.8711 + 0.013). The same procedure was used for the Machine task, with the proportion of time spent on setups equaling 0.002 and the total proportion of time (pr_{ijt}) a worker is needed at the Machine task is 0.4980. For the simulation model, setups were handled as set-ups that occurred outside of the processing time. The simulation model uses variables to determine if the current motor is the same as the previous motor, and if not, then a setup requiring both the machine and the worker was required. The following sections provide information about the experimental design factors and parameters for the case application.

4.4.2 Experimental Design for the Case Application

The purpose of the experimental design is to determine how the worker assignment model performs under different settings within a case application. The experimental design for the case application is designed such that it matches as closely as possible the experimental design for the hypothetical cell described in Section 4.3.2, yet also reflects actual conditions in the line. The differences between the experimental designs are described in the following sections.

As with the hypothetical cell, a simulation model of the actual cell was created. The simulation model of the case application has been developed throughout the last three years in cooperation with the research partner. The simulation model uses the information provided by the research partner for demand level, worker information, and task information. The results from the worker assignment model were entered into the simulation model to determine the impact varying multi-skilling levels and job rotation frequencies have on flowtime, work-in-process, and monthly shipments. The model has been verified and validated (See Appendix F) and has been used for other research analysis for the sponsor.

After verification, the model was executed, and Welch's method was used to determine the warm-up period. The warm-up period was determined to be 80 days. Since the worker assignment model was for a 20-day time period, the simulation model was executed for 100 simulated days with data collected for only the last 20 simulated days. To ensure a 95% confidence interval within ±10% of the mean of the performance measure, 15 replications of the model were executed. The levels of multi-skilling, job rotation frequency, and the other model parameters are described in detail in the following sections.

4.4.3 Values for the Design Factors for the Case Application

The values for the multi-skilling levels and job rotation frequency were obtained from the research sponsor and are described in this section. The values for the multi-skilling levels differ from those in the hypothetical cell. First, the value for Level 1 represents the current state of employee skill levels in the cell at Industrial Motors. The cell has several workers who have prior experience in performing the tasks within the cell. Three of the thirteen workers can perform 16 (64%) or more of the 25 tasks (see the following section – point 2). In order to make this research applicable to the organization, it was not feasible to set the lowest level of multi-skilling to be the same as in the hypothetical cell (i.e., workers can perform one-third of the tasks). Second, in Levels 2 – 4 workers are trained on half of the tasks, rather than all tasks. It is believed that training on half of the tasks would be acceptable for a cell of this size to reflect increased multi-skilling levels. Further, workers would not be able to perform all 25 tasks within a 20-day time period as would be required by the worker assignment model. In other words, being trained on half (12) of the 25 tasks is considered to be the highest level of multi-skilling for an individual worker, with the exception of the three workers who were capable of performing at least 64% of the tasks initially.

The multi-skilling levels used in this research are shown below. As mentioned previously, the initial multi-skilling level corresponds to the training level workers have in the current state of the cell.

a. Level 1: all workers are trained on at least 16% of the tasks (with three workers trained on at least 64% of the tasks),
b. Level 2: 33% of all workers are fully trained on half of the tasks (with three workers trained on at least 64% of the tasks),
c. Level 3: 67% of all workers are fully trained on half of the tasks (with three workers trained on at least 64% of the tasks), and
d. Level 4: all workers are fully trained on half of the tasks (with three workers trained on at least 64% of the tasks).

The job rotation levels used in this research for the case application are below. These values are the same as in the hypothetical cell.

a. Level 1: workers are rotated on a daily basis (i.e., every eight hours),
b. Level 2: workers are rotated every four hours, and
c. Level 3: workers are rotated every two hours.

4.4.4 Values for the Design Parameters for the Case Application

The main parameters are: number of workers, number of tasks, number of assignment periods, skill levels, minimum task required skill level for each tasks, customer demand, productivity rate, quality level, individual training time, total training time, and training budget. These design parameters are listed below:

1. There are 13 workers available that perform tasks within the cell, (this is approximately double the number of workers in the hypothetical cell).
2. There are 25 tasks within the cell (this is 250% the size of the hypothetical cell).
3. The evaluation period is 20 days or a working month (as it is in the hypothetical cell).
4. Customer demand is a total of 28 motors per day (560/month) across all motor variants (customer demand in the hypothetical cell is 45 units/day or 900/month).
5. Four levels are used to categorize employee skill level (the same as in the hypothetical cell). The categorization of the skill levels is shown in Table 4.10. While the number of levels is the same as the hypothetical cell, the descriptions are slightly different. The most important difference is that in the case application, at skill level 1, a worker cannot perform the task, (and therefore, cannot be assigned) whereas in the hypothetical cell, a worker at skill level 1 can minimally perform the task and can be assigned to it.

Table 4.10: Description of Skill Level for the Case Application

Skill Level	Description of Skill Level	Abbreviation
1	Can not perform the task	**CNP**
2	Can work in the area while being supervised by an experienced associate	**CDW**
3	Can perform all functions in the given work area	**CD**
4	Can perform all functions in the given work area and train others	**CDT**

6. The required skill level for tasks in the case application was obtained from Industrial Motors. The task name, number, minimum required skill level, and task processing times are shown in Table 4.9.
7. The productivity rate is the production level for each employee at each of the skill levels for each task. The productivity rates were determined from the production manager and floor associates at IM (see Table 4.11). The rates for the four-hour and two-hour rotation frequencies are calculated by dividing the eight-hour rates by two and four, respectively. Productivity rates for skill level 1 are not shown because workers cannot be assigned to a task at this skill level.

8. The quality levels were obtained from the quality assurance department at the organization (see Table 4.12). Defects are measured (and caught) only at the certain points (e.g., Final Test, Encapsulation, and Post Encapsulation Test). Quality levels for all other tasks are set at 100% because no defects are caught these tasks. This is different from the hypothetical cell. Another difference relates to the quality level associated with increasing skill levels. In the hypothetical cell, quality is increased with increasing skill level for all tasks. For the case application, the experience of the production manager and the quality assurance manager suggest that the quality levels do not increase as worker skill level increases for most tasks because the majority of defects are due to variation in the process (machines, materials, etc.). Quality levels do increase with increasing skill level for those tasks which are less machine dependent. Quality levels are not shown for skill level 1, because workers cannot perform or be assigned to a task at this skill level.
9. The training in the cell at IM is accomplished through on the job training. Because all training is on the job it is possible for workers to be in training for the entire 20-day time period. Therefore, the allowed number of training days for each worker is set to 20. This is different from the hypothetical cell which used classroom training or seminars as a means of training. Table 4.13 shows the training time and training cost to reach the next skill level for each task. The training time for each task was determined from discussions with the production manager and production associates in the cell. The training cost for a task is determined by multiplying the average salary ($11.35/hour) of workers in the cell by the total number of hours required for training and represents the cost of having a higher skilled worker train and oversee the worker in training. For example, it takes five days to train from skill level 1 (CNP) to skill level 2 (CDW) on Encapsulation, therefore, the cost of training is $454.00 ($11.35/hour*8 hours/day*5 days).

10. As with the hypothetical cell, the total training time allowed for all workers in the cell at IM is determined by multiplying the number of individual training days by the number of workers in the cell. Total training time is set at 260 days (20 days*13 workers). The budget for the working month is set at $23,608, which is equivalent to

all 13 workers training all 20 working days (13 workers*20 days*8 hours/day*$11.35/hour/worker).

11. The training in the cell at IM is accomplished through on the job training. Because all training is on the job it is possible for workers to be in training for the entire 20-day time period. Therefore, the allowed number of training days for each worker is set to 20. This is different from the hypothetical cell which used classroom training or seminars as a means of training. Table 4.13 shows the training time and training cost to reach the next skill level for each task. The training time for each task was determined from discussions with the production manager and production associates in the cell. The training cost for a task is determined by multiplying the average salary ($11.35/hour) of workers in the cell by the total number of hours required for training and represents the cost of having a higher skilled worker train and oversee the worker in training. For example, it takes five days to train from skill level 1 (CNP) to skill level 2 (CDW) on Encapsulation, therefore, the cost of training is $454.00 ($11.35/hour*8 hours/day*5 days).

Table 4.11: Productivity Levels Associated with Each Skill Level for the Case Application

Task	Task Number	Productivity (units/period)								
		Eight-hour Period			Four-hour Period			Two-Hour Period		
		Skill Level			Skill Level			Skill Level		
		CDW (2)	CD (3)	CDT (4)	CDW (2)	CD (3)	CDT (4)	CDW (2)	CD (3)	CDT (4)
Encapsulation	394	22	28	30	11	14	15	5.5	7	7.5
Post Connect Test	395	28	30	32	14	15	16	7	7.5	8
Post Encapsulation Test	396	28	30	32	14	15	16	7	7.5	8
Skew/Shrink Housing	397	22	28	30	11	14	15	5.5	7	7.5
Assemble Connector	400	22	28	30	11	14	15	5.5	7	7.5
Connect	401	24	28	30	12	14	15	6	7	7.5
Stack Lams	403	28	30	32	14	15	16	7	7.5	8
Final Test	404	28	30	32	14	15	16	7	7.5	8
Inspect Machining	405	28	30	32	14	15	16	7	7.5	8
Machine	406	24	28	30	12	14	15	6	7	7.5
Assemble Rotor Field	407	26	28	30	13	14	15	6.5	7	7.5
Install Bearings	408	28	30	32	14	15	16	7	7.5	8
Assemble Shaft/Frame	409	24	28	30	12	14	15	6	7	7.5
Rotor/Spacer/Shaft	410	24	28	30	12	14	15	6	7	7.5
Assemble. Stator/Frame	411	24	28	30	12	14	15	6	7	7.5
Install Brake	412	24	28	30	12	14	15	6	7	7.5
Balance	413	26	28	30	13	14	15	6.5	7	7.5
Shape and Lace	414	24	28	30	12	14	15	6	7	7.5
Pack & Ship	416	24	28	30	12	14	15	6	7	7.5
Magnetize	417	28	30	32	14	15	16	7	7.5	8
Primary Encoder	418	26	28	30	13	14	15	6.5	7	7.5
Install End Bell	419	26	28	30	13	14	15	6.5	7	7.5
Rescue Encoder	420	24	28	30	12	14	15	6	7	7.5
Machine Wind	426	22	28	30	11	14	15	5.5	7	7.5
Vibration Test	427	28	30	32	14	15	16	7	7.5	8

Table 4.12: Task Quality Levels for the Case Application

Task	Task Number	Quality		
		Skill Level		
		CDW (2)	CD (3)	CDT (4)
Encapsulation	394	0.940	0.960	0.980
Post Connect Test	395	.970	0.990	1.000
Post Encapsulation Test	396	0.900	0.930	0.970
Skew and Shrink Housing	397	1.000	1.000	1.000
Assemble Connector	400	1.000	1.000	1.000
Connect	401	1.000	1.000	1.000
Stack Lams	403	1.000	1.000	1.000
Final Test	404	0.980	0.980	0.980
Inspect Machining	405	1.000	1.000	1.000
Machine	406	1.000	1.000	1.000
Assemble Rotor Field	407	0.950	0.970	1.000
Install Bearings	408	0.950	0.970	0.990
Assemble Shaft to Frame	409	1.000	1.000	1.000
Assemble Rotor, Spacer, and Shaft	410	1.000	1.000	1.000
Assemble Stator to Frame	411	1.000	1.000	1.000
Install Brake	412	1.000	1.000	1.000
Balance	413	1.000	1.000	1.000
Shape and Lace	414	1.000	1.000	1.000
Pack and Ship	416	0.997	0.997	0.997
Magnetize	417	1.000	1.000	1.000
Install Primary Encoder	418	1.000	1.000	1.000
Install End Bell	419	1.000	1.000	1.000
Install Rescue Encoder	420	1.000	1.000	1.000
Machine Wind	426	0.980	0.980	0.980
Vibration Test	427	0.920	0.940	0.960

Table 4.13: Time to Train and Cost of Training for each Level of Each Task for the Case Application

Task	Task Number	Time to Train to Next Level (Days)			Cost of Training ($)		
		Skill Level			Skill Level		
		CDW (2)	CD (3)	CDT (4)	CDW (2)	CD (3)	CDT (4)
Encapsulation	394	5	10	20	454.00	908.00	1,816.00
Post Connect Test	395	2	4	6	181.60	363.20	544.80
Post Encapsulation Test	396	2	4	6	181.60	363.20	544.80
Skew and Shrink Housing	397	5	10	20	454.00	908.00	1,816.00
Assemble Connector	400	5	10	20	454.00	908.00	1,816.00
Connect	401	5	10	20	454.00	908.00	1,816.00
Stack Lams	403	2	4	8	181.60	363.20	726.40
Final Test	404	2	4	6	181.60	363.20	544.80
Inspect Machining	405	2	4	6	181.60	363.20	544.80
Machine	406	10	20	40	908.00	1,816.00	3,632.00
Assemble Rotor Field	407	2	4	6	181.60	363.20	544.80
Install Bearings	408	1	2	3	90.80	181.60	272.40
Assemble Shaft to Frame	409	5	10	20	454.00	908.00	1,816.00
Assemble Rotor, Spacer, and Shaft	410	5	10	20	454.00	908.00	1,816.00
Assemble Stator to Frame	411	5	10	20	454.00	908.00	1,816.00
Install Brake	412	2	4	9	181.60	363.20	817.20
Balance	413	1	3	6	90.80	272.40	544.80
Shape and Lace	414	5	10	20	454.00	908.00	1,816.00
Pack and Ship	416	5	10	20	454.00	908.00	1,816.00
Magnetize	417	1	3	6	90.80	272.40	544.80
Install Primary Encoder	418	2	4	6	181.60	363.20	544.80
Install End Bell	419	4	6	7	363.20	544.80	635.60
Install Rescue Encoder	420	7	14	31	635.60	1,271.20	2,814.80
Machine Wind	426	20	40	120	1,816.00	3,632.00	10,896.00
Vibration Test	427	2	4	6	181.60	363.20	544.80

4.5 Summary of Solution Approach and Analysis of the Research Questions

In this chapter, the solution approach and the experimental designs for the hypothetical and case application cells are described. The worker assignment model is solved as a sequential goal programming model using CPLEX. Then the model is used to investigate the impact of alternative levels of multi-skilling and job rotation on a lean production cell's performance. The model is first applied to a hypothetical cell and then to an actual lean production cell.

The solution approach was to develop a hypothetical cell and apply a full factorial design to the worker assignment model using four levels of multi-skilling and three levels of job rotation frequency to evaluate their impact on overproduction, cost of poor quality, and cost of training. The output from the worker assignment model was implemented in a simulation model for each of the 12 experiments to evaluate the affect of multi-skilling and job rotation on flowtime, work-in-process, and monthly shipments. The same approach was used to apply the worker assignment model to an actual cell at an industrial research sponsor.

The experimental design for the case application is kept as similar as possible to the hypothetical cell design while still allowing the research to represent the actual cell. The main differences are: definition of the first level of multi-skilling, the number of tasks on which a worker is fully trained when increasing the level of multi-skilling, and the manner in which quality levels increase when skill level increases. The results for both the worker assignment model and simulation model are analyzed using various methods.

The results from the worker assignment model are analyzed by tabulating them by factor and evaluating them for patterns. The results from the simulation model are analyzed by univariate analysis of variance. Levene's test for homogeneity of variances is used to evaluate the variances. Tamhane's T2 post-hoc analysis is used for evaluating the levels of each factor to determine if there are differences between levels of the other factor. Tamhane's T2 post-hoc analysis is also used to determine which experimental results are significantly different. The results from both the hypothetical cell and the case application are presented and discussed in the next chapter.

Chapter 5 : Results and Discussion for the Hypothetical Cell

The purpose of the experimental study is to determine how the level of multi-skilling and the frequency of job rotation affect the performance of a hypothetical lean manufacturing cell. Table 5.1 summarizes the experiments according to multi-skilling and job rotation levels. All experiments for the worker assignment model were solved with integrality set to at least 1.0e-3. Results from the worker assignment model are presented in Section 5.1 and discussed in Section 5.2, while the results for the simulation model are presented in Section 5.3 and discussed in Section 5.4. Section 5.5 discusses the limitations of the research and Section 5.6 discusses the overall results for the hypothetical cell.

Table 5.1: Description of Experiments and Factor Levels

Experiment	Multi-skilling Level	Description	Job Rotation Level	Description
1	1	All workers are trained on at least two tasks	1	8-hour rotation
2	1		2	4-hour rotation
3	1		3	2-hour rotation
4	2	33% (2) of all workers are fully trained (100% quality)on all tasks	1	8-hour rotation
5	2		2	4-hour rotation
6	2		3	2-hour rotation
7	3	67% (4) of all workers are fully trained (100% quality)on all tasks	1	8-hour rotation
8	3		2	4-hour rotation
9	3		3	2-hour rotation
10	4	All (6) workers are fully trained (100% quality)on all tasks	1	8-hour rotation
11	4		2	4-hour rotation
12	4		3	2-hour rotation

5.1 *Results for the Worker Assignment Model for the Hypothetical Cell*

Results for the number of units overproduced, the cost of poor quality, and the cost of training for each experiment are shown in Table 5.2 and Table 5.3, grouped by job rotation and multi-skilling, respectively. Overproduction is the number of units overproduced on a monthly basis. The cost of poor quality is the cost for producing defects incurred on a monthly basis. The incremental cost of training is the one-time cost of training workers during the working month.

Detailed information on the task each worker was trained on, the beginning skill, the ending skill level, and the incremental cost of training for each worker for each experiment in the hypothetical cell is in Appendix B.1.

Table 5.2: Worker Assignment Model Results Grouped by Job Rotation Level

Number	Experiment	Overproduction (units)	Cost of Poor Quality ($/month)	Incremental Cost of Training ($)
1	**L1 MS, L1 JR**	1.04	76,404	7,150
4	**L2 MS, L1 JR**	0.24	141,496	4,650
7	**L3 MS, L1 JR**	1.18	31,271	2,400
10	**L4 MS, L1 JR**	0	0	0
2	**L1 MS, L2 JR**	0.85	76,412	7,200
5	**L2 MS, L2 JR**	1.11	40,654	5,200
8	**L3 MS, L2 JR**	4.55	27,076	2,700
11	**L4 MS, L2 JR**	0	0	0
3	**L1 MS, L3 JR**	0.38	58,282	7,300
6	**L2 MS, L3 JR**	0.36	8,930	5,250
9	**L3 MS, L3 JR**	0.15	7,363	2,700
12	**L4 MS, L3 JR**	0	0	0

Table 5.3: Worker Assignment Model Results Grouped by Multi-skilling Level

Number	Experiment	Overproduction (units/month)	Cost of Poor Quality ($/month)	Incremental Cost of Training ($)
1	**L1 MS, L1 JR**	1.04	76,404	7,150
2	**L1 MS, L2 JR**	0.85	76,412	7,200
3	**L1 MS, L3 JR**	0.38	58,282	7,300
4	**L2 MS, L1 JR**	0.24	141,496	4,650
5	**L2 MS, L2 JR**	1.11	40,654	5,200
6	**L2 MS, L3 JR**	0.36	8,930	5,250
7	**L3 MS, L1 JR**	1.18	31,271	2,400
8	**L3 MS, L2 JR**	4.55	27,076	2,700
9	**L3 MS, L3 JR**	0.28	7,363	2,700
10	**L4 MS, L1 JR**	0	0	0
11	**L4 MS, L2 JR**	0	0	0
12	**L4 MS, L3 JR**	0	0	0

For further analysis of the experimental results, the net present cost (NPC) for a one-year period is calculated for each of the experiments to evaluate the results on a cost basis. The NPC is comprised of the cost of the current multi-skilling level, the cost of overproduction, the cost of poor quality, and the incremental cost of training. The cost of the current multi-skilling level is the cumulative cost for training workers to reach the current multi-skilling level for the line from skill level 1 (an unskilled state). The NPC for each of the experiments is shown in Table 5.4. For example, the cost to fully train all workers to skill level 4 on all tasks (Level 4 multi-skilling) is $110,500. The cost of overproduction is determined using the number of units overproduced, the cost of a unit at the end of the line ($1,000), and a 15% holding cost as suggested in Bedworth and Bailey (1987). An interest rate of 12% per year compounded monthly is used.

Table 5.4: Net Present Cost of the Experiments

Number	Experiment	Cost of MS Level ($)	Cost of Overproduction ($/month)	Cost of Poor Quality ($/month)	Incremental Cost of Training ($)	Net Present Cost ($)
1	**L1 MS, L1 JR**	45,550	1,196	76,404	7,150	926,023
2	**L1 MS, L2 JR**	45,550	978	76,412	7,200	923,704
3	**L1 MS, L3 JR**	45,550	437	58,282	7,300	713,665
4	**L2 MS, L1 JR**	70,350	276	141,496	4,650	1,670,609
5	**L2 MS, L2 JR**	70,350	1,277	40,654	5,200	547,430
6	**L2 MS, L3 JR**	70,350	414	8,930	5,250	180,715
7	**L3 MS, L1 JR**	88,100	1,357	31,271	2,400	457,707
8	**L3 MS, L2 JR**	88,100	5,233	27,076	2,700	454,408
9	**L3 MS, L3 JR**	88,100	173	7,363	2,700	175,586
10	**L4 MS, L1 JR**	110,500	0	0	0	110,500
11	**L4 MS, L2 JR**	110,500	0	0	0	110,500
12	**L4 MS, L3 JR**	110,500	0	0	0	110,500

5.2 Discussion of the Results of the Worker Assignment Model for Hypothetical Cell

Several points can be made overall about Level 4 multi-skilling experiments (Experiments 10, 11, and 12). First, in Level 4 multi-skilling, all workers are fully trained on all tasks, resulting in no incremental cost of training workers. Second, for a worker trained to the highest skill level quality (first pass yield) is 100%, resulting in no defects, and thus, no cost of poor quality. If values less than 100% had been used for quality at the highest skill level then the cost of poor quality for Level 4 multi-skilling would have been non-zero. Third, these experiments also have no overproduction, and thus, no overproduction costs. Therefore, the NPC for these experiments is only comprised of the cost of achieving Level 4 multi-skilling. Based on these results from the worker assignment model, the highest level of multi-skilling (Level 4) has the lowest costs for overproduction, quality, and incremental training, and thus, the lowest net present cost. The following sections describe the worker assignment results across all experiments for each of the three goals (overproduction, cost of poor quality, and incremental cost of training) and the net present cost.

5.2.1 Overproduction

As shown in Table 5.2, there is no consistent pattern in overproduction across job rotation levels as multi-skilling level increases. From Table 5.3, Level 1 multi-skilling has the lowest overproduction at the two-hour rotation frequency and the highest overproduction at the eight-hour rotation frequency. Level 2 multi-skilling has the lowest overproduction at the eight-hour rotation frequency and highest at the four-hour rotation frequency. Level 3 multi-skilling has the lowest overproduction at the two-hour rotation frequency and highest at the four-hour rotation frequency. Level 4 multi-skilling has the lowest overproduction across all levels of multi-skilling. The overproduction results for Level 4 multi-skilling are constant across all levels of job rotation at zero (0) units. In Level 4 multi-skilling (Experiments 10, 11, and 12) all six workers are fully trained on all ten tasks, and as shown in Section 4.3.4, the productivity level for the first skill level is exactly the number of units per day needed to meet customer demand. That is, the productivity rate at skill level 1 is 45 units, which is exactly customer demand on a daily basis. Because workers can be assigned at a productivity rate lower than their maximum productivity while still producing at their maximum quality level, customer demand can be met exactly.

As seen in Table 5.3, the lowest overproduction typically occurs for Level 3 job rotation frequency (two-hour) while the highest overproduction typically occurs for Level 2 job rotation frequency (four-hour). If Level 2 multi-skilling had had the lowest overproduction at the two-hour rotation frequency, then that frequency would have consistently had the lowest overproduction for the first three levels of multi-skilling. Therefore, it appears that Experiment 4 (Level 2 multi-skilling at eight-hour rotation) may be anomalous. A possible reason why Level 3 job rotation appears to have the lowest overproduction relates to the assignment period length. As the level of job rotation increases, the length of the assignment period is reduced by half (i.e., Level 1 is an eight-hour rotation, Level 2 is a four-hour rotation, and Level 3 is a two-hour rotation). Subsequently, the reduction in assignment period length reduces the productivity associated with a worker performing a task at a skill level by half (see Section 4.3.4). For the Level 2 job rotation, all productivity rates happen to be rounded up, which may explain why the highest overproduction occurs at that level. That is, when dividing the Level 1 job rotation productivity values in half, the resulting numbers were rounded up (i.e., 45/2 = 22.5 which rounded to 23). Therefore, Level 3 job rotation may have had the lowest overproduction because of the combination of smaller productivity rates and smaller assignment periods, allowing the worker assignment model more flexibility in assigning workers for minimizing overproduction. The next section discusses the result for the cost of poor quality.

5.2.2 Cost of Poor Quality

Because the worker assignment model is a sequential goal-programming model, the cost-of-poor-quality goal is constrained by the overproduction goal. That is, the solution from the overproduction goal must be maintained for the cost-of-poor-quality goal. There is no requirement in the overproduction goal for limiting the cost of poor quality. Because the worker assignment model does not consider the cost of poor quality when solving the overproduction goal and work-in-process is not considered overproduction, the model may make worker assignments that minimize overproduction at the last task, but generate defects at other tasks.

As seen in Table 5.2, the cost of poor quality decreases as the multi-skilling level increases, with the exception of Experiment 4. As the multi-skilling level increases, an increasing number of workers become higher skilled on all tasks. Because the quality level increases as the skill level increases, the number of defects is reduced, thus reducing the cost of poor quality. The lowest cost of poor quality occurred at Level 4 multi-skilling for all job rotation levels as shown in Table 5.3. As discussed earlier, in Level 4 multi-skilling, all six workers are fully trained on all ten tasks, making the first pass yield for all workers 100%, thus eliminating all defects, and resulting in no cost of poor quality.

Experiment 4 does not maintain the pattern described above. Experiment 4 has by far the highest cost of poor quality; thus providing additional evidence that Experiment 4 may be anomalous. A possible reason Experiment 4 has the largest cost of poor quality relates to the relative skill level of workers and the frequency of job rotation. To minimize overproduction at the final task, highly skilled workers are assigned to the final task more often while lower skilled workers are assigned at other tasks. The lower skilled workers then produce a large number of costly defective units that greatly increase the cost of poor quality when the cost-of-poor-quality goal is solved. In the other experiments, the worker assignment model may not have been able to make the assignments in the same manner due to constraints on training and rotating workers to tasks they are already trained to perform. That is, due to the smaller number of assignment periods in the eight-hour rotation, fewer workers could receive training to improve quality and productivity compared to the four-hour and two-hour rotation frequencies.

The cost of poor quality typically decreases as job rotation level increases (see Table 5.3). The exceptions to this pattern are an $8 difference between the eight-hour and four-hour job rotation levels in multi-skilling Level 1 and the constant results for Level 4 multi-skilling. A possible reason why is that increasing levels of job rotation allow for a greater number of rotation periods for assigning workers to tasks. That is, workers are only required to work at a task that they are trained on for a single rotation period per working month. With an increased number of rotation periods, workers have greater opportunity for training. Therefore, it is easier for them to meet the requirement of working one rotation period at all tasks for which they are already trained.

5.2.3 Incremental Cost of Training

The incremental cost of training is constrained by the overproduction and cost-of-poor-quality goals. The overproduction goal attempts to minimize overproduction by training as many workers as possible within the budget constraint. The cost-of-poor-quality goal reinforces the model's attempt to increase training to reduce the number of defects.

As seen in Table 5.2, the incremental cost of training decreases as the level of multi-skilling increases. As the level of multi-skilling increases, there are fewer tasks on which workers can be trained because workers have more training initially, thus resulting in lower incremental cost of training. Therefore, the higher levels of multi-skilling result in lower incremental cost of training, but with a higher initial cost (as shown in Table 5.4).

As seen in Table 5.3, the incremental cost of training increases as the frequency of job rotation increases, although it is the same for Experiments 8 and 9. As the level of job rotation increases, there are additional assignment periods, providing additional opportunities for the worker assignment model to train workers and assign them to tasks at a higher skill level to reduce the number of defects. Accordingly, the worker assignment model attempts to train as many workers as possible to reduce overproduction and the effect quality levels have on overproduction. That is, at higher levels of training (skill levels), the first pass yield is higher. Workers can be assigned at lower levels of productivity while still maintaining the higher quality levels associated with a higher skill level. For further analysis of the experimental results, the net present cost (NPC) for a one-year period is calculated to evaluate the results on a cost basis.

5.2.4 Net Present Cost

The net present cost is heavily influenced by the difference between the cost of the multi-skilling level and the cost of poor quality associated with that level of multi-skilling. For example, the one-time cost to go from Level 1 (cost of multi-skilling level is $45,550) to Level 3 multi-skilling (cost of multi-skilling level is $88,100) at the eight-hour job rotation frequency is $42,550 ($88,100 – $45,550 = $42,550) with a quality savings of $45,133/month. This savings due to higher quality levels greatly offsets the cost associated with increasing the workers skill level. That is, the $45,133/month savings offsets the $42,550 cost of increasing the level of multi-skilling. The NPC decreases from $926,023 to $457,707, or a savings of $468,316, between Experiments 1 (L1 MS, L1 JR) and 7 (L3 MS, L1 JR).

From Table 5.4, as multi-skilling level increases, both the cost of poor quality and the incremental cost of training typically decrease, while the cost of the multi-skilling level increases. The only cost for NPC for Level 4 multi-skilling is the cost associated with obtaining that level of multi-skilling. That is, all workers in Level 4 multi-skilling are fully trained on all tasks with a quality level of 100% resulting in no cost of overproduction, cost of poor quality, or incremental cost of training. Therefore, the lowest NPC is for Level 4 multi-skilling.

As seen in Table 5.4, the net present cost appears to decrease as the frequency of job rotation increases. As job rotation frequency increases, the cost of poor quality decreases, while the incremental cost of training increases. The reduction in the cost of poor quality is greater than the increase in incremental cost of training, thus reducing the net present cost. The following sections discuss the results from the simulation model.

5.3 Results for the Simulation Model for the Hypothetical Cell

The worker assignment schedules (Appendix B.2) and associated quality levels from each of the experiments were entered into a simulation model of the hypothetical cell. The results for each experiment for flowtime, work-in-process, and monthly shipments are shown in Tables 5.5 5.6 grouped by job rotation frequency and multi-skilling level, respectively. These results are discussed in Sections 5.4.1 through 5.4.3. A 95% confidence interval for each of the three performance measures for the simulation model is shown in the corresponding section (see Figures 5.1, 5.2, 5.5, 5.6, 5.9, and 5.10).

Table 5.5: Simulation Model Results Grouped by Job Rotation Level

Number	Experiment	Average Flowtime (days)	Average WIP (units)	Average Monthly Shipments (units/month)
1	**L1 MS, L1 JR**	1.1549	52.0128	899.81
4	**L2 MS, L1 JR**	2.9358	122.6804	850.13
7	**L3 MS, L1 JR**	0.3598	16.1886	899.91
10	**L4 MS, L1 JR**	0.2464	11.0877	900.00
2	**L1 MS, L2 JR**	1.3378	60.2465	902.41
5	**L2 MS, L2 JR**	0.4030	18.1384	899.83
8	**L3 MS, L2 JR**	1.0071	43.8604	886.05
11	**L4 MS, L2 JR**	0.2575	11.5878	900.00
3	**L1 MS, L3 JR**	1.7636	79.4733	895.00
6	**L2 MS, L3 JR**	0.3678	16.5509	899.99
9	**L3 MS, L3 JR**	0.6757	30.4911	900.06
12	**L4 MS, L3 JR**	0.3093	13.9171	900.00

5.4 Discussion of the Results of the Simulation Model for the Hypothetical Cell

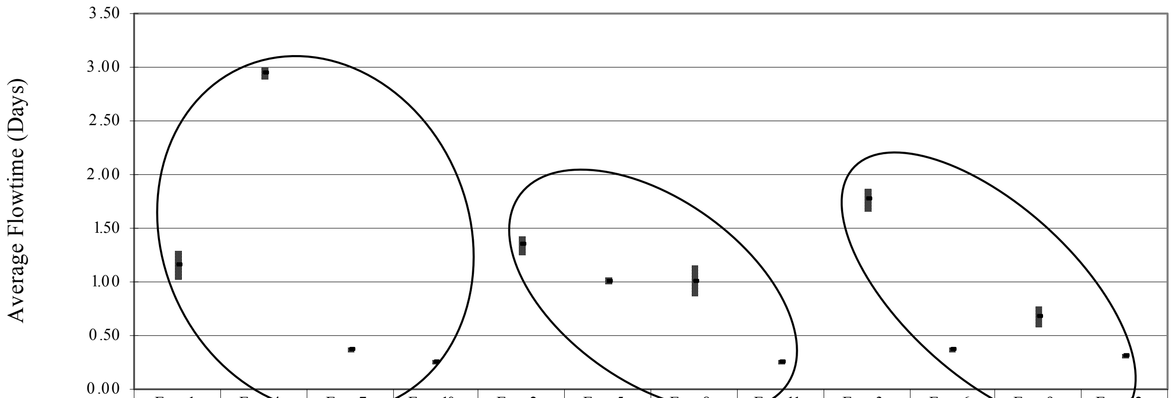
The following sections describe the results for each of the three performance measures in the simulation model: average flowtime, average work-in-process, and average monthly shipments. Flowtime is defined as the time a unit stays in the system from start to finish. If a unit is scrapped, a replacement unit starts back at the beginning of the cell and the flowtime is then calculated as the time the scrapped unit was in the system plus the time for the replacement unit to be completed. Work-in-process is defined as all uncompleted units within the system. A finished unit is defined as a unit that is ready to be shipped to the customer.

Table 5.6: Simulation Model Results Grouped by Multi-skilling Level

Number	Experiment	Average Flowtime (days)	Average WIP (units)	Average Monthly Shipments (units/month)
1	**L1 MS, L1 JR**	1.1549	52.0128	899.81
2	**L1 MS, L2 JR**	1.3378	60.2465	902.41
3	**L1 MS, L3 JR**	1.7636	79.4733	895.00
4	**L2 MS, L1 JR**	2.9358	122.6804	850.13
5	**L2 MS, L2 JR**	0.4030	18.1384	899.83
6	**L2 MS, L3 JR**	0.3678	16.5509	899.99
7	**L3 MS, L1 JR**	0.3598	16.1886	899.91
8	**L3 MS, L2 JR**	1.0071	43.8604	886.05
9	**L3 MS, L3 JR**	0.6757	30.4911	900.06
10	**L4 MS, L1 JR**	0.2464	11.0877	900.00
11	**L4 MS, L2 JR**	0.2575	11.5878	900.00
12	**L4 MS, L3 JR**	0.3093	13.9171	900.00

5.4.1 Average Flowtime

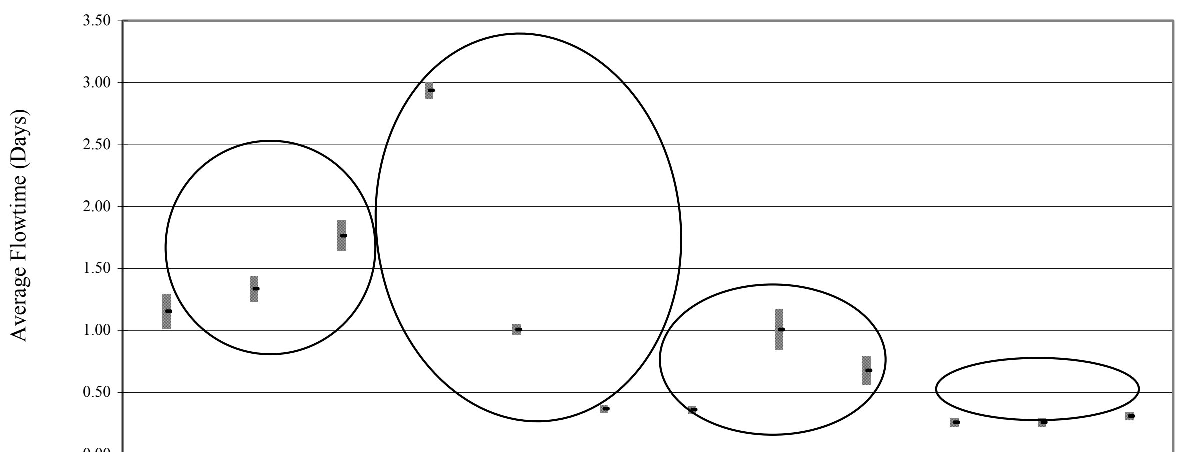
Figures 5.1 and 5.2 show the 95% confidence intervals for flowtime grouped by job rotation and multi-skilling, respectively. Figure 5.3 shows the flowtime for each level of multi-skilling and job rotation, using a Lowess plot. This plot uses an iterative locally weighted least-squares method to fit a curve to a set of points. The Lowess plot was used to compensate for the effect outliers have on the mean for each multi-skilling or job rotation level. The non-parallel lines in the Lowess plot for average flowtime indicate there is an interaction effect between multi-skilling and job rotation. Table 5.7 shows the results of an ANOVA, which indicate multi-skilling, job rotation, and the interaction effect are all significant at the .05 level. Because the interaction effect is significant, inferences about the effect of one factor should not be made without considering the level of the second factor. That is, the effect of job rotation on flowtime is not the same at all levels of multi-skilling.



	Exp 1: L1MS L1JR	Exp 4: L2MS L1JR	Exp 7: L3MS L1JR	Exp 10: L4MS L1JR	Exp 2: L1MS L2JR	Exp 5: L2MS L2JR	Exp 8: L3MS L2JR	Exp 11: L4MS L2JR	Exp 3: L1MS L3JR	Exp 6: L2MS L3JR	Exp 9: L3MS L3JR	Exp 12: L4MS L3JR
High	1.26	2.97	0.36	0.26	1.41	1.02	1.14	0.26	1.85	0.37	0.76	0.31
Low	1.04	2.90	0.36	0.26	1.27	1.00	0.88	0.26	1.67	0.37	0.60	0.31
- Average	1.15	2.94	0.36	0.26	1.34	1.01	1.01	0.26	1.76	0.37	0.68	0.31

Experiment

Figure 5.1: 95% Confidence Interval for Average Flowtime Grouped by Job Rotation



	Exp 1: L1MS L1JR	Exp 2: L1MS L2JR	Exp 3: L1MS L3JR	Exp 4: L2MS L1JR	Exp 5: L2MS L2JR	Exp 6: L2MS L3JR	Exp 7: L3MS L1JR	Exp 8: L3MS L2JR	Exp 9: L3MS L3JR	Exp 10: L4MS L1JR	Exp 11: L4MS L2JR	Exp 12: L4MS L3JR
High	1.26	1.41	1.85	2.97	1.02	0.37	0.36	1.14	0.76	0.26	0.26	0.31
Low	1.04	1.27	1.67	2.90	1.00	0.37	0.36	0.88	0.60	0.26	0.26	0.31
- Average	1.15	1.34	1.76	2.94	1.01	0.37	0.36	1.01	0.68	0.26	0.26	0.31

Experiment

Figure 5.2: 95% Confidence Interval for Average Flowtime Grouped by Multi-skilling

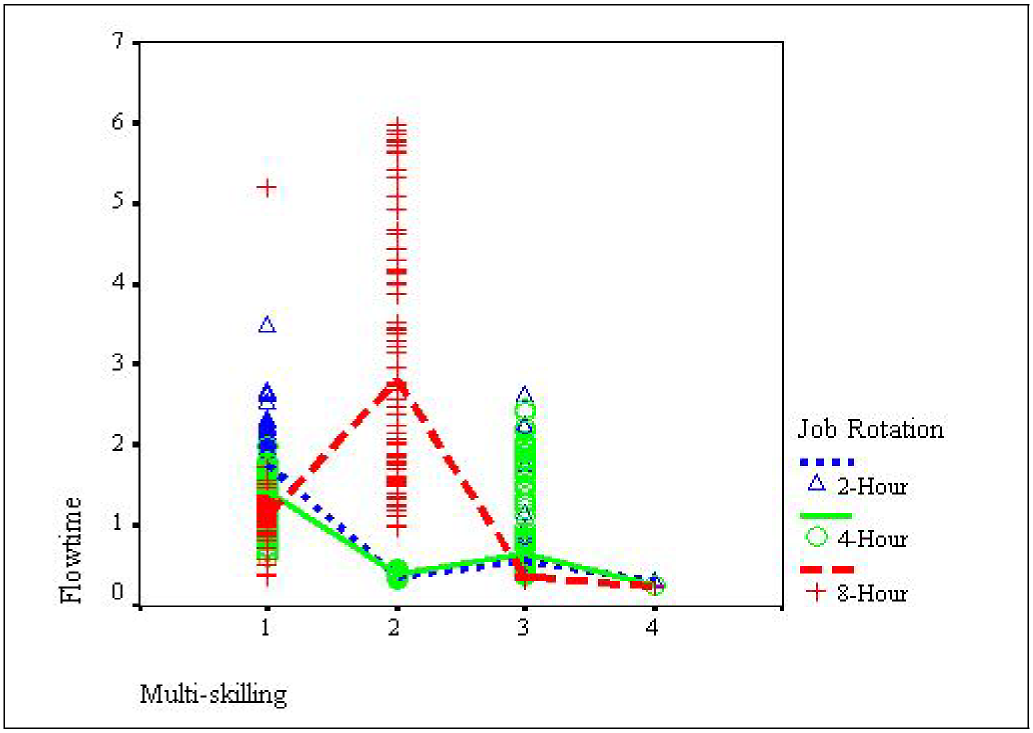


Figure 5.3: Lowess Plot for Average Flowtime by Multi-skilling Level

Table 5.7: ANOVA for Average Flowtime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	556.148*	11	50.559	159.924	**.000**
Intercept	869.875	1	869.875	2751.527	**.000**
MS	237.650	3	79.217	250.573	**.000**
JR	26.155	2	13.078	41.366	**.000**
MS * JR	292.343	6	48.724	154.120	**.000**
Error	299.703	948	0.316		
Total	1725.726	960			
Corrected Total	855.851	959			

*Adjusted R Squared = 0.646

From Figure 5.3, it appears that there may be non-homogeneous variances across all job rotation levels. For example, the individual data points for Level 2 job rotation at Level 2 multi-skilling are tightly clustered, while the individual data points for Level 2 job rotation at Level 3 multi-skilling are dispersed across a much greater range of flowtimes. Thus, the variances of flowtime across each experiment do not appear to be homogeneous. Levene's test for equality of variances was conducted to investigate if there are significant differences in variances for flowtime results across job rotation levels at each of the first three multi-skilling levels (see Table 5.8). For Level 1 multi-skilling, the variances in flowtime results across job rotation levels are not significantly different at the .05 level. For multi-skilling levels 2 and 3, the variances in flowtime results across job rotation levels are significantly different at the .05 level.

Table 5.8: Levene's Test for Flowtime across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	F	df1	df2	Sig.
Level 1	1.442	2	237	**.239**
Level 2	241.122	2	237	**.000***
Level 3	80.952	2	237	**.000***

*Significant at the .05 level

There may be several reasons for the unequal variances. First, a possible reason is that the simulation model is based on the output from the worker assignment model, which does not take into account the number of defects created in the cell for the overproduction goal. The solution from the overproduction goal constrains the cost-of-poor-quality goal and may result in a greater number of defects than if the cost-of-poor-quality goal was run before the overproduction goal. An increased number of defects would increase the number of units in the system, thus increasing the flowtime. Second, differences may also have been caused by where within the cell units were scrapped. The flowtime for a defective unit is the total amount of time the unit scrapped was in the system plus the time the replacement unit took to be completed. Units scrapped at the later tasks would increase the flowtime more than units scrapped at earlier tasks. For example, because a new unit must be started at the beginning of the cell to replace a defective unit, units scrapped at Task 9 increase the average flowtime more than a unit scrapped at Task 4, due to more time in the system before being scrapped. Because flowtime is only calculated for completed units, any unit that was scrapped and restarted, but still in the system when the simulation model ends is not considered. The differences in the variances may also have been caused by the simulation model requiring workers to finish a unit at a task before rotating to the next scheduled task. That is, workers may have just began processing a unit when a rotation was scheduled to occur, but had to complete the unit prior to rotating, thus increasing the waiting time and flowtime for units at tasks they are to rotate to next.

The interaction between multi-skilling and job rotation prevents interpretations at the factor level, but observations within the levels of each factor can be made. From Figure 5.3 and Table 5.6, it appears that for all levels of multi-skilling except Level 2, the eight-hour job rotation has the lowest average flowtimes. An ANOVA was conducted to investigate if there are significant differences in flowtime across job rotation levels at each multi-skilling level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). Because some of the variances are unequal, Tamhane's T2 unequal variances test, which is a conservative pairwise comparison test based on a t-test, is used to determine if there are significant differences in flowtime within levels of multi-skilling, within levels of rotation frequency, and across experiments.

Table 5.9: ANOVA for Flowtimes across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	15.608	2	7.804	42.697	**.000**
	Intercept	483.105	1	483.105	2643.078	**.000**
	JR	15.608	2	7.804	42.697	**.000***
Level 2	Corrected Model	346.948	2	173.474	217.913	**.000**
	Intercept	366.369	1	366.369	460.223	**.000**
	JR	346.948	2	173.474	217.913	**.000***
Level 3	Corrected Model	16.766	2	8.383	50.358	**.000**
	Intercept	111.261	1	111.261	668.373	**.000**
	JR	16.766	2	8.383	50.358	**.000***

*Significant at the .05 level

At each multi-skilling level, flowtime results across job rotation levels are significantly different (see Table 5.9) at the .05 level. Because the results from Level 4 multi-skilling are constant at each job rotation frequency there is no variance, therefore, ANOVA could not be performed for that level to determine if there are differences in the flowtime across the three job rotation levels. The results from Tamhane's T2 tests ($\alpha = 0.05$), shown in Table 5.10, indicate where the differences are. The first column in Table 5.10 shows the level of multi-skilling. The "I" and "J" columns, are the levels of job rotation being compared. The "mean difference" column is the difference between the mean flowtime for column J and the mean flowtime for column I. For example, at Level 1 multi-skilling the mean difference between Level 1 job rotation and Level 2 job rotation is negative 0.1829076, indicating the mean flowtime for Level 1 job rotation is shorter than the mean flowtime for Level 2 job rotation.

In Levels 1 and 3 multi-skilling, all levels of rotation are significantly different from each other, with the eight-hour job rotation frequency having the shortest flowtime. In Level 2 multi-skilling, all levels of job rotation are significantly different from each other, with the two-hour rotation frequency having the shortest flowtime. Because the post-hoc analysis could not be performed for Level 4 multi-skilling, the results for each experiment in that level were directly compared to each other. Because the results for each experiment within Level 4 multi-skilling are not equal (see Table 5.6), they are significantly different from each other with the eight-hour rotation having the shortest flowtime.

Table 5.10: Tamhane's Test for Average Flowtime across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	(I) Job Rotation	(J) Job Rotation	Mean Difference (I-J)	Std. Error	Sig.
1	Level 1	Level 2	-.1829076*	.06929176	**.028**
		Level 3	-.6087228*	.07342240	**.000**
	Level 2	Level 3	-.4258152*	.05929919	**.000**
2	Level 1	Level 2	2.5327452*	.17277848	**.000**
		Level 3	2.5679764*	.17275174	**.000**
	Level 2	Level 3	.0352312*	.00309664	**.000**
3	Level 1	Level 2	-.6473521*	.06696524	**.000**
		Level 3	-.3158989*	.04196430	**.000**
	Level 2	Level 3	.3314532*	.07899107	**.000**

*The mean difference is significant at the .05 level.

While it is easier for an organization to adjust job rotation frequency than the multi-skilling level of its employees, there may be some organizations that must maintain a certain rotation policy due to other concerns such as ergonomics, union rules, or hazardous conditions. Therefore, an analysis to investigate differences in multi-skilling levels for each job rotation level was conducted.

From Figure 5.4, it appears that there may be non-homogeneous variances across all multi-skilling levels. Levene's test for equality of variances was conducted to investigate if there are significant differences in variances across multi-skilling levels at each job rotation level. Table 5.11 shows that, for all job rotation levels, the variances between multi-skilling levels are significantly different at the .05 level. The difference in variances may have been caused by the same reasons discussed in the analysis of multi-skilling levels.

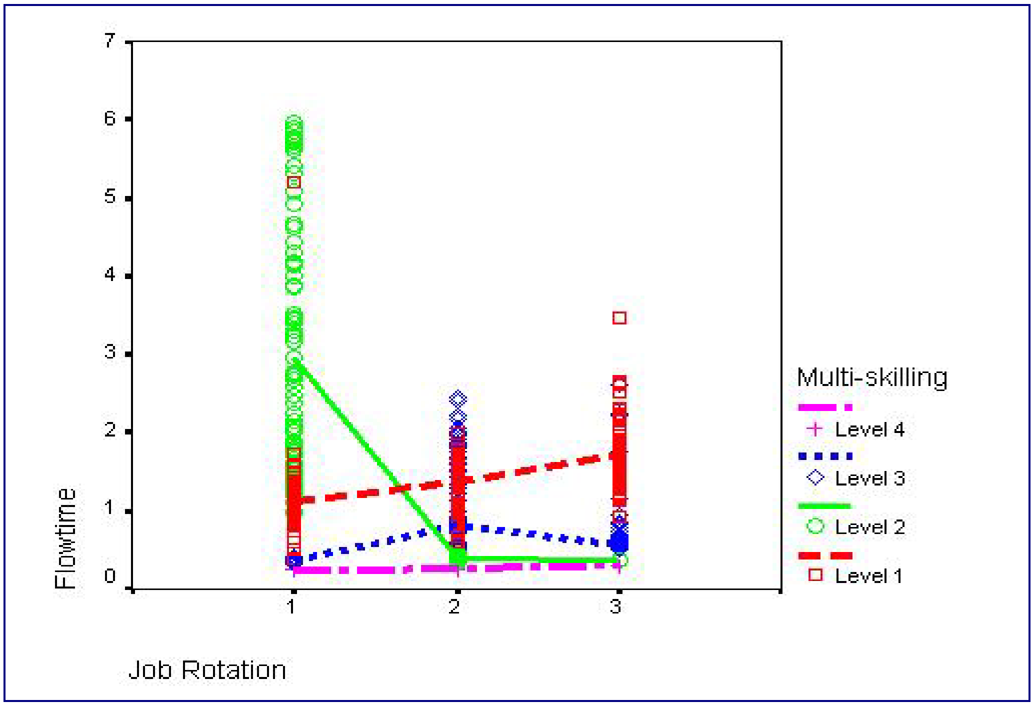


Figure 5.4: Lowess Plot for Average Flowtime by Job Rotation Level

Table 5.11: Levene's Test for Flowtimes across Multi-skilling Levels at Job Rotation Level

Job Rotation Level	F	df1	df2	Sig.
Level 1	162.898	3	316	**.000***
Level 2	158.010	3	316	**.000***
Level 3	41.073	3	316	**.000***

*Significant at the .05 level

The interaction between multi-skilling and job rotation prevents interpretations at the factor level, but observations within the levels of each factor can be made. From Figure 5.4 and Table 5.5, it appears that for all levels of job rotation, Level 4 multi-skilling has the shortest average flowtimes. An ANOVA was conducted to investigate if there are significant differences in flowtime across multi-skilling levels at each job rotation level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). As with the multi-skilling analysis, Tamhane's T2 test is used to determine in there are significant differences in work-in-process within each job rotation frequency.

At each job rotation level, flowtime results across multi-skilling levels are significantly different (see Table 5.12) at the .05 level. The results from Tamhane's T2 tests ($\alpha = 0.05$), shown in Table 5.13, indicate where the differences are. Within each job rotation level, the levels of multi-skilling are significantly different from each other with the shortest flowtime occurring at Level 4.

Table 5.12: ANOVA for Average Flowtimes across Multi-skilling Levels for each Job Rotation Level

Job Rotation Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	370.208	3	123.403	185.938	**.000***
	Intercept	441.210	1	441.210	664.797	**.000***
	MS	370.208	3	123.403	185.938	**.000***
Level 2	Corrected Model	61.966	3	20.655	173.449	**.000***
	Intercept	180.659	1	180.659	1517.039	**.000***
	MS	61.966	3	20.655	173.449	**.000***
Level 3	Corrected Model	109.592	3	36.531	479.248	**.000***
	Intercept	194.236	1	194.236	2548.202	**.000***
	MS	109.592	3	36.531	479.248	**.000***

*Significant at the .05 level

Because Level 4 multi-skilling has the shortest flowtimes and the eight-hour rotation frequency typically has the shortest flowtimes, an ANOVA was conducted to determine if flowtimes for experiments are significantly different. The ANOVA showed that flowtime results across experiments are significantly different (see Table 5.14). As with the multi-skilling analysis, Tamhane's T2 test is used to determine if there are significant differences in flowtimes across experiments. .The Tamhane's T2 test (see Table 5.15) shows that Experiment 10 (Level 4 MS at eight-hour JR) has significantly shorter flowtimes than all other experiments. As mentioned earlier, there is no variance for the results for Experiments 10 – 12. However, by evaluating the mean difference column in Table 5.15, it can be seen that Experiment 10 has the shortest flowtime because all values in the column are negative. Therefore, to obtain the best flowtime, workers should be trained to the highest level of multi-skilling and rotated at the beginning of every shift. The results for average work-in-process are discussed in the next section.

Table 5.13: Tamhane's Test for Average Flowtime across Multi-skilling Levels at each Job Rotation Level

Job Rotation Frequency	(I) Multi-skilling	(J) Multi-skilling	Mean Difference (I-J)	Std. Error	Sig.
8-Hour (Level 1)	Level 1	Level 2	-1.7808684*	.18215623	**.000**
		Level 3	.7951137*	.05779948	**.000**
		Level 4	.9085101*	.05777457	**.000**
	Level 2	Level 3	2.5759820*	.17275957	**.000**
		Level 4	2.6893785*	.17275124	**.000**
	Level 3	Level 4	.1133965*	.00169656	**.000**
4-Hour (Level 2)	Level 1	Level 2	.9347845*	.03837787	**.000**
		Level 3	.3306691*	.07710325	**.000**
		Level 4	1.0803047*	.03825502	**.000**
	Level 2	Level 3	-.6041153*	.06701402	**.000**
		Level 4	.1455203*	.00306822	**.000**
	Level 3	Level 4	.7496356*	.06694374	**.000**
2-Hour (Level 3)	Level 1	Level 2	1.3958309*	.04531139	**.000**
		Level 3	1.0879376*	.06173387	**.000**
		Level 4	1.4543563*	.04530945	**.000**
	Level 2	Level 3	-.3078933*	.04193208	**.000**
		Level 4	.0585254*	.00041856	**.000**
	Level 3	Level 4	.3664187*	.04192999	**.000**

*The mean difference is significant at the .05 level.

Table 5.14: ANOVA for Average Flowtimes across Experiments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	577.572*	11	52.507	183.378	.000
Intercept	780.299	1	780.299	2725.182	.000
Exp	577.572	11	52.507	183.378	.000
Error	271.440	948	.286		
Total	1629.310	960			
Corrected Total	849.012	959			

*Adjusted R Squared = .677

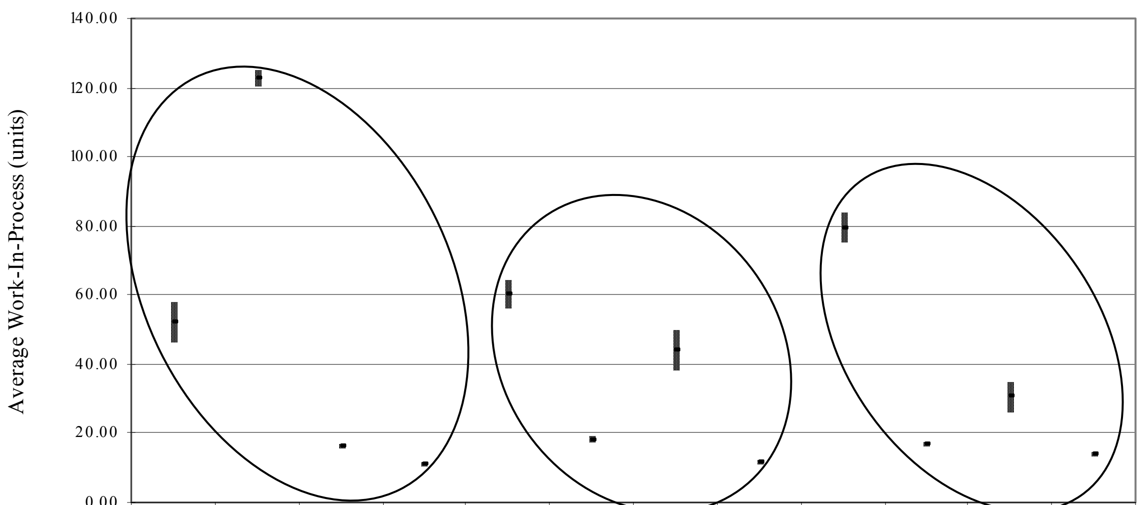
Table 5.15: Tamhane's Test for Average Flowtime by Experiment

(I) Experiment	(J) Experiment	Mean Difference (I-J)	Std. Error	Sig.
10.00	1.00	-.9085101	.05777457	**.000***
	2.00	-1.0914177	.03825502	**.000***
	3.00	-1.5172329	.04530945	**.000***
	4.00	-2.6893785	.17275124	**.000***
	5.00	-.1566332	.00306822	**.000***
	6.00	-.1214021	.00041856	**.000***
	7.00	-.1133965	.00169656	**.000***
	8.00	-.7607486	.06694374	**.000***
	9.00	-.4292953	.04192999	**.000***
	11.00	-.0111130	.00000000	
	12.00	-.0628766	.00000000	
11.00	1.00	-.8973972	.05777457	**.000***
	2.00	-1.0803047	.03825502	**.000***
	3.00	-1.5061200	.04530945	**.000***
	4.00	-2.6782655	.17275124	**.000***
	5.00	-.1455203	.00306822	**.000***
	6.00	-.1102891	.00041856	**.000***
	7.00	-.1022835	.00169656	**.000***
	8.00	-.7496356	.06694374	**.000***
	9.00	-.4181824	.04192999	**.000***
	12.00	-.0517637	.00000000	
12.00	1.00	-.8456335	.05777457	**.000***
	2.00	-1.0285411	.03825502	**.000***
	3.00	-1.4543563	.04530945	**.000***
	4.00	-2.6265019	.17275124	**.000***
	5.00	-.0937566	.00306822	**.000***
	6.00	-.0585254	.00041856	**.000***
	7.00	-.0505198	.00169656	**.000***
	8.00	-.6978720	.06694374	**.000***
	9.00	-.3664187	.04192999	**.000***

*The mean difference is significant at the .05 level.

5.4.2 Average Work-In-Process

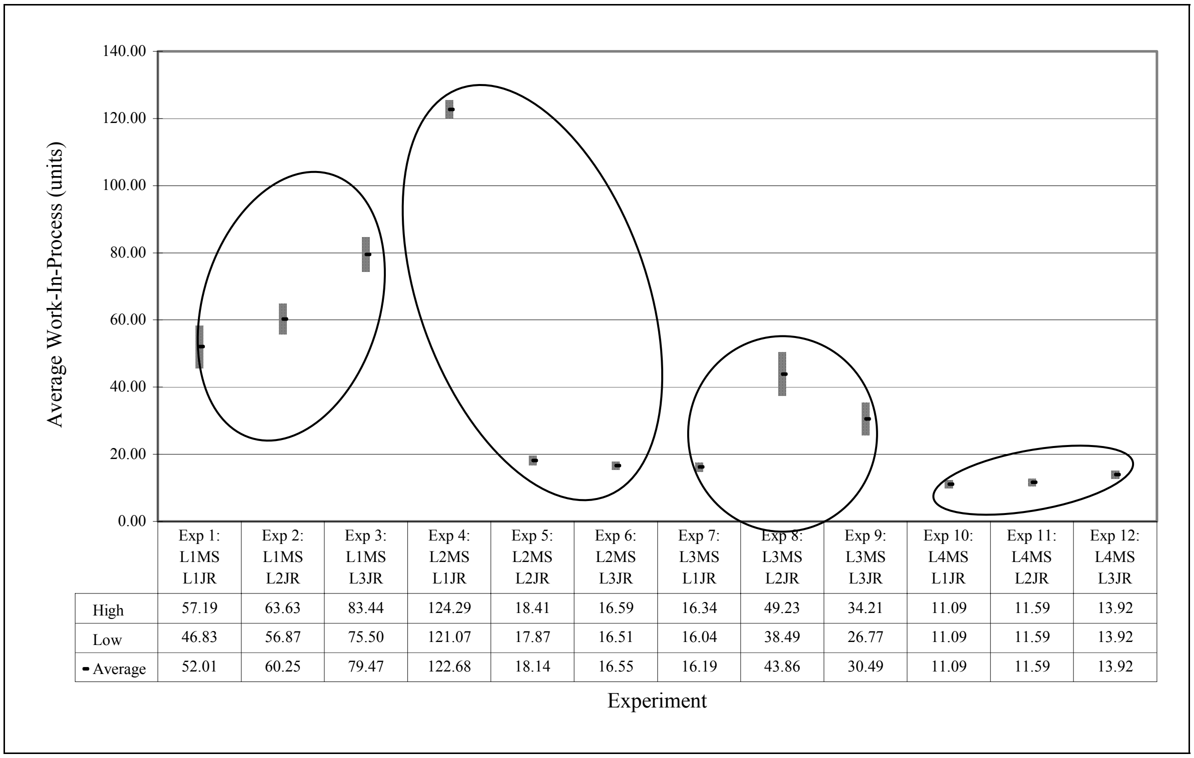
Figures 5.5 and 5.6 show the 95% confidence intervals for work-in-process grouped by job rotation and multi-skilling, respectively. Figure 5.7 shows the work-in-process for each level of multi-skilling and job rotation using a Lowess plot. As described in the previous section, this plot uses an iterative locally weighted least-squares method to fit a curve to a set of points. The Lowess plot was used to compensate for the effect outliers have on the mean for each multi-skilling level and job rotation frequency. The non-parallel lines in the Lowess plot for average work-in-process indicate there is an interaction effect between multi-skilling and job rotation. Table 5.16 shows the results of an ANOVA, which indicate that multi-skilling, job rotation, and the interaction effect are all significant at the .05 level. Because the interaction effect is significant, inferences about the effect of one factor should not be made without considering the level of the second factor. That is, the effect of job rotation on work-in-process is not the same at all levels of multi-skilling.



	Exp 1: L1MS L1JR	Exp 4: L2MS L1JR	Exp 7: L3MS L1JR	Exp 10: L4MS L1JR	Exp 2: L1MS L2JR	Exp 5: L2MS L2JR	Exp 8: L3MS L2JR	Exp 11: L4MS L2JR	Exp 3: L1MS L3JR	Exp 6: L2MS L3JR	Exp 9: L3MS L3JR	Exp 12: L4MS L3JR
High	57.19	124.29	16.34	11.09	63.63	18.41	49.23	11.59	83.44	16.59	34.21	13.92
Low	46.83	121.07	16.04	11.09	56.87	17.87	38.49	11.59	75.50	16.51	26.77	13.92
Average	52.01	122.68	16.19	11.09	60.25	18.14	43.86	11.59	79.47	16.55	30.49	13.92

Experiment

Figure 5.5: 95% Confidence Interval for Average WIP Grouped by Job Rotation



	Exp 1: L1MS L1JR	Exp 2: L1MS L2JR	Exp 3: L1MS L3JR	Exp 4: L2MS L1JR	Exp 5: L2MS L2JR	Exp 6: L2MS L3JR	Exp 7: L3MS L1JR	Exp 8: L3MS L2JR	Exp 9: L3MS L3JR	Exp 10: L4MS L1JR	Exp 11: L4MS L2JR	Exp 12: L4MS L3JR
High	57.19	63.63	83.44	124.29	18.41	16.59	16.34	49.23	34.21	11.09	11.59	13.92
Low	46.83	56.87	75.50	121.07	17.87	16.51	16.04	38.49	26.77	11.09	11.59	13.92
- Average	52.01	60.25	79.47	122.68	18.14	16.55	16.19	43.86	30.49	11.09	11.59	13.92

Figure 5.6: 95% Confidence Interval for Average WIP Grouped by Multi-skilling

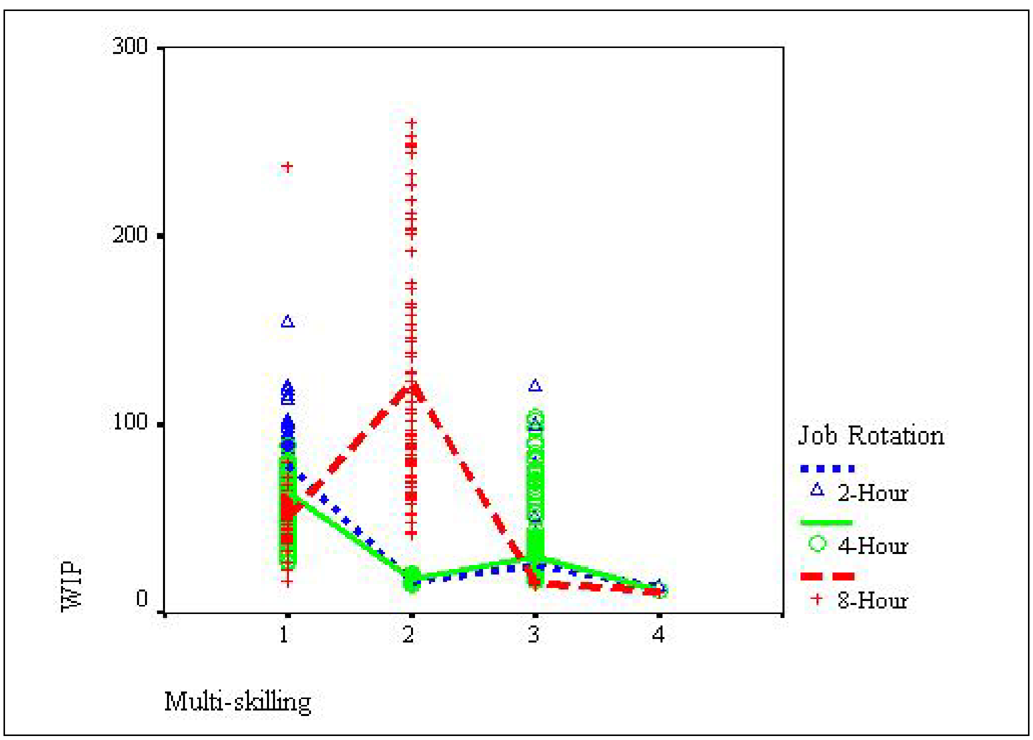


Figure 5.7: Lowess Plot for Average WIP by Multi-skilling Level

Table 5.16: ANOVA for Average Work-In-Process

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1037666.511*	11	94333.319	182.568	**.000**
Intercept	1511999.546	1	1511999.546	2926.247	**.000**
MS	383018.549	3	127672.850	247.092	**.000**
JR	56486.319	2	28243.159	54.660	**.000**
MS * JR	598161.644	6	99693.607	192.942	**.000**
Error	489834.079	948	516.703		
Total	3039500.136	960			
Corrected Total	1527500.590	959			

*Adjusted R Squared = .676

From Figure 5.7 it appears that there may be non-homogeneous variances across all job rotation levels. For example, the individual data points for Level 2 job rotation at Level 2 multi-skilling are tightly clustered, while the individual data points for Level 2 job rotation at Level 3 multi-skilling are dispersed across a much greater range of work-in-process values. Thus, the variances of work-in-process across each experiment do not appear to be homogeneous. Levene's test for equality of variances was conducted to investigate if there are significant differences in variances in work-in-process results across job rotation levels at each multi-skilling level (see Table 5.17). For Level 1 multi-skilling, the variances in WIP results across job rotation levels are not significantly different at the .05 level. For multi-skilling levels 2 and 3, the variances in WIP results across job rotation levels are significantly different at the .05 level. The difference in variances may have been caused by the same reasons discussed for flowtime.

Table 5.17: Levene's Test for Average WIP across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	F	df1	df2	Sig.
Level 1	1.319	2	237	**.269**
Level 2	202.970	2	237	**.000***
Level 3	67.964	2	237	**.000***

*Significant at the .05 level

The interaction between multi-skilling and job rotation prevents interpretations across each factor, but observations within the levels of each factor can be made. From Figure 5.7

and Table 5.6, it appears that for all levels of multi-skilling except Level 2, the eight-hour job rotation has the least work-in-process. An ANOVA was conducted to investigate if there are significant differences in work-in-process across job rotation levels at each multi-skilling level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). As with flowtime, Tamhane's T2 test is used to determine if there are significant differences in work-in-process within each multi-skilling level.

At each multi-skilling level, work-in-process results across job rotation levels are significantly different at the .05 level (see Table 5.18). Because the results from Level 4 multi-skilling are constant at each job rotation frequency, there is no variance; therefore ANOVA could not be performed at Level 4 multi-skilling to determine if there are differences in the WIP for the three job rotation levels. The results from Tamhane's T2 tests ($\alpha = 0.05$), shown in Table 5.19, indicate where the differences are.

Table 5.18: ANOVA for Average WIP across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	31774.319	2	15887.159	42.390	**.000**
	Intercept	980304.501	1	980304.501	2615.611	**.000**
	JR	31774.319	2	15887.159	42.390	**.000***
Level 2	Corrected Model	591867.973	2	295933.987	212.048	**.000**
	Intercept	660405.666	1	660405.666	473.207	**.000**
	JR	591867.973	2	295933.987	212.048	**.000***
Level 3	Corrected Model	30640.822	2	15320.411	51.684	**.000**
	Intercept	218600.722	1	218600.722	737.459	**.000**
	JR	30640.822	2	15320.411	51.684	**.000***

*Significant at the .05 level

For multi-skilling Levels 1 and 3, all job rotation levels are significantly different from each other, with the eight-hour job rotation frequency having the least work-in-process. For Level 2 multi-skilling, only the eight-hour rotation is significantly different from the other two levels and it has the highest WIP. As with flowtime, the results for the experiments in Level 4 multi-skilling are constant at each job rotation level. Therefore, an ANOVA, and thus a post-hoc analysis, could not be conducted at Level 4 multi-skilling. Because the post-hoc analysis could not be performed for Level 4 multi-skilling, the results for each job rotation level in that level were directly compared to each other. Because these results are not equal (see Table 5.6), they are significantly different from each other with the eight-hour rotation having the least WIP.

Table 5.19: Tamhane's Test for Average WIP across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	(I) Job Rotation	(J) Job Rotation	Mean Difference (I-J)	Std. Error	Sig.
1	Level 1	Level 2	-8.2336986*	3.06100446	**.030**
		Level 3	-27.4604379*	3.06100446	**.000**
	Level 2	Level 3	-8.2336986*	3.06100446	**.000**
2	Level 1	Level 2	104.5420723*	5.90676805	**.000**
		Level 3	106.1295623*	5.90676805	**.000**
	Level 2	Level 3	1.5874899	5.90676805	**.961**
3	Level 1	Level 2	-27.6718313*	2.74002654	**.000**
		Level 3	-14.3025354*	1.90105174	**.000**
	Level 2	Level 3	13.3692959*	3.33317717	**.000**

*The mean difference is significant at the .05 level

For the same reasons discussed in flowtime, an analysis of each job frequency was conducted to investigate differences in multi-skilling levels.

From Figure 5.8, it appears that there may be non-homogeneous variances across all multi-skilling levels. Levene's test for equality of variances was conducted to investigate if there are significant differences in variances across multi-skilling levels at each job rotation level. For all job rotation levels, Levene's test (Table 5.20) showed that the variances between multi-skilling levels are significantly different at the .05 level. The difference in variances may have been caused by the same reasons discussed in flowtime.

Table 5.20: Levene's Test for Average WIP across Multi-skilling Levels at Job Rotation Levels

Job Rotation Level	F	df1	df2	Sig.
Level 1	134.401	3	316	**.000***
Level 2	145.673	3	316	**.000***
Level 3	42.148	3	316	**.000***

*Significant at the .05 level

From Figure 5.8 and Table 5.5, it appears that for all levels of job rotation, Level 4 multi-skilling has the least work-in-process. An ANOVA was conducted to investigate if there are significant differences in WIP across multi-skilling levels at each job rotation level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). As with flowtime, Tamhane's T2 test is used to determine in there are significant differences in work-in-process within each job rotation frequency.

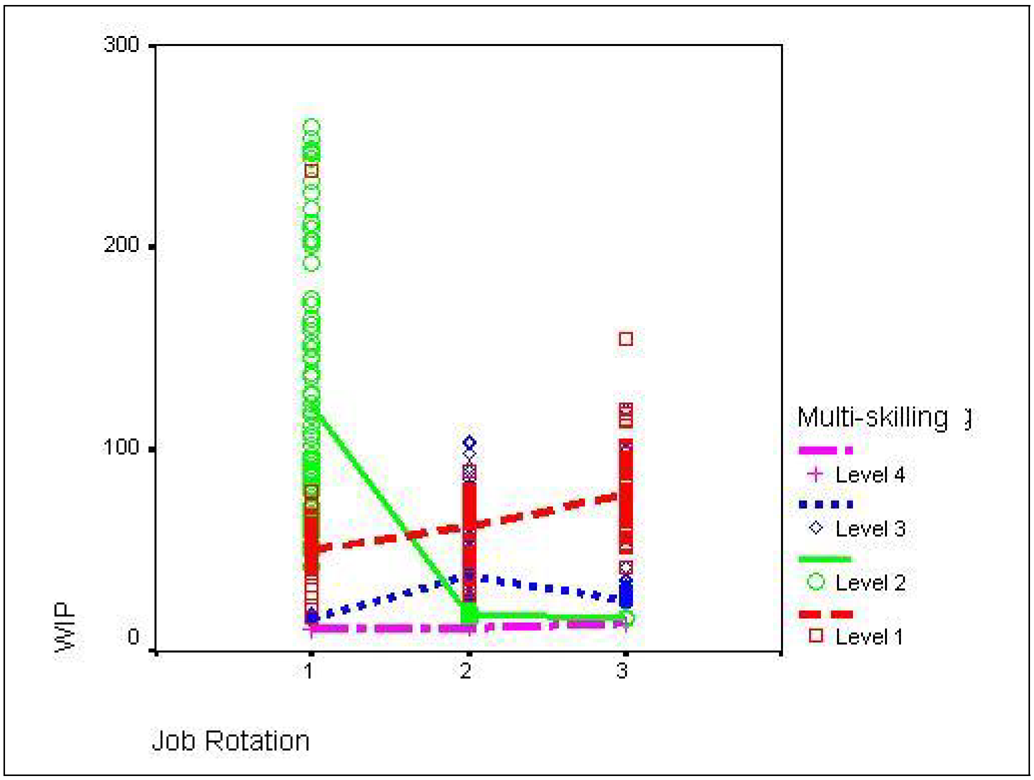


Figure 5.8: Lowess Plot for Average WIP by Job Rotation Frequency

Table 5.21 shows that at each job rotation level, WIP results across multi-skilling levels are significantly different at the .05 level. The results from Tamhane's T2 test (α = 0.05), shown in Table 5.22, indicate where the differences are. Within each job rotation level, the levels of multi-skilling are significantly different from each other with the least amount of WIP occurring at Level 4.

Table 5.21: ANOVA for Average WIP across Multi-skilling Levels at Job Rotation Levels

Job Rotation Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	635432.370	3	211810.790	178.560	**.000**
	Intercept	815834.291	1	815834.291	687.762	**.000**
	MS	635432.370	3	211810.790	178.560	**.000***
Level 2	Corrected Model	123106.776	3	41035.592	195.621	**.000**
	Intercept	358226.129	1	358226.129	1707.703	**.000**
	MS	123106.776	3	41035.592	195.621	**.000***
Level 3	Corrected Model	222641.047	3	74213.682	481.531	**.000**
	Intercept	394425.444	1	394425.444	2559.205	**.000**
	MS	222641.047	3	74213.682	481.531	**.000***

*Significant at the .05 level

Table 5.22: Tamhane's Test for Average WIP across Multi-skilling Levels at each Job Rotation Level

Job Rotation Frequency	(I) Multi-skilling	(J) Multi-skilling	Mean Difference (I-J)	Std. Error	Sig.
8-Hour (Level 1)	Level 1	Level 2	-70.6675880*	7.70097426	**.000**
		Level 3	35.8242365*	2.64479636	**.000**
		Level 4	40.9251484*	2.64369272	**.000**
	Level 2	Level 3	106.4918245*	7.23337611	**.000**
		Level 4	111.5927364*	7.23297265	**.000**
	Level 3	Level 4	5.1009118*	.07639739	**.000**
4-Hour (Level 2)	Level 1	Level 2	42.1081829*	1.72818641	**.000**
		Level 3	16.3861038*	3.23572568	**.000**
		Level 4	48.6587636*	1.72279187	**.000**
	Level 2	Level 3	-25.7220791*	2.74235762	**.000**
		Level 4	6.5505807*	.13644207	**.000**
	Level 3	Level 4	32.2726598*	2.73896127	**.000**
2-Hour (Level 3)	Level 1	Level 2	62.9224122*	2.02431540	**.000**
		Level 3	48.9821390*	2.77590716	**.000**
		Level 4	65.5561383*	2.02422810	**.000**
	Level 2	Level 3	-13.9402732*	1.89960907	**.000**
		Level 4	2.6337262*	.01879993	**.000**
	Level 3	Level 4	16.5739994*	1.89951603	**.000**

*The mean difference is significant at the .05 level

Because the least work-in-process occurs at the Level 4 multi-skilling and at the eight-hour job rotation frequency (Experiment 10), an ANOVA was conducted to determine if work-in-process for experiments is significantly different. The ANOVA showed that WIP is significantly different at the .05 level (see Table 5.23). As with flowtime, Tamhane's T2 test is used to determine in there are significant differences in work-in-process across experiments. The Tamhane's T2 test (see Table 5.24) shows that Experiment 10 has significantly smaller work-in-process values at the .05 level. As mentioned earlier, there is no variance for Experiments 10 – 12. That is, the results for each of those experiments are constant. However, by evaluating the mean difference column Table 5.24, it can be seen that Experiment 10 has the least work-in-process since all values in the column are negative. Therefore, to obtain the lowest work-in-process, workers should be trained to the highest multi-skilling level and rotated at the beginning of every shift.

The impact of multi-skilling and job rotation on work-in-process appears to follow the same trends as found in flowtime. This is to be expected since there is a relationship between flowtime and work-in-process. As WIP increases, additional units are in the system causing units to have to wait longer before being processed. This additional time before processing increases the flowtime. The next section discusses the results for the monthly shipments.

Table 5.23: ANOVA for Average WIP across Experiments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1037666.511*	11	94333.319	182.568	.000
Intercept	1511999.546	1	1511999.546	2926.247	.000
Exp	1037666.511	11	94333.319	182.568	.000
Error	489834.079	948	516.703		
Total	3039500.136	960			
Corrected Total	1527500.590	959			

*Adjusted R Squared = .676

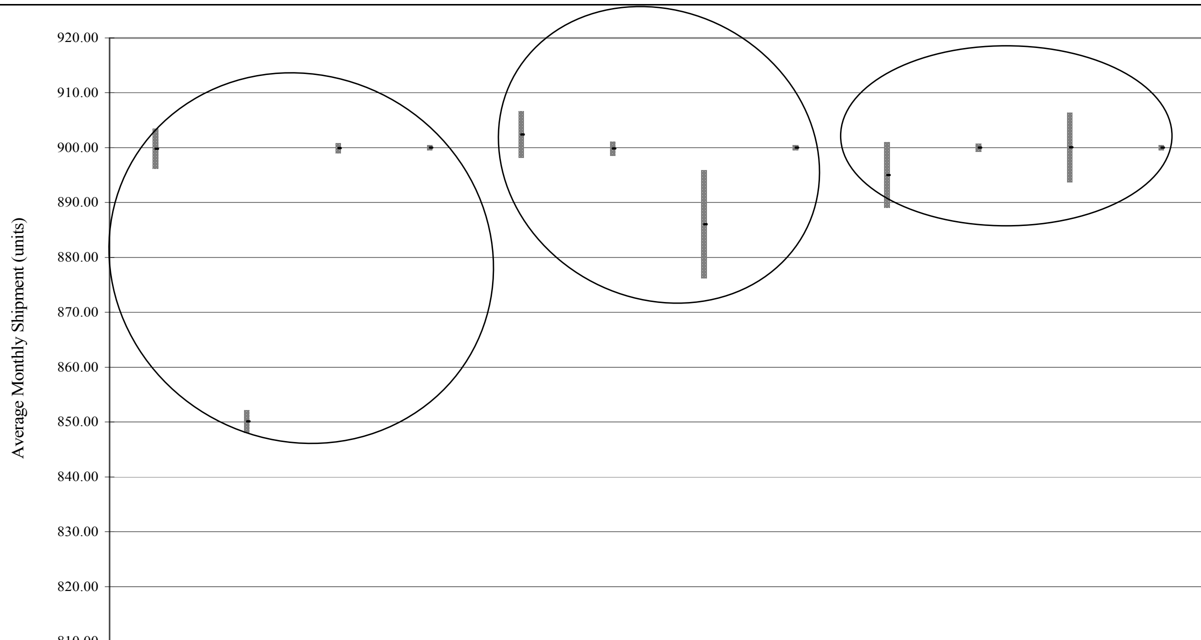
Table 5.24: Tamhane's Test for Average WIP by Experiment

(I) Experiment	(J) Experiment	Mean Difference (I-J)	Std. Error	Sig.
10.00	1.00	-40.9251484	2.64369272	**.000***
	2.00	-49.1588470	1.72279187	**.000***
	3.00	-68.3855863	2.02422810	**.000***
	4.00	-111.5927364	7.23297265	**.000***
	5.00	-7.0506640	.13644207	**.000***
	6.00	-5.4631741	.01879993	**.000***
	7.00	-5.1009118	.07639739	**.000***
	8.00	-32.7727431	2.73896127	**.000***
	9.00	-19.4034473	1.89951603	**.000***
	11.00	-.5000833	.00000000	
	12.00	-2.8294479	.00000000	
11.00	1.00	-40.4250650	2.64369272	**.000***
	2.00	-48.6587636	1.72279187	**.000***
	3.00	-67.8855029	2.02422810	**.000***
	4.00	-111.0926530	7.23297265	**.000***
	5.00	-6.5505807	.13644207	**.000***
	6.00	-4.9630908	.01879993	**.000***
	7.00	-4.6008285	.07639739	**.000***
	8.00	-32.2726598	2.73896127	**.000***
	9.00	-18.9033639	1.89951603	**.000***
	12.00	-2.3293646	.00000000	
12.00	1.00	-38.0957004	2.64369272	**.000***
	2.00	-46.3293990	1.72279187	**.000***
	3.00	-65.5561383	2.02422810	**.000***
	4.00	-108.7632884	7.23297265	**.000***
	5.00	-4.2212161	.13644207	**.000***
	6.00	-2.6337262	.01879993	**.000***
	7.00	-2.2714639	.07639739	**.000***
	8.00	-29.9432952	2.73896127	**.000***
	9.00	-16.5739994	1.89951603	**.000***

*The mean difference is significant at the .05 level

5.4.3 Average Monthly Shipments

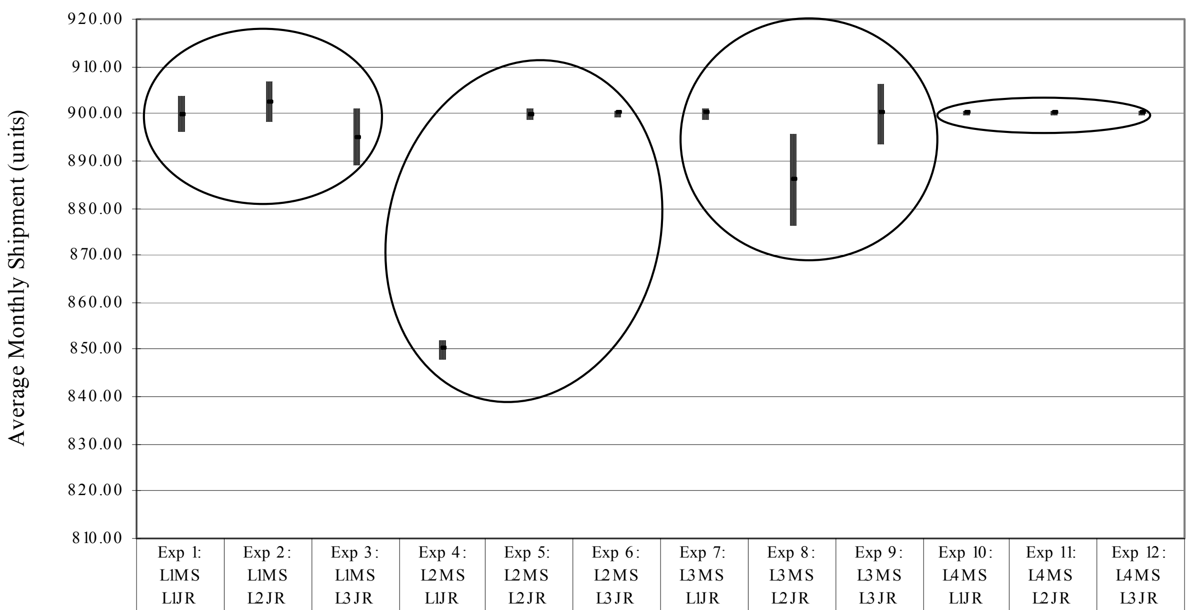
Figures 5.9 and 5.10 show the 95% confidence intervals for monthly shipments grouped by job rotation and multi-skilling, respectively. Figure 5.11 shows the monthly shipments for each level of multi-skilling and job rotation using a Lowess plot. The non-parallel lines in the Lowess plot for average monthly shipments indicate there is an interaction effect. Table 5.25 shows the results of an ANOVA, which indicate that multi-skilling, job rotation, and the interaction effect are all significant at the .05 level. Because the interaction effect is significant, inferences about the effect of one factor should not be made without considering the level of the other factor. That is, the effect of job rotation on monthly shipments is not the same at all levels of multi-skilling.



	Exp 1: L1MS L1JR	Exp 4: L2MS L1JR	Exp 7: L3MS L1JR	Exp 10: L4MS L1JR	Exp 2: L1MS L2JR	Exp 5: L2MS L2JR	Exp 8: L3MS L2JR	Exp 11: L4MS L2JR	Exp 3: L1MS L3JR	Exp 6: L2MS L3JR	Exp 9: L3MS L3JR	Exp 12: L4MS L3JR
High	903.04	848.54	900.38	900.00	906.20	900.64	895.40	900.00	900.53	900.26	905.97	900.00
Low	896.58	851.72	899.44	900.00	898.62	899.02	876.70	900.00	889.47	899.72	894.15	900.00
- Average	899.81	850.13	899.91	900.00	902.41	899.83	886.05	900.00	895.00	899.99	900.06	900.00

Experiment

Figure 5.9: 95% Confidence Interval for Average Monthly Shipments Grouped by Job Rotation



	Exp 1: L1MS L1JR	Exp 2: L1MS L2JR	Exp 3: L1MS L3JR	Exp 4: L2MS L1JR	Exp 5: L2MS L2JR	Exp 6: L2MS L3JR	Exp 7: L3MS L1JR	Exp 8: L3MS L2JR	Exp 9: L3MS L3JR	Exp 10: L4MS L1JR	Exp 11: L4MS L2JR	Exp 12: L4MS L3JR
High	903.04	906.20	900.53	848.54	900.64	900.26	900.38	895.40	905.97	900.00	900.00	900.00
Low	896.58	898.62	889.47	851.72	899.02	899.72	899.44	876.70	894.15	900.00	900.00	900.00
▪ Average	899.81	902.41	895.00	850.13	899.83	899.99	899.91	886.05	900.06	900.00	900.00	900.00

Figure 5.10: 95% Confidence Interval for Average Monthly Shipments Grouped by Multi-skilling

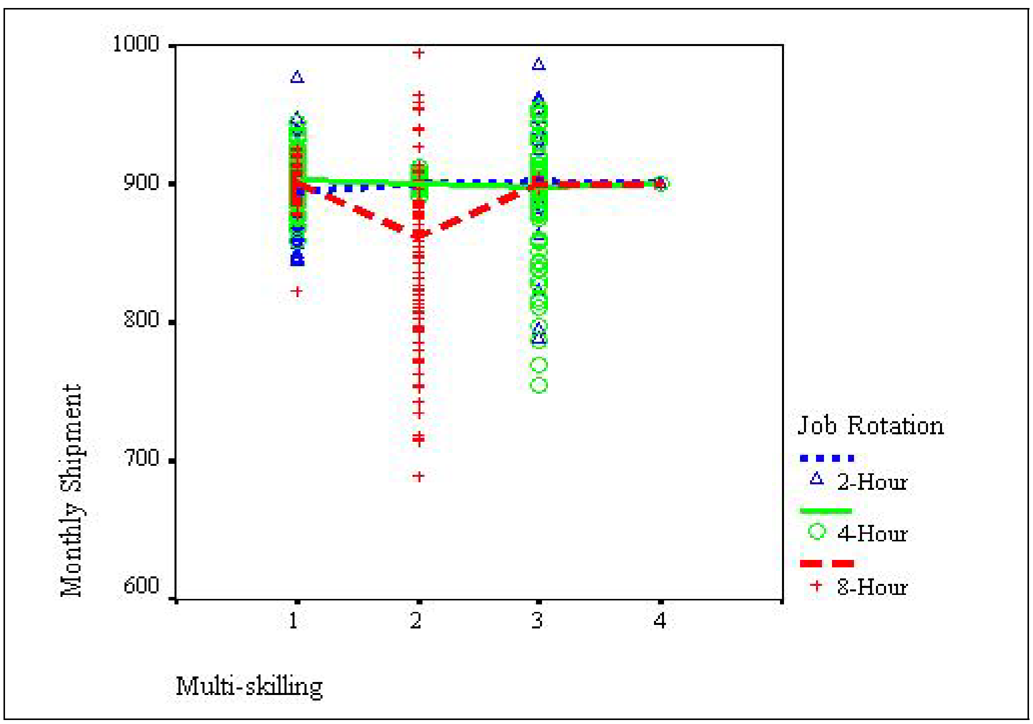


Figure 5.11: Lowess Plot for Average Monthly Shipments

Table 5.25: ANOVA for Average Monthly Shipments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	187281.861*	11	17025.624	26.045	**.000**
Intercept	768008759.401	1	768008759.401	1174860.196	**.000**
MS	42487.403	3	14162.468	21.665	**.000**
JR	23774.752	2	11887.376	18.185	**.000**
MS * JR	121019.706	6	20169.951	30.855	**.000**
Error	619709.738	948	653.702		
Total	768815751.000	960			
Corrected Total	806991.599	959			

*Adjusted R Squared = .223

From Figure 5.11, it appears that there may be non-homogeneous variances across all levels of job rotation. For example, the individual data points for Level 2 job rotation at Level 2 multi-skilling are tightly clustered, while the individual data points for Level 2 job rotation at Level 3 multi-skilling are dispersed across a greater range of monthly shipments. Thus, the variances of monthly shipments across each experiment do not appear to be homogeneous. Levene's test was conducted to determine is there are differences in variances across job rotation levels at each of the first three multi-skilling levels. Levene's test showed that variances for all multi-skilling levels are significantly different at the .05 level (see Table 5.26). The unequal variances for monthly shipments may be caused by the same reasons discussed for flowtime and work-in-process.

Table 5.26: Levene's Test for Average Monthly Shipments across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	F	df1	df2	Sig.
Level 1	9.867	2	237	**.000***
Level 2	141.514	2	237	**.000***
Level 3	43.848	2	237	**.000***

*Significant at the .05 level

The interaction between multi-skilling and job rotation prevents interpretations across each factor, but observations within the levels of each factor can be made. From Figure 5.11 and Table 5.6, the only observation that can be made is that the lowest average monthly shipments occur at Level 2 multi-skilling and eight-hour rotation. An ANOVA was conducted to investigate if there are significant differences in monthly shipments across job rotation levels at each multi-skilling level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). As with flowtime and WIP, Tamhane's T2 test is used to determine in there are significant differences in work-in-process within each multi-skilling level.

Table 5.27 shows that for Level 1 multi-skilling, monthly shipment results across job rotation levels are not significantly different at the .05 level. Table 5.27 also shows that for Levels 2 and 3 multi-skilling, monthly shipment results across job rotation levels are significantly different at the .05 level. Because the monthly shipment results at Level 4 multi-skilling are constant at each job rotation frequency, there is no variance; therefore, ANOVA could not be performed at that level. The results from Tamhane's T2 test (α = 0.05), shown in Table 5.28, indicate where the differences are.

Table 5.27: ANOVA for Average Monthly Shipments across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	2263.075	2	1131.538	2.945	**.055**
	Intercept	194000605.350	1	194000605.350	504957.037	**.000**
	JR	2263.075	2	1131.538	2.945	**.055**
Level 2	Corrected Model	132170.275	2	66085.137	47.893	**.000**
	Intercept	187257833.438	1	187257833.438	135709.316	**.000**
	JR	132170.275	2	66085.137	47.893	**.000***
Level 3	Corrected Model	10361.108	2	5180.554	6.089	**.003**
	Intercept	192392808.017	1	192392808.017	226139.192	**.000**
	JR	10361.108	2	5180.554	6.089	**.003***

*Significant at the .05 level

In Level 2 multi-skilling, only the eight-hour rotation was significantly different, with significantly lower monthly shipments. In Level 3 multi-skilling, only the four-hour rotation was significantly different, with significantly lower monthly shipments. In Level 4 multi-skilling the monthly shipments results for each job rotation frequency are equal (see Table 5.6), and therefore, not significantly different from each other.

Table 5.28: Tamhane's Test for Average Monthly Shipments across Multi-skilling Levels at each Job Rotation Level

Multi-skilling Level	(I) Job Rotation	(J) Job Rotation	Mean Difference (I-J)	Std. Error	Sig.
2	Level 1	Level 2	-49.70*	7.192	**.000**
		Level 3	-49.86*	7.181	**.000**
	Level 2	Level 1	49.70*	7.192	**.000**
		Level 3	-.16	.436	**.976**
3	Level 1	Level 2	13.86*	4.776	**.014**
		Level 3	-.15	3.026	**1.000**
	Level 2	Level 1	-13.86*	4.776	**.014**
		Level 3	-14.01*	5.643	**.042**

*The mean difference is significant at the .05 level

For the same reasons discussed in flowtime, an analysis of each job frequency was conducted to investigate differences in multi-skilling levels.

From Figure 5.12, it appears that there may be non-homogeneous variances across all multi-skilling levels. Levene's test was conducted to investigate if there are significant differences in variances across multi-skilling levels at each job rotation level. For all job rotation levels, Levene's test (Table 5.29) showed that the variances between multi-skilling levels are significantly different at the .05 level. The differences in variances may have been caused by the same reasons discussed in flowtime and work-in-process.

An ANOVA was conducted to investigate if there are significant differences in monthly shipments across multi-skilling levels at each job rotation level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). As with flowtime and WIP, Tamhane's T2 test is used to determine in there are significant differences in work-in-process within each job rotation frequency. Table 5.30 shows that for job rotation Levels 1 and 2, monthly shipment results across multi-skilling levels are significantly different at the .05 level. Table 5.30 also shows that for Level 3 job rotation, monthly shipment results across multi-skilling levels are not significantly different at the .05 level. The results from Tamhane's T2 test ($\alpha = 0.05$), shown in Table 5.31 indicate where the differences are. For Level 1 job rotation, only Level 2 multi-skilling is significantly different from the other three levels, with significantly lower monthly shipments. For Level 2 job rotation, only Level 3 multi-skilling is significantly different , with significantly lower monthly shipments.

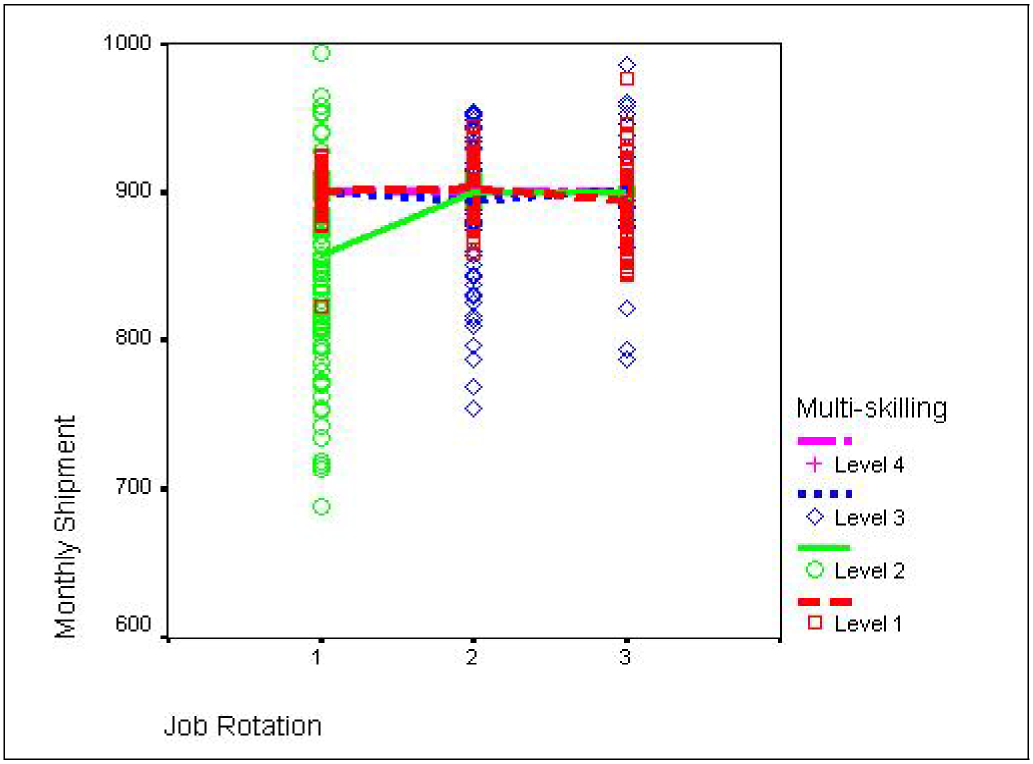


Figure 5.12: Lowess Plot for Average Monthly Shipments by Job Rotation Frequency

Table 5.29: Levene's Test for Average Monthly Shipments across Multi-skilling Levels at Job Rotation Levels

Job Rotation Level	F	df1	df2	Sig.
Level 1	124.853	3	316	**.000***
Level 2	79.451	3	316	**.000***
Level 3	32.653	3	316	**.000***

*Significant at the .05 level

Table 5.30: ANOVA for Average Monthly Shipments across Multi-skilling Levels at Job Rotation Levels

Job Rotation Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	148704.225	3	49568.075	45.619	**.000**
	Intercept	252028700.450	1	252028700.450	231949.422	**.000**
	MS	148704.225	3	49568.075	45.619	**.000***
Level 2	Corrected Model	13292.609	3	4430.870	8.309	**.000**
	Intercept	257516143.653	1	257516143.653	482884.590	**.000**
	MS	13292.609	3	4430.870	8.309	**.000***
Level 3	Corrected Model	1510.275	3	503.425	1.475	**.221**
	Intercept	258487690.050	1	258487690.050	757468.343	**.000**
	MS	1510.275	3	503.425	1.475	**.221**

*Significant at the .05 level

Table 5.31: Tamhane's Test for Average Monthly Shipments across Multi-skilling Levels at each Job Rotation Level

Job Rotation Frequency	(I) Multi-skilling	(J) Multi-skilling	Mean Difference (I-J)	Std. Error	Sig.
8-Hour (Level 1)	Level 1	Level 2	49.69*	7.367	**.000**
		Level 3	-.10	1.666	**1.000**
		Level 4	-.19	1.648	**1.000**
	Level 2	Level 3	-49.79*	7.184	**.000**
		Level 4	-49.87*	7.180	**.000**
	Level 3	Level 4	-.09	.239	**.999**
4-Hour (Level 2)	Level 1	Level 2	2.59	1.979	**.727**
		Level 3	16.36*	5.147	**.012**
		Level 4	2.41	1.935	**.768**
	Level 2	Level 3	13.78*	4.788	**.030**
		Level 4	-.17	.414	**.999**
	Level 3	Level 4	-13.95*	4.770	**.027**

*The mean difference is significant at the .05 level

From Figure 5.12, it appears that Level 1 job rotation at Level 2 multi-skilling has the lowest monthly shipments. An ANOVA was conducted to determine if monthly shipments across experiments are significantly different. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). As with flowtime and WIP, Tamhane's T2 test is used to determine if there are significant differences in monthly shipments across experiments. The ANOVA (Table 5.32) showed that monthly shipment results across experiments are significantly different at the .05 level. Tamhane's T2 test (see Table 5.33) shows that Experiment 4 has significantly lower average monthly shipments. Experiment 4 is the one considered anomalous based on worker assignment model results. The high number of defects observed in Experiment 4 is reflected in the lower average monthly shipments. The following section discusses limitations of the research for the hypothetical cell.

Table 5.32: ANOVA for Average Monthly Shipments across Experiments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	187281.861*	11	17025.624	26.045	.000
Intercept	768008759.401	1	768008759.401	1174860.196	.000
Exp	187281.861	11	17025.624	26.045	.000
Error	619709.738	948	653.702		
Total	768815751.000	960			
Corrected Total	806991.599	959			

*Adjusted R Squared = .223

Table 5.33: Tamhane's Test for Average Monthly Shipments across Experiments

(I) Experiment	(J) Experiment	Mean Difference (I-J)	Std. Error	Sig.
4.00	1.00	-49.69	7.367	**.000***
	2.00	-52.29	7.436	**.000***
	3.00	-44.87	7.714	**.000***
	5.00	-49.70	7.192	**.000***
	6.00	-49.86	7.181	**.000***
	7.00	-49.79	7.184	**.000***
	8.00	-35.92	8.620	**.004***
	9.00	-49.94	7.788	**.000***
	10.00	-49.87	7.180	**.000***
	11.00	-49.87	7.180	**.000***
	12.00	-49.87	7.180	**.000***

*The mean difference is significant at the .05 level

5.5 Limitations of Hypothetical Cell

In interpreting results from the hypothetical cell, it is important to consider limitations of the study. A limitation of the worker assignment model is that the experiments are interdependent. All of the multi-skilling levels are developed from the initial given set of inputs used in the first level. When going to Level 2 multi-skilling, the data for two of the workers from Level 1 were changed such that they were fully trained on all tasks within the cell. This was continued as the level of multi-skilling was increased until all workers were fully trained on all tasks. A second limitation is that the productivity and quality levels associated with each skill level are deterministic. That is, all tasks at a certain skill level have the same productivity and quality levels. Third, the model does not address changing supplier quality, machine downtime, etc. Fourth, the quality level associated with a worker trained to the highest skill level is 100% first pass yield. Because the first pass yield is 100%, there is no expected cost of poor quality for Level 4 multi-skilling. If values other than 100% were used for quality at the highest skill level, then the results for the Level 4 multi-skilling would have non-zero values. Fifth, for Level 4 multi-skilling, all workers are fully trained on all tasks resulting in no expected incremental cost of training. An incremental cost of training would be expected if the workers were not fully trained on all tasks at Level 4 multi-skilling. Sixth, the optimization results are for a single replication of the worker assignment model. Multiple replications of each factor combination would increase generalizability.

5.6 Summary of the Results for the Hypothetical Cell

To provide a subjective assessment of the overall performance across all measures, the experiments were rated as either "good," "neutral," or "poor" based on results for each measure. The rating criteria for each dependent measure from the worker assignment model and the simulation model, as well as for the net present cost, are shown in Table 5.34. The criteria for all measures except monthly shipments were developed by rank ordering the results in ascending order and determining where natural divisions within each measure occur. For the ascending values of the cost of poor quality shown in Figure 5.13, there is a cluster below $20,000, another cluster between $20,000 and $50,000, and all other points are above $50,000. The criteria for monthly shipments were determined by how well the model met customer demand with minimum overproduction. Table 5.35 shows how the experiments compare to each other within each of the dependent measures as well as providing an overall view across all of the measures.

While all of the performance measures from the worker assignment model and the simulation model are shown in Table 5.35, only the net present cost, average flowtime, average work-in-process, and average monthly shipments are shaded and discussed for the subjective assessment. Overproduction, the cost of poor quality, and the incremental cost of training influence the net present cost. Thus, the NPC provides a cost-based measure of the results from the worker assignment model. Average flowtime, work-in-process, and monthly shipments are the performance measures associated with the simulation model.

Table 5.34: Criteria Ratings for Hypothetical Cell

Performance Measure	"Good" Rating	"Neutral" Rating	"Poor" Rating
Overproduction	< 0.5 units	0.5 – 2 units	> 2 units
Cost of Poor Quality	< $20,000	$20,000 – $50,000	> $50,000
Cost of Incremental Training	< $3,000	$3,000 – $6,000	> $6,000
Net present cost	< $200,000	$200,000 – $750,000	> $750,000
Average Flowtime	< 0.75 days	0.75 – 1.5 days	> 1.5 days
Average Work-In-Process	< 35 units	35 – 70 units	> 70 units
Average Monthly Shipment	899.5 – 901 units	>901 units	< 899.5 units

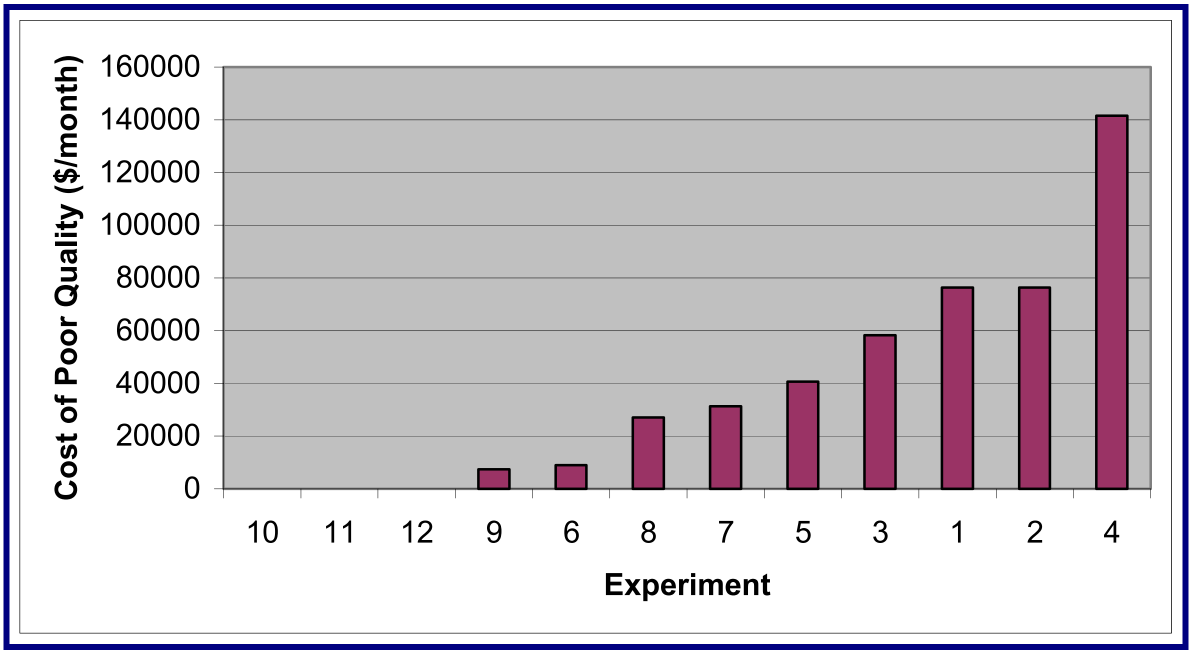


Figure 5.13: Column Chart for Ascending Values of the Cost of Poor Quality

The performance for the NPC is worst for Level 1 job rotation and best for Level 3 as seen in Table 5.35. The performance for the NPC is worst for the Level 1 multi-skilling and best for Level 4. Net present cost improves as the level of multi-skilling increases.

As found in the discussion of the simulation results, the average flowtime and average WIP follow the same trends. Both measures perform worst at Level 1 multi-skilling and best at Level 4 multi-skilling. Level 2 job rotation has the worst performance for average flowtime and average work-in-process. Average monthly shipments remain similar throughout the levels of multi-skilling and job rotation. However, the highest level of multi-skilling has the best performance on monthly shipments. Overall, the two-hour job rotation level performs the best for monthly shipments.

Table 5.35: Relative Performance for all Dependent Variables for the Hypothetical Cell

Number	Experiment	Over-production	Cost of Poor Quality	Incremental Cost of Training	Net Present Cost	Avg. Flowtime	Avg. WIP	Average Monthly Shipment
1	**L1 MS, L1 JR**	○	◊	◊	◊	○	○	○
2	**L1 MS, L2 JR**	●	◊	◊	◊	○	○	○
3	**L1 MS, L3 JR**	●	◊	◊	○	◊	◊	◊
4	**L2 MS, L1 JR**	●	◊	○	◊	◊	◊	◊
5	**L2 MS, L2 JR**	○	○	○	○	●	●	●
6	**L2 MS, L3 JR**	●	●	○	●	●	●	●
7	**L3 MS, L1 JR**	○	○	●	○	●	●	●
8	**L3 MS, L2 JR**	◊	○	●	○	○	○	◊
9	**L3 MS, L3 JR**	●	●	●	●	○	○	●
10	**L4 MS, L1 JR**	●	●	●	●	●	●	●
11	**L4 MS, L2 JR**	●	●	●	●	●	●	●
12	**L4 MS, L3 JR**	●	●	●	●	●	●	●

● = Good, ○ = Neutral, ◊ = Poor

Level 4 multi-skilling, regardless of job rotation frequency, has the lowest levels of overproduction, lowest cost of poor quality, lowest cost of training, and lowest net present cost. Experiments 10 – 12 (Level 4 multi-skilling experiments) have significantly ($\alpha = 0.05$) shorter flowtimes and lower levels of WIP. A possible reason for Level 4 multi-skilling having the best results is that all workers are fully trained on all tasks, resulting in no overproduction, no cost of poor quality, and no incremental cost of training. With no overproduction, cost of poor quality, or incremental cost of training, the net present cost decreases significantly. The costs associated with the first two of these measures are monthly costs that would be carried throughout the year. Because workers are fully trained at Level 4 multi-skilling, there are no defects, and thus fewer units that need to be processed. Improving quality and reducing the number of units processed have a two-fold effect on flowtime and work-in-process. By processing less, fewer units are in the system. The fewer units in the system, the less time any unit has to wait before being processed, thus reducing the flowtime. By improving quality there is a better chance the unit is processed through all tasks without having to be reworked, resulting in an improved flowtime and less work-in-process.

Chapter 6 : Results and Discussion for the Case Application

To test the applicability of the model for an actual production cell, data was collected from Industrial Motors, and entered into the worker assignment model and the simulation model to analyze the impact of alternative levels of multi-skilling and job rotation. As with the hypothetical cell, the worker assignment model was solved using CPLEX. All experiments for the worker assignment model were solved with integrality set to at least 1.0e-3. Table 6.1 provides a summary of each experiment in terms of multi-skilling and job rotation.

Table 6.1: Description of Experiments and Factors

Experiment	Multi-skilling Level	Description	Job Rotation Level	Description
1	1	All workers are trained on at least two tasks	1	8-hour rotation
2	1		2	4-hour rotation
3	1		3	2-hour rotation
4	2	33% of all workers are fully trained on half (12) of the tasks	1	8-hour rotation
5	2		2	4-hour rotation
6	2		3	2-hour rotation
7	3	67% of all workers are fully trained on half (12) of the tasks	1	8-hour rotation
8	3		2	4-hour rotation
9	3		3	2-hour rotation
10	4	All workers are fully trained on half (12) of the tasks	1	8-hour rotation
11	4		2	4-hour rotation
12	4		3	2-hour rotation

As described in Chapter 4, the experimental design for the case application is modeled similarly to the hypothetical cell, but there are unavoidable differences because the actual production cell is already in existence. First, a skill level of four for a task does not correspond to 100% quality levels for all tasks (first pass yield), as it does in the hypothetical cell. Second, not all tasks in the case application detect defects as the tasks in the hypothetical cell do. That is, in the case application defects are only detected at certain testing and inspection points while defects in the hypothetical cell are detected at all tasks. Third, workers are fully trained on at least half of the tasks, to represent the highest level of multi-skilling for a worker, rather than on all tasks when going from one multi-skilling level to the next. Lastly, workers in the case application cannot be assigned to a task at skill level 1, while workers in the hypothetical cell could be assigned to a task at skill level 1.

The results from the worker assignment model are presented in Section 6.1 and discussed in Section 6.2. The results for the simulation model are presented in Section 6.3 and discussed in Section 6.4. Section 6.5 discusses the limitation of the case application. Section 6.6 discusses the overall results for the case application. The last section of this chapter compares the results from the hypothetical and case application cells.

6.1 Results for the Worker Assignment Model for the Case Application

The results for the number of units overproduced, the cost of poor quality, and the cost of training for each experiment are shown in Table 6.3 and Table 6.2, grouped by multi-skilling and job rotation, respectively. Overproduction is the number of units overproduced on a monthly basis for each experiment. The cost of poor quality is the cost for producing defects on a monthly basis. The incremental cost of training is the one-time cost associated with training workers during the current working month. Detailed information on the task each worker was trained on, the beginning skill level, the ending skill level, and the incremental cost of training for each worker in the case application can be found in Appendix D.1.

Table 6.2: Worker Assignment Model Results Grouped by Job Rotation Level

Number	Experiment	Overproduction (units/month)	Cost of Poor Quality ($/month)	Incremental Cost of Training ($)
1	**L1 MS, L1 JR**	0	94,463	18,796
4	**L2 MS, L1 JR**	0	92,830	16,979
7	**L3 MS, L1 JR**	0	82,207	14,074
10	**L4 MS, L1 JR**	0	81,242	9,443
2	**L1 MS, L2 JR**	0	96,161	16,979
5	**L2 MS, L2 JR**	0	89,758	16,979
8	**L3 MS, L2 JR**	1	87,036	11,986
11	**L4 MS, L2 JR**	0	95,470	12,349
3	**L1 MS, L3 JR**	0	98,943	18,251
6	**L2 MS, L3 JR**	0	91,412	15,981
9	**L3 MS, L3 JR**	0.5	86,134	15,436
12	**L4 MS, L3 JR**	0	96,650	13,075

For further analysis of the experimental results, the net present cost for a one-year period is calculated for each of the experiments to evaluate the results on a cost basis. The NPC is comprised of the cost of the current multi-skilling level, the cost of overproduction, the cost of poor quality, and the incremental cost of training. The cost of the current multi-skilling level is determined by totaling the cost for workers to reach their current level of training from an unskilled state (skill level 1). For example, the cost to fully train all workers to skill level 4 on half of the tasks (Level 4 multi-skilling) is $172,520. The NPC for each of the experiments is shown in Table 6.4. The net present cost is the sum of the cost of the multi-skilling level, the cost of overproduction, the cost of poor quality, and the incremental cost of training. The cost of overproduction is determined using the number of units overproduced, the cost of a unit at the end of the line ($1,373), plus a 15% holding cost. An interest rate of 12% per year compounded monthly was used.

Table 6.3: Worker Assignment Model Results Grouped by Multi-skilling Level

Number	Experiment	Overproduction (units/month)	Cost of Poor Quality ($/month)	Incremental Cost of Training ($)
1	**L1 MS, L1 JR**	0	94,463	18,796
2	**L1 MS, L2 JR**	0	96,161	16,979
3	**L1 MS, L3 JR**	0	98,943	18,251
4	**L2 MS, L1 JR**	0	92,830	16,979
5	**L2 MS, L2 JR**	0	89,758	16,979
6	**L2 MS, L3 JR**	0	91,412	15,981
7	**L3 MS, L1 JR**	0	82,207	14,074
8	**L3 MS, L2 JR**	1	87,036	11,986
9	**L3 MS, L3 JR**	0.5	86,134	15,436
10	**L4 MS, L1 JR**	0	81,242	9,443
11	**L4 MS, L2 JR**	0	95,470	12,349
12	**L4 MS, L3 JR**	0	96,650	13,075

6.2 *Discussion of the Worker Assignment Model Results*

Due to the sequential goal programming approach, the overproduction goal of the model limits the solutions for the cost-of-poor-quality and cost-of-training goals and the cost-of-poor-quality goal limits the solution of the cost-of-training goal. The cost-of-poor-quality goal attempts to minimize the cost of defects by training as many workers as possible to improve quality levels and thus, reduce the number of defects.

Table 6.4: Net Present Cost of Experiments

Number	Experiment	Cost of MS Level ($)	Cost of Overproduction ($)/month	Cost of Poor Quality ($/month)	Incremental Cost of Training ($)	Net Present Cost ($)
1	**L1 MS, L1 JR**	68,554	0	94,463	18,796	1,150,354
2	**L1 MS, L2 JR**	68,554	0	96,161	16,979	1,167,667
3	**L1 MS, L3 JR**	68,554	0	98,943	18,251	1,200,238
4	**L2 MS, L1 JR**	78,270	0	92,830	16,979	1,139,892
5	**L2 MS, L2 JR**	78,270	0	89,758	16,979	1,105,316
6	**L2 MS, L3 JR**	78,270	0	91,412	15,981	1,122,944
7	**L3 MS, L1 JR**	112,774	0	82,207	14,074	1,051,957
8	**L3 MS, L2 JR**	112,774	1,579	87,036	11,986	1,122,012
9	**L3 MS, L3 JR**	112,774	790	86,134	15,436	1,106,390
10	**L4 MS, L1 JR**	172,520	0	81,242	9,443	1,096,256
11	**L4 MS, L2 JR**	172,520	0	95,470	12,349	1,259,271
12	**L4 MS, L3 JR**	172,520	0	96,650	13,075	1,273,271

6.2.1 Overproduction

There was minimal overproduction for the case application (see Table 6.2). Only two, or 16.7%, of the experiments had any overproduction, with a worst case of one unit being overproduced for a monthly demand of twenty-eight units. There is no consistent pattern for overproduction across levels of multi-skilling. There is no overproduction for Levels 1, 2 and 4 multi-skilling, while Level 3 multi-skilling has two experiments with overproduction.

From Table 6.3, it can be seen that there is no consistent pattern in overproduction across job rotation levels. The eight-hour rotation frequency is the only level that does not have any overproduction. Next is a discussion of the cost of poor quality.

6.2.2 Cost of Poor Quality

As described earlier, the manufacturing cell at Industrial Motors is a mature cell that has high current quality levels due to previous kaizen and process improvement "events" targeted at improving quality. In addition, the cell is dedicated to a single customer, which is one of the most important customers for the plant. Therefore, there has historically been a strong emphasis on achieving and sustaining high quality since the startup of the line.

There is no consistent pattern in the cost of poor quality across multi-skilling levels (see Table 6.2). At Level 1 job rotation, the cost of poor quality decreases as the multi-skilling level increases. At job rotation Levels 2 and 3, the cost of poor quality decreases from Level 1 through Level 3 multi-skilling, then increases from Level 3 to Level 4.

As seen in Table 6.3, Level 1 job rotation typically has the lowest cost of poor quality. A possible reason for Level 1 job rotation having the lowest cost of poor quality is that higher skilled workers may perform the high cost of poor quality tasks longer, thus creating fewer defects at high cost tasks. The following section discusses the results for the incremental cost of training.

6.2.3 Incremental Cost of Training

As shown in Table 6.2, the incremental cost of training typically decreases as the level of multi-skilling increases. As the level of multi-skilling increases, additional workers are fully trained on more tasks, resulting in fewer tasks left that workers can be trained on during the working month, and thus a lower incremental cost of training.

As seen in Table 6.3, the lowest incremental cost of training is typically associated with Level 2 job rotation, while the highest incremental cost is typically associated with Level 3 job rotation. A possible explanation is that Level 2 job rotation provides the greatest flexibility in meeting customer demand without having to train workers to improve productivity and quality. Additionally, the constraints placed on the cost-of-training goal by the first two goals of the worker assignment model greatly affect the outcome for the incremental cost of training. That is, as previously mentioned, the cost-of-training goal is constrained by the solutions of the overproduction goal and the cost-of-poor-quality goal. Next, the net present cost results are discussed.

6.2.4 Net Present Cost

The net present cost is comprised of the cost of the multi-skilling level, the cost of overproduction, the cost of poor quality, and the incremental cost of training. Each higher level of multi-skilling has an increased initial cost measured by the cost of the multi-skilling level. This cost associated with the initial level of multi-skilling is determined by adding the cost required for each worker to reach his/her current level of training from an unskilled state. The case application cell has been in operation for approximately four years, and is a mature cell with four of the thirteen workers not starting from an unskilled state. That is, four of the thirteen workers had some level of training on some of the tasks prior to entering the worker pool for the cell. The costs for the skills these four workers already have are not included in the cost of the multi-skilling level. The net present cost is heavily influenced by the difference between the cost to obtain the next higher level of multi-skilling and the cost of poor quality associated with that level of multi-skilling. For example, the one time cost to go from Level 2 to Level 3 multi-skilling at the highest level of job rotation is $34,504 ($112,774 – $78,270), with a resultant savings of only $5,278/month. Therefore, NPC decreases from $1,122,944 to $1,106,390, or a savings of $16,554 between Experiment 6 (L2 MS, L3 JR) and Experiment 9 (L3 MS, L3 JR).

As shown in Table 6.4, there is no consistent pattern in NPC at each multi-skilling level as job rotation level increases. For Level 1 and Level 4 multi-skilling, NPC increases as the level of job rotation increases. For Level 2 multi-skilling, NPC is lowest for Level 2 job rotation and highest for Level 1. For Level 3 multi-skilling, NPC is lowest for Level 1 job rotation and highest for Level 2. As mentioned previously, the net present cost is strongly influenced by the cost of poor quality. The patterns observed here within each level of multi-skilling are the same patterns observed in the discussion of the cost of poor quality. Also, if Level 3 multi-skilling did not have any overproduction, then Level 3 multi-skilling would have had the lowest NPC across all experiments.

As shown in Table 6.4, there is no consistent pattern in NPC at each job rotation level as multi-skilling level increases. For Level 1 and Level 3 job rotation, NPC decreases from Level 1 through Level 3 multi-skilling, then increases from Level 3 to Level 4 multi-skilling. For Level 2 job rotation, NPC decreases from Level 1 to Level 2 multi-skilling and then increases from Level 2 through Level 4.

6.3 Results for the Simulation Model for the Case Application

The worker assignment schedules (Appendix D.2) from each of the twelve experiments were entered into a simulation model of the case application. The results for each experiment for flowtime, work-in-process, and monthly shipments are shown in Table 6.5 and Table 6.6 grouped by job rotation and multi-skilling, respectively. A 95% confidence interval grouped by job rotation and multi-skilling, respectively, for each of the three performance measures is shown in the corresponding section. See Figures 6.2, 6.3, 6.5, 6.6, 6.8, and 6.9.

Table 6.5: Simulation Model Results Grouped by Job Rotation Level

Number	Experiment	Average Flowtime (days)	Average WIP (units)	Average Monthly Shipments (units)
1	**L1 MS, L1 JR**	2.3475	65.7845	560.00
4	**L2 MS, L1 JR**	2.3370	65.5024	559.80
7	**L3 MS, L1 JR**	2.5223	70.7102	559.93
10	**L4 MS, L1 JR**	2.3534	65.9510	560.07
2	**L1 MS, L2 JR**	2.3214	65.0544	560.07
5	**L2 MS, L2 JR**	2.3515	65.9054	560.07
8	**L3 MS, L2 JR**	2.3478	65.7706	560.00
11	**L4 MS, L2 JR**	2.3539	65.9565	560.00
3	**L1 MS, L3 JR**	2.3856	66.8700	560.00
6	**L2 MS, L3 JR**	2.4017	67.2944	559.80
9	**L3 MS, L3 JR**	2.3979	67.1999	559.87
12	**L4 MS, L3 JR**	2.4060	67.4080	559.80

Table 6.6: Simulation Model Results Grouped by Multi-skilling Level

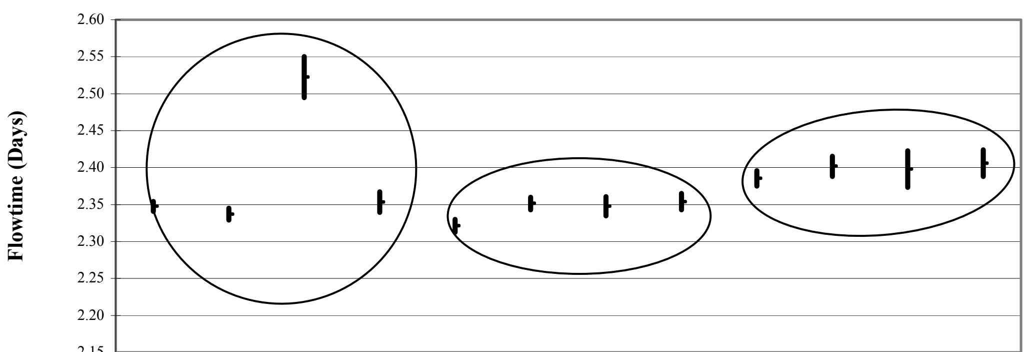
Number	Experiment	Average Flowtime (days)	Average WIP (units)	Average Monthly Shipments (units)
1	**L1 MS, L1 JR**	2.3475	65.7845	560.00
2	**L1 MS, L2 JR**	2.3214	65.0544	560.07
3	**L1 MS, L3 JR**	2.3856	66.8700	560.00
4	**L2 MS, L1 JR**	2.3370	65.5024	559.80
5	**L2 MS, L2 JR**	2.3515	65.9054	560.07
6	**L2 MS, L3 JR**	2.4017	67.2944	559.80
7	**L3 MS, L1 JR**	2.5223	70.7102	559.93
8	**L3 MS, L2 JR**	2.3478	65.7706	560.00
9	**L3 MS, L3 JR**	2.3979	67.1999	559.87
10	**L4 MS, L1 JR**	2.3534	65.9510	560.07
11	**L4 MS, L2 JR**	2.3539	65.9565	560.00
12	**L4 MS, L3 JR**	2.4060	67.4080	559.80

6.4 Discussion of the Simulation Model Results

The following sections describe the simulation results for each of the same three performance measures as in the hypothetical cell: flowtime, work-in-process, and monthly shipments. Definitions for these measures are provided in Chapter 4.

6.4.1 Average Flowtimes

Figures 6.1 and 6.2 show the 95% confidence intervals for flowtimes grouped by job rotation and multi-skilling, respectively. Figure 6.3 shows the flowtime for each level of multi-skilling and job rotation, using a Lowess plot, just as with the hypothetical cell. The non-parallel lines in the Lowess plot for average flowtime indicate there is an interaction effect between multi-skilling and job rotation. Table 6.7 shows the results of an ANOVA, which indicate multi-skilling, job rotation, and the interaction effect are all significant at the .05 level. Because the interaction effect is significant, inferences about the effect of one factor should not be made without considering the level of the second factor. That is, the effect of job rotation on flowtime is not the same at all levels of multi-skilling.

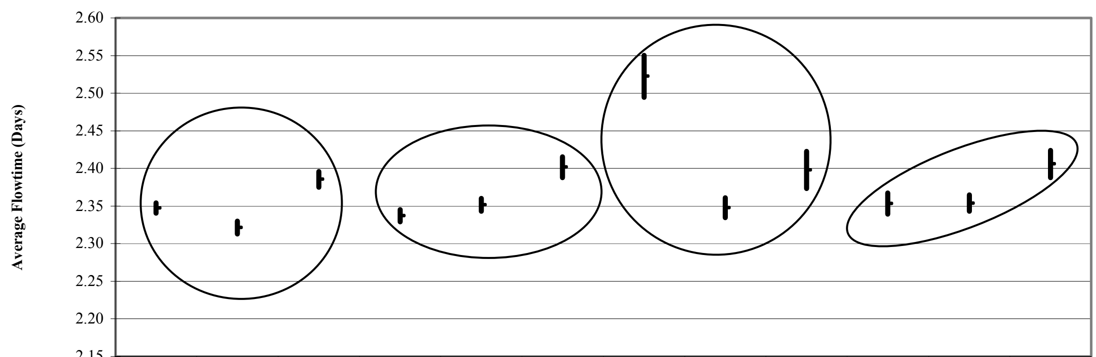


	Exp 1: L1MS L1JR	Exp 4: L2MS L1JR	Exp 7: L3MS L1JR	Exp 10: L4MS L1JR	Exp 2: L1MS L2JR	Exp 5: L2MS L2JR	Exp 8: L3MS L2JR	Exp 11: L4MS L2JR	Exp 3: L1MS L3JR	Exp 6: L2MS L3JR	Exp 9: L3MS L3JR	Exp 12: L4MS L3JR
High	2.3543	2.3451	2.5503	2.3673	2.3301	2.3600	2.3608	2.3649	2.3960	2.4155	2.4226	2.4240
Low	2.3408	2.3289	2.4945	2.3395	2.3127	2.3431	2.3347	2.3429	2.3752	2.3878	2.3733	2.3879
- Average	2.3475	2.3370	2.5224	2.3534	2.3214	2.3515	2.3478	2.3539	2.3856	2.4017	2.3980	2.4060

Experiment

Figure 6.1: 95% Confidence Interval for Average Flowtime Grouped by Job Rotation

From Figure 6.3 it appears that there may be non-homogeneous variances across all levels of multi-skilling. For example, the individual data points for Level 2 job rotation and Level 2 multi-skilling are tightly clustered, while the individual data points for Level 2 job rotation and Level 3 multi-skilling are dispersed across a much greater range of flowtimes. Thus, the variances of flowtime across each experiment do not appear to be homogeneous. Levene's test for equality of variances was conducted to investigate if there are significant differences in variances for flowtime results across job rotation levels at each multi-skilling level (see Table 5.8). For multi-skilling levels 1 and 4, the variances in flowtime results across job rotation levels are not significantly different at the .05 level. For multi-skilling levels 2 and 3, the variances in flowtime results across job rotation levels are significantly different at the .05 level.



	Exp 1: L1MS L1JR	Exp 2: L1MS L2JR	Exp 3: L1MS L3JR	Exp 4: L2MS L1JR	Exp 5: L2MS L2JR	Exp 6: L2MS L3JR	Exp 7: L3MS L1JR	Exp 8: L3MS L2JR	Exp 9: L3MS L3JR	Exp 10: L4MS L1JR	Exp 11: L4MS L2JR	Exp 12: L4MS L3JR
High	2.3543	2.3301	2.3960	2.3451	2.3600	2.4155	2.5503	2.3608	2.4226	2.3673	2.3649	2.4240
Low	2.3408	2.3127	2.3752	2.3289	2.3431	2.3878	2.4945	2.3347	2.3733	2.3395	2.3429	2.3879
- Average	2.3475	2.3214	2.3856	2.3370	2.3515	2.4017	2.5224	2.3478	2.3980	2.3534	2.3539	2.4060

Experiment

Figure 6.2: 95% Confidence Interval for Average Flowtime Grouped by Multi-skilling

There may be several reasons for the unequal variances. First, a possible reason is that the simulation model is based on the output from the worker assignment model, which does not take into account the number of defects created within the cell for the overproduction goal. The solution from the overproduction goal constrains the cost-of-poor-quality goal and may result in a greater number of defects than if the cost-of-poor-quality goal was run before the overproduction goal. An increased number of defects would increase the number of units in the system, thus increasing the flowtime. Second, the difference in variances may have been caused by where within the cell units were scrapped. The flowtime for defective units is the total amount of time the unit was in the system before being scrapped plus the time the replacement unit took to be completed. Units scrapped at the later tasks would increase the flowtime more than units scrapped at earlier tasks would.

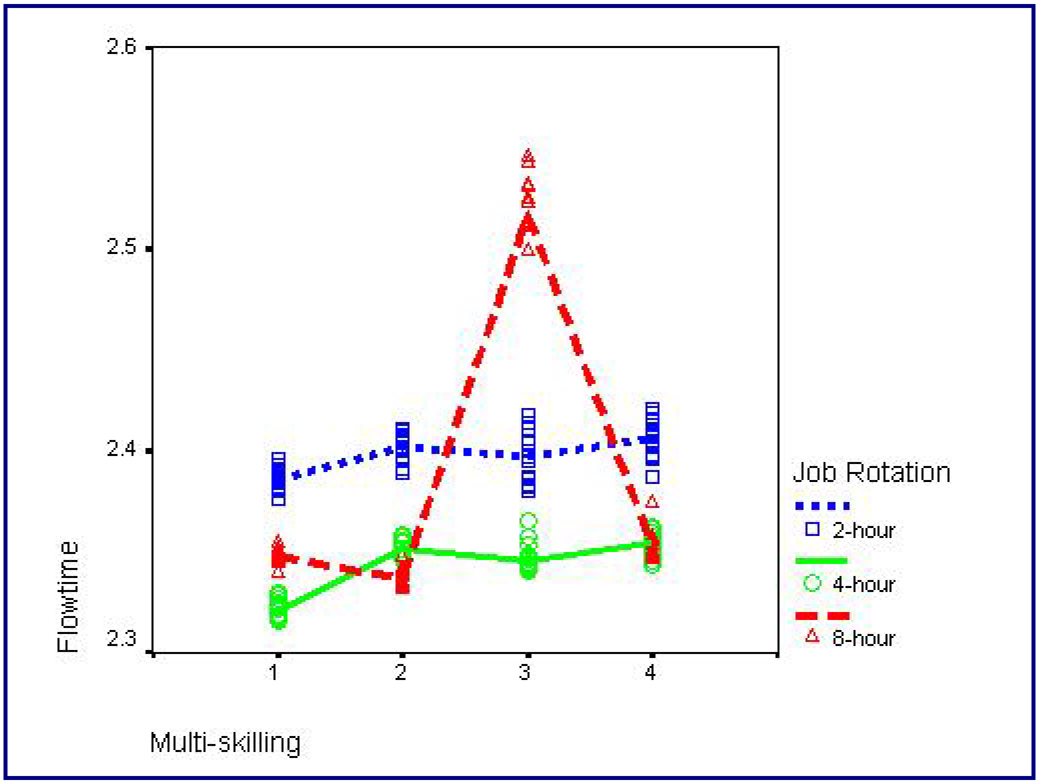


Figure 6.3: Lowess Plot for Average Flowtime by Multi-skilling Level

Table 6.7: ANOVA for Average Flowtime

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.469*	11	4.262E-02	718.192	**.000**
Intercept	1017.174	1	1017.174	17141118.885	**.000**
MS	.133	3	4.437E-02	747.781	**.000**
JR	.103	2	5.147E-02	867.325	**.000**
MS * JR	.233	6	3.879E-02	653.687	**.000**
Error	9.969E-03	168	5.934E-05		
Total	1017.653	180			
Corrected Total	.479	179			

*Adjusted R Squared = .978

Table 6.8: Levene's Test for Flowtime across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	F	df1	df2	Sig.
Level 1	2.068	2	42	**.139**
Level 2	3.674	2	42	**.034***
Level 3	4.743	2	42	**.014***
Level 4	1.336	2	42	**.274**

For example, because a new unit must be started at the beginning of the cell to replace a defective unit, units scrapped at Task 9 increase the average flowtime more than a unit scrapped at Task 4 due to more time in the system before being scrapped. Because flowtime is only calculated for completed units, any unit that was scrapped and restarted, but still in the system when the simulation model ended, is not considered. Third, the differences in the variances may also have been caused by the simulation model requiring workers to finish a unit at a task before rotating to the next scheduled task. That is, workers may have just began processing a unit when a rotation was scheduled to occur, but had to complete the unit prior to rotating, thus increasing the queue time and flowtime of parts at the task the worker was scheduled to work at next.

The interaction between multi-skilling and job rotation prevents interpretations at the factor level, but observations within the levels of each factor can be made. An ANOVA was conducted to investigate if there are significant differences in flowtime across job rotation levels at each multi-skilling level. Because ANOVA assumes homogeneous variances, care must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). Because the variances are unequal, Tamhane's T2 unequal variances test is used to determine if there are significant differences in flowtime within levels of multi-skilling, and across experiments for flowtime. At each multi-skilling level, flowtime results across job rotation levels are significantly different at the .05 level. The results from Tamhane's T2 test ($\alpha = 0.05$), shown in Table 6.9 indicate where the differences are. In Levels 1 and 3 multi-skilling, all levels of job rotation are significantly different from each other with Level 2 job rotation having the shortest flowtime. In Level 2 multi-skilling, all levels of job rotation are significantly different from each other with Level 1 job rotation having the shortest flowtime. In Level 4 multi-skilling, only Level 3 job rotation is significantly different and it has longer flowtimes.

The research sponsor was more interested in, for a given multi-skilling level, what is the best job rotation frequency. The sponsor was not interested in, for a given job rotation frequency, what is the best multi-skilling level, simply because multi-skilling level is not as easily changed as job rotation frequency. Therefore, an analysis of the best level of multi-skilling for a given level of job rotation was not performed.

From Figures 6.1 – 6.3, it appears that Experiment 2 (Level 1 multi-skilling and Level 2 job rotation) has the lowest overall flowtime. An ANOVA was conducted to investigate if the average flowtimes are different across all experiments. The ANOVA (see Table 6.12) showed that flowtimes are significantly different from each other at the .05 level. Tamhane's T2 test (see Table 6.13), shows that Experiment 2 has significantly lower flowtimes than all other experiments, and indicates that the current level of multi-skilling combined with a four-hour job rotation frequency provides the lowest flowtime. The next section discusses the results for work-in-process.

Table 6.9: ANOVA for Flowtimes across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	3.128E-02	2	1.564E-02	790.904	**.000**
	Intercept	248.831	1	248.831	12584830.981	**.000**
	JR	3.128E-02	2	1.564E-02	790.904	**.000***
Level 2	Corrected Model	3.453E-02	2	1.727E-02	606.900	**.000**
	Intercept	251.355	1	251.355	8835029.238	**.000**
	JR	3.453E-02	2	1.727E-02	606.900	**.000***
Level 3	Corrected Model	.243	2	.121	905.918	**.000**
	Intercept	264.127	1	264.127	1973239.500	**.000**
	JR	.243	2	.121	905.918	**.000***
Level 4	Corrected Model	2.735E-02	2	1.367E-02	247.330	**.000**
	Intercept	252.994	1	252.994	4575922.556	**.000**
	JR	2.735E-02	2	1.367E-02	247.330	**.000***

*Significant at the .05 level

Table 6.10: Tamhane's Test for Average Flowtime across Job Rotation Levels at each Multi-skilling Level

Multi-skilling Level	(I) Job Rotation	(J) Job Rotation	Mean Difference (I-J)	Std. Error	Sig.
1	Level 1	Level 2	.026154*	.0014462	**.000**
		Level 3	-.038056*	.0016299	**.000**
	Level 2	Level 3	-.064210*	.0017779	**.000**
2	Level 1	Level 2	-.014535*	.0015417	**.000**
		Level 3	-.064668*	.0021110	**.000**
	Level 2	Level 3	-.050133*	.0021323	**.000**
3	Level 1	Level 2	.174638*	.0040392	**.000**
		Level 3	.124446*	.0048833	**.000**
	Level 2	Level 3	-.050191*	.0036579	**.000**
4	Level 1	Level 2	-.000524	.0023309	**.995**
		Level 3	-.052556*	.0029948	**.000**
	Level 2	Level 3	-.052032*	.0027772	**.000**

*The mean difference is significant at the .05 level.

Table 6.11: ANOVA for Average Flowtimes across Experiments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.469	11	4.262E-02	718.192	.000
Intercept	1017.174	1	1017.174	17141118.885	.000
Exp	.469	11	4.262E-02	718.192	.000
Error	9.969E-03	168	5.934E-05		
Total	1017.653	180			
Corrected Total	.479	179			

*Adjusted R Squared = .979

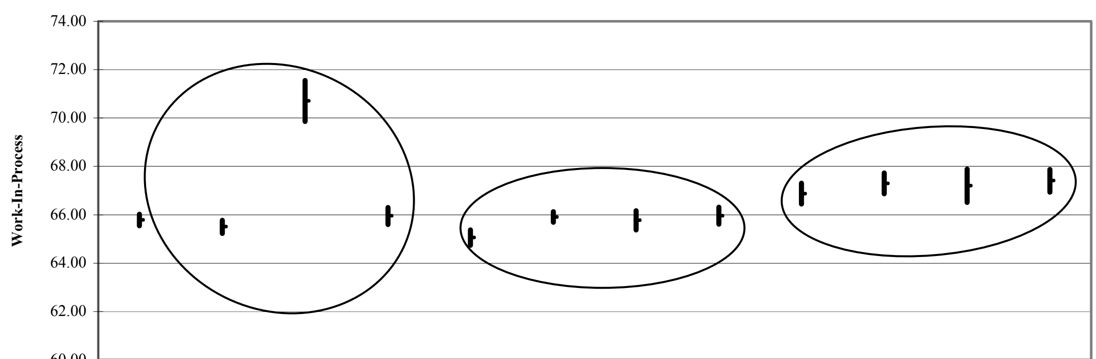
Table 6.12: Tamhane's Test for Flowtime for Experiment 2

(I) Experiment	(J) Experiment	Mean Difference (I-J)	Std. Error	Sig.
2.00	1.00	-.026154	.0014462	**.000***
	3.00	-.064210	.0017779	**.000***
	4.00	-.015615	.0015625	**.000***
	5.00	-.030149	.0015911	**.000***
	6.00	-.080282	.0021473	**.000***
	7.00	-.201011	.0038326	**.000***
	8.00	-.026374	.0020549	**.000***
	9.00	-.076565	.0034284	**.000***
	10.00	-.032015	.0021547	**.000***
	11.00	-.032539	.0018403	**.000***
	12.00	-.084571	.0026310	**.000***

*The mean difference is significant at the .05 level.

6.4.2 Average Work-in-Process

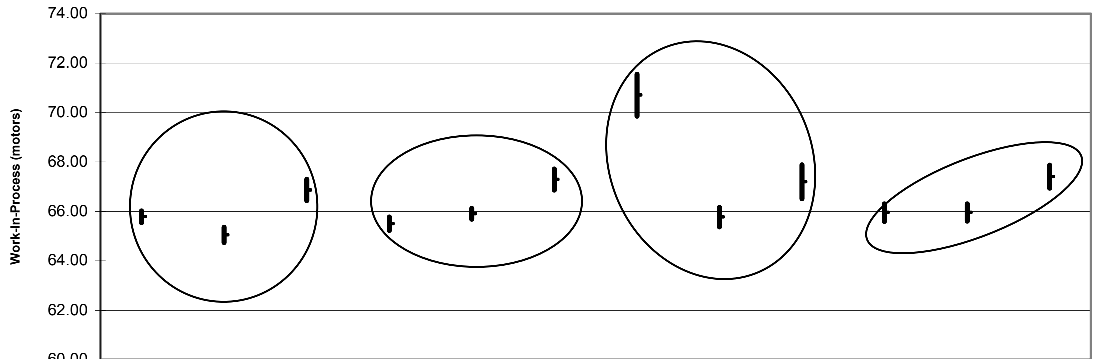
Figures 6.4 and 6.5 show the 95% confidence interval for WIP grouped by job rotation and multi-skilling, respectively. Figure 6.6 shows the work-in-process for each level of multi-skilling and job rotation using a Lowess plot. The non-parallel lines in the Lowess plot for average work-in-process indicate there is an interaction effect. Table 6.13 shows the results of an ANOVA, which indicate that multi-skilling, job rotation, and the interaction effect are all significant at the .05 level. Because the interaction effect is significant, inferences about the effect of one factor should not be made without considering the level of the second factor. That is, the effect of job rotation on WIP is not the same at all levels of multi-skilling.



	Exp 1: L1MS L1JR	Exp 4: L2MS L1JR	Exp 7: L3MS L1JR	Exp 10: L4MS L1JR	Exp 2: L1MS L2JR	Exp 5: L2MS L2JR	Exp 8: L3MS L2JR	Exp 11: L4MS L2JR	Exp 3: L1MS L3JR	Exp 6: L2MS L3JR	Exp 9: L3MS L3JR	Exp 12: L4MS L3JR
High	66.0239	65.7738	71.5583	66.3050	65.3679	66.1231	66.1705	66.3060	67.3024	67.7219	67.8844	67.8793
Low	65.5450	65.2310	69.8621	65.5971	64.7410	65.6878	65.3707	65.6071	66.4376	66.8669	66.5154	66.9368
Average	65.7845	65.5024	70.7102	65.9510	65.0544	65.9054	65.7706	65.9565	66.8700	67.2944	67.1999	67.4080

Experiment

Figure 6.4: 95% Confidence Interval for Average Work-In-Process Grouped by Job Rotation



	Exp 1: L1MS L1JR	Exp 2: L1MS L2JR	Exp 3: L1MS L3JR	Exp 4: L2MS L1JR	Exp 5: L2MS L2JR	Exp 6: L2MS L3JR	Exp 7: L3MS L1JR	Exp 8: L3MS L2JR	Exp 9: L3MS L3JR	Exp 10: L4MS L1JR	Exp 11: L4MS L2JR	Exp 12: L4MS L3JR
High	66.0239	65.3679	67.3024	65.7738	66.1231	67.7219	71.5583	66.1705	67.8844	66.3050	66.3060	67.8793
Low	65.5450	64.7410	66.4376	65.2310	65.6878	66.8669	69.8621	65.3707	66.5154	65.5971	65.6071	66.9368
Average	65.7845	65.0544	66.8700	65.5024	65.9054	67.2944	70.7102	65.7706	67.1999	65.9510	65.9565	67.4080

Experiment

Figure 6.5: 95% Confidence Interval for Average Work-In-Process Grouped by Multi-skilling

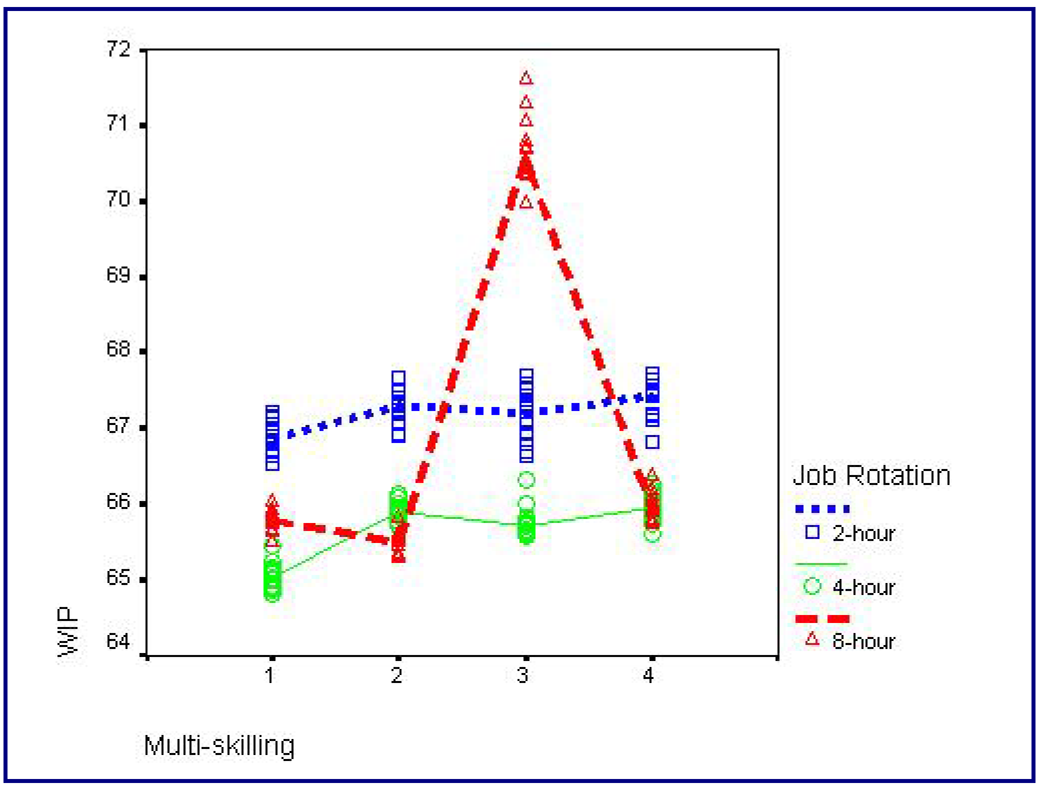


Figure 6.6: Lowess Plot for Average Work-In-Process

Table 6.13: ANOVA for Average WIP

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	370.837*	11	33.712	635.370	**.000**
Intercept	798815.444	1	798815.444	15055053.110	**.000**
MS	104.308	3	34.769	655.290	**.000**
JR	81.739	2	40.870	770.256	**.000**
MS * JR	184.790	6	30.798	580.447	**.000**
Error	8.914	168	5.306E-02		
Total	799195.195	180			
Corrected Total	379.751	179			

*Adjusted R Squared = .975

From Figure 6.6, it appears that there may be non-homogeneous variances across all levels of job rotation. For example, the individual data points for Level 2 job rotation at Level 2 multi-skilling are tightly clustered, while the individual data points for Level 2 job rotation at Level 3 multi-skilling are dispersed across a much greater range of work-in-process values. Thus, the variances of work-in-process across each experiment do not appear to be homogeneous. Levene's test for equality of variances was conducted to investigate if there are significant differences in variances for WIP results across job rotation levels at each multi-skilling level (See Table 6.14). For multi-skilling levels 1 and 4, the variances in WIP results across job rotation levels are not significantly different at the .05 level. For multi-skilling levels 2 and 3, the variances in WIP for job rotation levels are significantly different at the .05 level. The difference in variances may have been caused by the same reasons discussed for flowtime.

Table 6.14: Levene's Test for WIP across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	F	df1	df2	Sig.
Level 1	3.194	2	42	**.051**
Level 2	3.515	2	42	**.039***
Level 3	3.482	2	42	**.040***
Level 4	1.336	2	42	**.274**

The interaction between multi-skilling and job rotation prevents interpretations at the factor level, but observations within the levels of each factor can be made. An ANOVA was conducted to investigate if there are significant differences in WIP across job rotation levels at each multi-skilling level. Because ANOVA assumes homogeneous variances, caution must be taken when interpreting the results and conducting post-hoc analyses (George and Mallery, 1999; Ott, 1993). Because some of the variances are unequal, Tamhane's T2 unequal variances test is used to determine if there are significant differences in WIP within levels of multi-skilling and across experiments for work-in-process. At each multi-skilling level, WIP results across job rotation levels are significantly different at the .05 level (see Table 6.15). The results from Tamhane's T2 test (α = 0.05), shown in Table 6.16, show where the differences are. In Level 1 and Level 3 multi-skilling, all levels of job rotation are significantly different from each other, with Level 2 job rotation having the least work-in-process. In Level 2 multi-skilling, all levels of job rotation are significantly different from each other, with Level 1 job rotation having the least work-in-process. In Level 4 multi-skilling only Level 3 job rotation is significantly different, and it has the highest work-in-process.

Table 6.15: ANOVA for WIP across Job Rotation Levels at Multi-skilling Levels

Multi-skilling Level	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Level 1	Corrected Model	3.128E-02	2	1.564E-02	790.904	**.000**
	Intercept	248.831	1	248.831	12584830.981	**.000**
	JR	3.128E-02	2	1.564E-02	790.904	**.000***
Level 2	Corrected Model	3.453E-02	2	1.727E-02	606.900	**.000**
	Intercept	251.355	1	251.355	8835029.238	**.000**
	JR	3.453E-02	2	1.727E-02	606.900	**.000***
Level 3	Corrected Model	.243	2	.121	905.918	**.000**
	Intercept	264.127	1	264.127	1973239.500	**.000**
	JR	.243	2	.121	905.918	**.000***
Level 4	Corrected Model	2.735E-02	2	1.367E-02	247.330	**.000**
	Intercept	252.994	1	252.994	4575922.556	**.000**
	JR	2.735E-02	2	1.367E-02	247.330	**.000***

*Significant at the .05 level

The research sponsor was more interested in for a given multi-skilling level, what is the best job rotation frequency. The sponsor was not interested in for a given job rotation frequency, what is the best multi-skilling level, simply because multi-skilling level is not as easy to changed as job rotation frequency.

Table 6.16: Tamhane's Test for Average WIP across Job Rotation Levels at each Multi-skilling Level

Multi-skilling Level	(I) Job Rotation	(J) Job Rotation	Mean Difference (I-J)	Std. Error	Sig.
1	Level 1	Level 2	.730055*	.0517766	**.000***
		Level 3	-1.085554*	.0648775	**.000***
	Level 2	Level 3	-1.815609*	.0701012	**.000***
2	Level 1	Level 2	-.403017*	.0456662	**.000***
		Level 3	-1.792000*	.0664672	**.000***
	Level 2	Level 3	-1.388983*	.0629688	**.000***
3	Level 1	Level 2	4.939631*	.1230824	**.000***
		Level 3	3.510329*	.1430600	**.000***
	Level 2	Level 3	-1.429302*	.1040577	**.000***
4	Level 1	Level 2	-.005497	.0652911	**1.000**
		Level 3	-1.456992*	.0773686	**.000***
	Level 2	Level 3	-1.451495*	.0770109	**.000***

*The mean difference is significant at the .05 level.

From Figures 6.4 – 6.6, it appears that Experiment 2 (Level 1 multi-skilling and Level 2 job rotation) has the lowest overall work-in-process. An ANOVA was conducted to investigate if the average work-in-process is different across all experiments. The ANOVA showed that WIP is significantly different at the .05 level (see Table 6.17). Tamhane's T2 test (see Table 6.18)), shows that Experiment 2 has significantly lower levels of work-in-process than all other experiments. This result indicates that the current level of multi-skilling (Level 1) combined with a four-hour job rotation frequency provides the lowest WIP. Next is a discussion of the results for the monthly shipments.

Table 6.17: ANOVA for Average WIP across Experiments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	370.837*	11	33.712	635.370	.000
Intercept	798815.444	1	798815.444	15055053.110	.000
Exp	370.837	11	33.712	635.370	.000
Error	8.914	168	5.306E-02		
Total	799195.195	180			
Corrected Total	379.751	179			

*Adjusted R Squared = .975

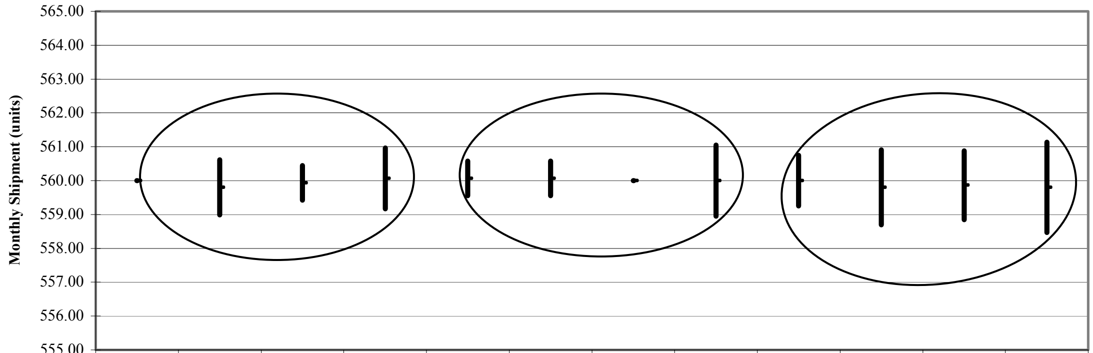
Table 6.18: Tamhane's Test for Average WIP for Experiment 2

(I) Experiment	(J) Experiment	Mean Difference (I-J)	Std. Error	Sig.
2.00	1.00	-.730055	.0517766	**.000***
	3.00	-1.815609	.0701012	**.000***
	4.00	-.448029	.0544248	**.000***
	5.00	-.851045	.0500923	**.000***
	6.00	-2.240028	.0695825	**.000***
	7.00	-5.655826	.1186873	**.000***
	8.00	-.716195	.0666971	**.000***
	9.00	-2.145497	.0988200	**.000***
	10.00	-.896632	.0620647	**.000***
	11.00	-.902129	.0616182	**.000***
	12.00	-2.353624	.0742951	**.000***

*The mean difference is significant at the .05 level.

6.4.3 Average Monthly Shipments

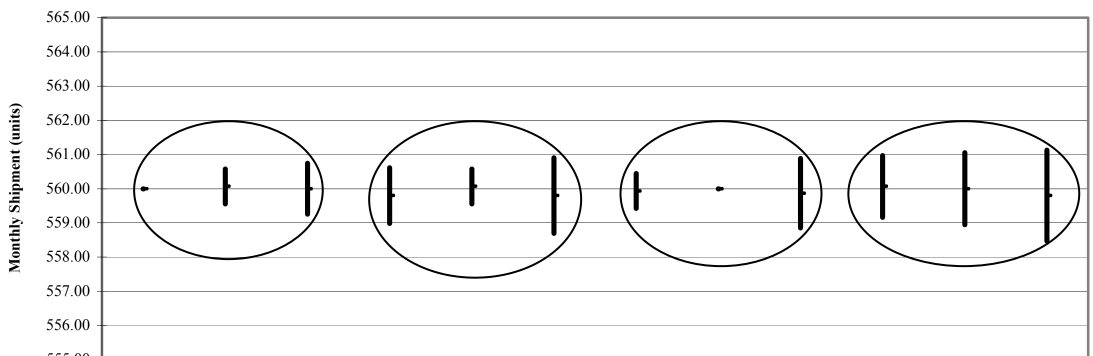
Figures 6.8 and 6.9 show the 95% confidence intervals for monthly shipments grouped by job rotation and multi-skilling, respectively. Figure 6.10 shows a plot of monthly shipments for each level of multi-skilling and job rotation using a Lowess plot. The non-parallel lines in the Lowess plot for average monthly shipments indicate there is an interaction effect. Table 6.19 shows that neither multi-skilling, job rotation, nor the interaction effect are significant at the .05 level. Therefore, no further analysis was conducted for monthly shipments. The next section discusses limitations of the research for the case application.



	Exp 1: L1MS L1JR	Exp 4: L2MS L1JR	Exp 7: L3MS L1JR	Exp 10: L4MS L1JR	Exp 2: L1MS L2JR	Exp 5: L2MS L2JR	Exp 8: L3MS L2JR	Exp 11: L4MS L2JR	Exp 3: L1MS L3JR	Exp 6: L2MS L3JR	Exp 9: L3MS L3JR	Exp 12: L4MS L3JR
High	560.0000	560.6144	560.4412	560.9670	560.5745	560.5745	560.0000	561.0514	560.7435	560.9027	560.8824	561.1299
Low	560.0000	558.9856	559.4255	559.1663	559.5588	559.5588	560.0000	558.9486	559.2565	558.6973	558.8509	558.4701
Average	560.0000	559.8000	559.9333	560.0667	560.0667	560.0667	560.0000	560.0000	560.0000	559.8000	559.8667	559.8000

Experiment

Figure 6.7: 95% Confidence Interval for Average Monthly Shipments Grouped by Job Rotation



	Exp 1: L1MS L1JR	Exp 2: L1MS L2JR	Exp 3: L1MS L3JR	Exp 4: L2MS L1JR	Exp 5: L2MS L2JR	Exp 6: L2MS L3JR	Exp 7: L3MS L1JR	Exp 8: L3MS L2JR	Exp 9: L3MS L3JR	Exp 10: L4MS L1JR	Exp 11: L4MS L2JR	Exp 12: L4MS L3JR
High	560.0000	560.5745	560.7435	560.6144	560.5745	560.9027	560.4412	560.0000	560.8824	560.9670	561.0514	561.1299
Low	560.0000	559.5588	559.2565	558.9856	559.5588	558.6973	559.4255	560.0000	558.8509	559.1663	558.9486	558.4701
Average	560.0000	560.0667	560.0000	559.8000	560.0667	559.8000	559.9333	560.0000	559.8667	560.0667	560.0000	559.8000

Experiment

Figure 6.8: 95% Confidence Interval for Average Monthly Shipments Grouped by Multi-skilling

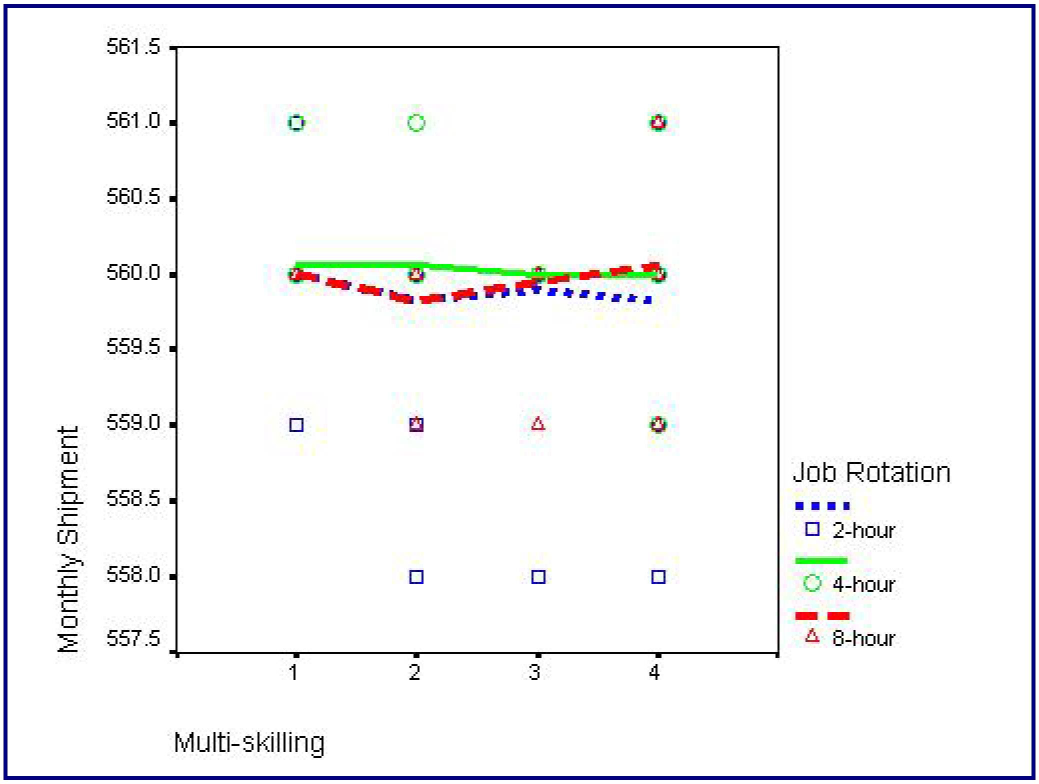


Figure 6.9:   Lowess Plot for Average Monthly Shipments

Table 6.19:   ANOVA for Average Monthly Shipments

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.883*	11	.171	1.003	.446
Intercept	56437920.450	1	56437920.450	330752464.033	.000
MS	.417	3	.139	.814	.488
JR	.833	2	.417	2.442	.090
MS * JR	.633	6	.106	.619	.715
Error	28.667	168	.171		
Total	56437951.000	180			
Corrected Total	30.550	179			

*Adjusted R Squared = .000

6.5   Limitation of Case Application

In interpreting results from the case application, it is important to consider the limitations of the study. A limitation of the study is that it represents the nature of the case application chosen. That is, attributes of the cell at IM limit the generalizability of these results to other production environments. For example, environments that may have more product variants, different distributions of productivity and quality at each task, or more machine-intensive tasks would not be expected to have the same results as the cell at IM. Additional differences could include size of the cell (both in number of workers and number of tasks), cell maturity, lean production maturity, etc. A limitation of the worker assignment model is that the experiments are interdependent. All of the multi-skilling levels are developed from the initial given set of inputs used in the first level (current state for the cell). When going to Level 2 multi-skilling, the data for four of the workers from Level 1 multi-skilling were changed such that they were fully trained on half the tasks within the cell. This was continued as the level of multi-skilling was increased until all workers were fully trained on at least half the tasks. Lastly, a limitation of the results is that they are for a single replication of the worker assignment model. Multiple replications of each factor combination would increase generalizability.

6.6 Summary of the Results for the Case Application

To provide a subjective assessment of the overall performance across all measures, the experiments for the case application were rated as either "good," "neutral," or "poor" for results on each measure. The rating criteria for each dependent measure from the worker assignment model and the simulation model, as well as for the net present cost are shown in Table 6.20. The criteria for all measures, except monthly shipments, were developed by rank ordering the results in ascending order and determining where natural divisions within each measure occur. For the ascending values of WIP shown in Figure 6.10, there is a cluster below 66 units, a cluster between 66 and 67.5 units, and a final cluster above 67.5 units. The criteria for monthly shipments were determined by how well the model met targeted customer demand with minimum overproduction. Tables 6.21 and 6.22 show how the experiments compare to each other for each of the dependent measures as well as providing an overall view across all of the measures.

While all of the performance measures from the worker assignment model and the simulation model are shown in Tables 6.21 and 6.22, only the net present cost, average flowtime, average work-in-process, and average monthly shipments are discussed in this subjective assessment. Overproduction, the cost of poor quality, and the incremental cost of training are not discussed here because they make up the net present cost. The NPC provides a cost-based measure of performance of the results of the worker assignment model.

Average flowtime, work-in-process, and monthly shipments are the performance measures associated with the simulation model.

Table 6.20: Criteria Ratings for Case Application

Performance Measure	"Good" Rating	"Neutral" Rating	"Poor" Rating
Overproduction	≤ 1 unit	> 1 – 2	> 2 units
Cost of Poor Quality	< $83,000	$83,000 – $88,000	> $88,000
Cost of Incremental Training	< $10,000	$10,000 – $15,000	> $15,000
Net present cost	< $1.13M	$1.13M – $1.210M	> $1.210M
Average Flowtime	< 2.36 days	2.36 – 2.41 days	> 2.41 days
Average Work-In-Process	< 66 units	66 – 67.5 units	> 67.5 units
Average Monthly Shipment	559.5 – 561 units	> 561 units	< 559.5 units

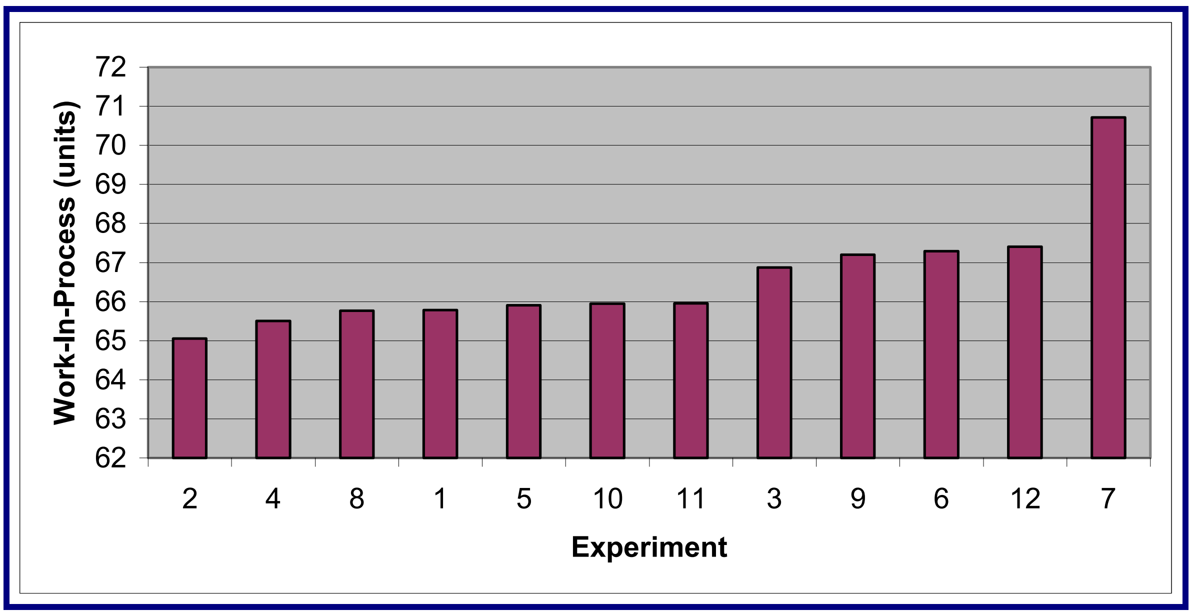


Figure 6.10: Column Chart of Ascending Values of WIP

Level 3 multi-skilling has the best performance for net present cost, while the other three levels perform better for average flowtime and average work-in-process. All levels of multi-skilling perform equally well for average monthly shipments. Level 1 job rotation has the best performance for net present cost, while Level 2 performs best for average flowtime and average work-in-process. As with multi-skilling, all levels of job rotation perform equally well for average monthly shipments.

Table 6.21: Relative Performance within Dependent Variables Grouped by Multi-skilling

Number	Experiment	Over-production	Cost of Poor Quality	Incremental Cost of Training	Net present cost	Avg. Flowtime	Avg. WIP	Average Monthly Shipment
1	**L1 MS, L1 JR**	●	◊	◊	○	●	●	●
2	**L1 MS, L2 JR**	●	◊	◊	○	●	●	●
3	**L1 MS, L3 JR**	●	◊	◊	○	○	○	●
4	**L2 MS, L1 JR**	●	◊	◊	○	●	●	●
5	**L2 MS, L2 JR**	●	◊	◊	●	●	●	●
6	**L2 MS, L3 JR**	●	◊	○	●	○	○	●
7	**L3 MS, L1 JR**	●	●	○	●	◊	◊	●
8	**L3 MS, L2 JR**	●	○	○	●	●	●	●
9	**L3 MS, L3 JR**	●	○	◊	●	○	○	●
10	**L4 MS, L1 JR**	●	●	●	●	●	●	●
11	**L4 MS, L2 JR**	●	◊	○	◊	●	●	●
12	**L4 MS, L3 JR**	●	◊	○	◊	○	○	●

● = Good, ○ = Neutral, ◊ = Poor

Table 6.22: Relative Performance within Dependent Variables Grouped by Job Rotation

Number	Experiment	Over-production	Cost of Poor Quality	Incremental Cost of Training	Net present cost	Avg. Flowtime	Avg. WIP	Average Monthly Shipment
1	**L1 MS, L1 JR**	●	◊	◊	○	●	●	●
4	**L2 MS, L1 JR**	●	◊	◊	○	●	●	●
7	**L3 MS, L1 JR**	●	●	○	●	◊	◊	●
10	**L4 MS, L1 JR**	●	●	●	●	●	●	●
2	**L1 MS, L2 JR**	●	◊	◊	○	●	●	●
5	**L2 MS, L2 JR**	●	◊	◊	●	●	●	●
8	**L3 MS, L2 JR**	●	○	○	●	●	●	●
11	**L4 MS, L2 JR**	●	◊	○	◊	●	●	●
3	**L1 MS, L3 JR**	●	◊	◊	○	○	○	●
6	**L2 MS, L3 JR**	●	◊	○	●	○	○	●
9	**L3 MS, L3 JR**	●	○	◊	●	○	○	●
12	**L4 MS, L3 JR**	●	◊	○	◊	○	○	●

● = Good, ○ = Neutral, ◊ = Poor

Overall, it appears that the higher levels of multi-skilling perform better for the goals of the worker assignment model and the net present cost. However, Level 4 is not the best level for all of the performance measures, indicating there is an inflection point between Level 3 and Level 4 multi-skilling. The inflection point is the point at which the benefits derived from the extra multi-skilling no longer outweigh the costs associated with the extra multi-skilling. There is no consistent pattern of performance across multi-skilling levels for the simulation model performance measures. That is, no one or two levels stand out above the other levels. There is no consistent pattern of performance across job rotation levels for the worker assignment model goals and the net present cost. The eight-hour and four-hour job rotation frequencies perform better for the simulation model performance measures.

6.7 Comparison of the Hypothetical Results and the Case Application Results

When comparing the hypothetical results to the case application results there are several differences that must be considered. First, the cell at Industrial Motors has been in operation for approximately four years and is a mature cell, with relatively high initial quality levels. The manufacturing cell at IM has been involved in several iterations of quality improvement methods resulting in the high initial quality levels. The hypothetical cell was treated as a start-up cell, with quality levels that would be expected during the start-up of a cell like this. Second, the incremental increase in quality levels for the case application are smaller than those in the hypothetical cell and these are used for a smaller proportion of tasks than in the hypothetical cell. While the quality levels for the hypothetical cell are initially lower than the levels in the case application, they surpass the case application's quality levels at the higher worker skill levels. Third, defects are possible at every task in the hypothetical cell, while defects are only found at testing and inspections points in the case application. Fourth, the initial values for the first level of multi-skilling for the case application are the current state levels in use at Industrial Motors. The cell has several workers who have prior experience in performing the tasks within the cell. Three of the thirteen workers can perform 16 or more of the 25 tasks. The initial levels of multi-skilling for the hypothetical cell are based on none of the workers having prior experience – again, what would be expected in a start-up cell. If additional applications of the worker assignment model were executed for the case application using initial values more similar to those in the hypothetical case, results may be more similar. Fifth, the number of tasks workers are trained on with increased multi-skilling levels are not the same. In the hypothetical cell, when increasing to the next level of multi-skilling, one-third of the workers are considered to receive full training in all tasks. That is, when increasing to the next multi-skilling level, two of the six workers are trained to skill level 4 (fully trained) on all of the tasks. For the case application, four of the thirteen workers are trained to skill level 4 (fully trained) on half of the tasks.

For the worker assignment model performance measures – overproduction, cost of poor quality, incremental cost of training, and net present cost – the higher levels of multi-skilling (Levels 3 and 4) typically performed better than the lower levels (Levels 1 and 2) for both the hypothetical and case application. Level 4 multi-skilling had the best performance for all four of the measures in the hypothetical cell. Level 3 multi-skilling had the best performance for the cost of poor quality, the incremental cost of training, and the net present cost in the case application, but had the worst performance for overproduction.

More frequent job rotation performed better than less frequent job rotation for all four performance measures in the hypothetical cell. Less frequent job rotation had better results than more frequent job rotation for overproduction and the cost of poor quality in the case application. No determination can be made about the best job rotation level for the incremental cost of training and the net present cost in the case application.

For the simulation model results – flowtime, work-in-process, and monthly shipments – the higher levels of multi-skilling performed best in the hypothetical cell, while the lower levels of multi-skilling performed best in the case application. Level 4 multi-skilling has the best performance for all three measures in the hypothetical cell. Levels 1 and 2 multi-skilling, depending on job rotation level, have the best performance for flowtime and WIP in the case application. Level 1 multi-skilling has the best performance for monthly shipments in the case application. No determination can be made about the best job rotation level for the hypothetical cell simulation results. Typically, Level 2 job rotation performed the best for case application simulation results, while Level 3 typically performed the worst.

Another difference between the simulation model results for the hypothetical cell and the case application is the magnitude of variation across the experiments. That is, for flowtime, work-in-process, and monthly shipments, the range of values for the results for the hypothetical cell are greater than the range of values for the results for the case application. The difference in variation could be caused by the difference in magnitude of the quality levels. For example, the quality levels for the hypothetical cell range from 88% - 100%, while the range for the case application is 92% - 100%. A second possible explanation is that every task in the hypothetical cell can have quality levels less than 100%, while only select tasks in the case application can have quality levels less than 100%.

Chapter 7 : Summary, Conclusions, and Future Research

7.1 Summary and Conclusions

Research on the assignment of machines and parts to cells has been conducted extensively. However, only a few publications have addressed assigning workers to the cells and then to tasks within the cells. Aspects that have rarely been addressed when developing a worker assignment model are overproduction, job rotation, and training as multi-skilling level is increased.

The primary focus of this research was investigating the impact that multi-skilling and job rotation have on the performance of a lean cell. A worker assignment model was developed that minimizes overproduction, cost of poor quality, and cost of training while including multi-skilling and job rotation policies. A sequential goal programming mixed integer mathematical model was developed that assigns multi-skilled workers to tasks while considering overproduction, cost of poor quality, and cost of training. In addition, the net present cost was evaluated by considering the cost of overproduction, cost of poor quality, cost of training, and cost of the multi-skilling level.

A simulation model was used to further investigate the impact multi-skilling and job rotation have on the performance measures of a lean cell. The worker assignment schedule generated from the worker assignment model and the associated quality levels were entered into a simulation model of the lean production cell, and results for flowtime, work-in-process, and monthly shipments were analyzed.

The results from the hypothetical cell indicate that the highest level (Level 4) of multi-skilling has the lowest levels of overproduction, lowest cost of poor quality, lowest incremental cost of training, and lowest net present cost. The results from the simulation model in the hypothetical cell indicate that the interaction between multi-skilling and job rotation was significant for all three performance measures. Additional analysis shows that the Level 4 multi-skilling experiments (Experiments 10 – 12) have significantly shorter flowtimes and lower levels of WIP ($\alpha = 0.05$).

In the case application, overproduction has the best performance at multi-skilling Levels 1 (lowest), 2, and 4 (highest). Cost of poor quality has the best performance at Level 3 multi-skilling. Incremental cost of training has the best performance at Level 4 multi-skilling and NPC has the best performance at Level 2 multi-skilling. However, Level 3 would have had the best NPC if it had not had any overproduction. Overproduction and cost of poor quality tend to have the best performance at Level 1 (eight-hour) job rotation. Incremental cost of training tends to have the best performance at Level 2 (four-hour) job rotation. NPC has the best performance at Level 2 job rotation.

When evaluating the case application, the maturity level of the cell influenced the benefits derived from increased multi-skilling. As a cell becomes more mature, it is expected that quality levels would increase and skill levels on tasks normally performed would increase. Because multi-skilling is achieved by cross-training workers and some workers are already at a high multi-skilling level, the return on investment for training may not be as significant as it would be for a less mature cell. Additionally, the mature cell has relatively high quality levels from the beginning and any improvements in quality would be in small increments rather than in large breakthroughs.

In the case application, a large portion of the tasks are assembly tasks. In a cell where there are more automated tasks or where supplied materials may play a larger role in how the cell operates, the results may be different. That is, for example, if the quality levels did not increase as the worker skill level increases, then different results would be expected.

For both the hypothetical cell and the case application, the interaction effect between multi-skilling and job rotation prevents any general statements about the overall effect of each on the performance measures. In fact, the interaction effect between multi-skilling and job rotation may have contributed to the differences found between the hypothetical cell and the case application. Additional research is needed to determine what the interaction effect is and how the interaction affects each of the performance measures. Next is a discussion of the practical implications of this research.

Park (1991) and Brusco and Johns (1998) found that when cross-training workers who are allowed to transfer between cells, the greatest return in performance was achieved when the workers were trained to the lowest level of cross-training. Additional levels of cross-training provided decreasing returns on performance. While this research did not allow workers to transfer between cells, the number of tasks the worker was able to perform within the cell was greater than the number of tasks the workers in either Park (1991) or Brusco and Johns (1998) were allowed to be cross-trained. The results for the case application also found that the lowest level of multi-skilling was the best level. However, the hypothetical cell found the opposite. Norman *et al.* (2000; 2002) found that training workers on both technical and human skills improved productivity; where productivity is a dollar measure of production rate, quality, and training; more than training on technical skills alone. Carnahan (2000) developed a worker assignment model for minimizing injuries due to heavy lifting tasks, but rotation was not considered a means of providing flexibility.

The worker assignment model proposed in this research extends the previous work performed in worker assignment by addressing some of the shortcomings. For example, the model extends the worker assignment research into lean production by using multi-skilled workers to produce to customer demand while minimizing overproduction. Additionally, the model provides a worker assignment and job rotation schedule. Finally, the model is solved using sequential goal programming to prioritize the three objectives. The contributions of this research can be summarized as follows:

- development of a mathematical model for worker assignment considering overproduction, cost of poor quality, and cost of training;
- solution of the mathematical model using sequential goal programming;
- expansion of the worker assignment research into the area of lean production;
- analysis of the impact of multi-skilling and job rotation policies on performance measures; and
- integration of optimization methods and simulation methods for analyzing the worker assignments schedule impact on performance measures

A major contribution of this research is that it is an initial investigation into worker assignment in a lean production environment.

7.2 Practical Implications

One purpose of the worker assignment model is to provide a method for production managers to assign workers to tasks within a cell. The model developed here provides that method and ensures job rotation. As requirements for a cell change, the data for the model can be updated and executed to determine how workers should be assigned and trained based on the new levels of demand, quality, and training. The model could also be used when the number of workers changes due to absenteeism or when new workers are added to the line due to either a demand increase or a loss of a skilled worker. The model provides a tool for both the production manager and the human resources manager to improve the return on investment for training. For the production manager, the model can provide information on the cost to train employees as well as the savings per month of the resultant training due to improved quality levels. The improved quality levels would provide increased capacity for meeting customer demand and improved lead times. The human resources manager could use multiple versions (one for each cell) of the model to determine which cell(s) would receive the greatest benefit from training.

The simulation model can be used in an on-going manner to show how the changes in the worker assignment model would affect the flowtime, work-in-process levels, and monthly shipments. Simulation can also be used to assess the impact of other changes to the cell without stopping actual production to determine how the change affects the cell. For example, if demand changes, the model could show whether additional (or fewer) workers would be required to meet demand. As the number of workers in the cell change, the worker assignment model could then be used to determine assignments and training.

7.3 Limitations of this Research

Limitation of the research are as follows:

- The results are for a single replication of the worker assignment model. Multiple replications of each combination of multi-skilling and job rotation would increase generalizability.
- The experiments are interdependent. That is, all of the multi-skilling levels are developed from the initial set of inputs used in Level 1 multi-skilling.
- Quality and productivity levels are deterministic at each skill level.
- For the hypothetical cell, the quality level associated with skill level 4 is 100%. If values other than 100% were used, then the results for Level 4 multi-skilling would have non-zero values.

- For the hypothetical cell, Level 4 multi-skilling has all workers fully trained on all tasks. If workers were not fully trained, then an incremental cost of training would be expected.
- For the case application, Level 4 multi-skilling has all workers fully trained on at least half the tasks.
- The attributes of the chosen case application limit the generalizability to other production environments.

While this research focused on a lean production environment, the model can be generalized to other environments. Other environments (e.g., service industries, offices) can have their processes broken down into the components used by the model. That is, the processes can be described in terms of the number of workers, number of tasks, routing, and processing times. The last section of this chapter discusses possible future research.

7.4 Future Research

An area of future research is to expand the study of the hypothetical cell to obtain additional insights. A new experimental design could be used to more fully investigate the impact of multi-skilling and job rotation. A future experimental design could place tighter controls around the randomness of determining which workers were trained on which tasks for each of the multi-skilling levels.

Another area for future research would be to investigate the order of the goals in the model. The current research minimized overproduction, then within that solution minimized the cost of poor quality, and then minimized the cost of training. Additional research on the order of the goals could provide insight into which goal had the greatest affect on the performance of the cell.

From the net present cost results for both the hypothetical cell and the case application, it can be seen that the cost of poor quality has a much greater impact on net present cost than does the cost of overproduction. In the models proposed by Norman *et al.* (2000, 2002), production costs, quality costs, and training costs were all combined in a single objective function that minimized the total cost. An additional area of future research would be to express each of the three goals in common units, such as cost, and converting the sequential goal-programming model to a single objective mixed-integer model that minimizes total cost. This would give the overall least cost option for assigning workers to tasks, but would not allow the organization flexibility in selecting which goal is most important. Additionally, other costs associated with training could be incorporated (i.e., costs in using a pay for skill system). Pay for skill systems increase a worker's salary as they become more skilled. The worker assignment model could be used to determine if the trade-off between the improved skill levels are worth the extra pay associated with the higher skill level.

Currently the worker assignment model does not directly address learning and forgetting. A forced rotation to all tasks a worker is trained in was how the model in this study avoids forgetting. An extension of the model could incorporate models of learning and forgetting or learning curves to better address this line of research.

One last area of future research would be to perform a post optimality analysis on the ergonomic issues in the production line. For example, the Strain Index could be used for evaluating the worker assignments for repetitive stress issues. Strain involves the worker's psychological and physiological reactions to a large number of work-related environmental conditions thought to impact the health and well-being of the worker (Hurrell, Nelson and Simmons, 1998). The strain index is a job analysis methodology to determine the risk of distal upper extremity disorders (Knox and Moore, 2001; Moore and Garg, 1995; Rucker and Moore, 2002).

In summary, this research developed a worker assignment model that minimizes overproduction, cost of poor quality, and cost of training for a lean production cell. The worker assignment model can be run on a periodic basis to determine where workers should be assigned, which workers need additional training, and how often workers should be rotated through the tasks they are trained. The performance of the product line could potentially be improved by utilizing the model when inputs to the model (i.e., customer demand, training budget, required training time, etc.) change. Additionally, use of the model could influence the selection of human resource policies concerning training and skill levels.

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