The Benefits of Structured Training on Manufacturing Process Ramp-Up: A Process Based Cost Model Approach

by

Colleen Beth Akehurst

B.S. in Engineering
Cornell University, 1998

Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirement for the Degree of

Master of Science in Technology and Policy
at the
Massachusetts Institute of Technology
June 2004

Signature of Author ……………………………………………………………………...............
Technology and Policy Program, Engineering Systems
Division
May 14, 2004

Certified by ………………………………………………………………………….....................
Richard Roth
Director, Materials Systems Laboratory
Thesis Supervisor

Certified by…………………………………………………………………………………..…
Randolph E. Kirchain, Jr.
Assistant Professor of Materials Science & Engineering and Engineering Systems
Thesis Supervisor

Certified by ………………………………………………………………………......................
Frank R. Field III
Senior Research Engineer, Center for Technology, Policy, & Industrial Development
Thesis Supervisor

Accepted by…………………………………………………………………………….............
Dava J. Newman
Associate Professor of Aeronautics & Astronautics and Engineering Systems
Director, Technology and Policy Program

The Benefits of Structured Training on Manufacturing Process Ramp-Up: A Process Based Cost Model Approach

by

Colleen Beth Akehurst

Submitted to the Engineering Systems Division on May 14, 2004
in Partial Fulfillment of the Requirements for
the Degree of Master of Science in Technology and Policy

Abstract

Manufacturing facilities ramping up a new production process are faced with critical decisions, which determine the ability of that process to be cost efficient. Without quantitative analyses, these decisions are made with limited data and may cause manufacturing problems. Two critical decisions are examined in this research: what level of structured training to provide to employees and what cycle time to run when compared with the long-term optimal cycle time. By examining these decisions and their impact on two production metrics, unplanned equipment downtime and reject rate, a series of analyses are presented.

A framework for conducting analyses is developed using Process Based Cost Modeling. This framework is applied to various automobile part manufacturing processes. The results indicate that production experience is critical for reducing the two performance metrics of unplanned downtime and reject rate. Additional analyses indicate that to achieve the best cycle times, a significant investment in structured training should be provided. Analytically determining the optimal cycle time is critical to improving production ramp-up because costs increase when running other cycle times. Future work would apply this framework to other manufacturing processes and gather additional data on the processes examined here.

Thesis Supervisor: Richard Roth
Thesis Supervisor's Title: Director, Materials Systems Laboratory

Thesis Supervisor: Randolph E. Kirchain, Jr.
Thesis Supervisor's Title: Assistant Professor of Materials Science &Engineering and Engineering Systems

Thesis Supervisor: Frank R. Field III
Thesis Supervisor's Title: Senior Research Engineer, Center for Technology, Policy, & Industrial Development

Acknowledgements

My deepest appreciation goes to everyone I have had the opportunity to learn from in the Materials Systems Laboratory, the Technology and Policy Program, and throughout MIT.

First, I would like to thank Rich Roth. He has spent countless hours advising both this thesis and me. Rich went beyond the call of duty as an advisor, for his concern and support for me as an individual beyond my student persona was unimaginable. Special thank you to Randy Kirchain for his unending patient help that made my experiences here so much more valuable and educational. Randy taught me everything from how to use Excel efficiently to how to think through problems systematically. And many thanks to Frank Field, for his complete support on everything from class schedules to thesis topics to life after graduation. I am forever indebted for his generosity of spirit every day of my time at MIT. A final thank you goes to Joel Clark. He encouraged me in a research project to meet my interests and a life to meet my goals.

The students of the Materials Systems Laboratory who create an interesting and fun environment to spend my days in, best of luck to Laeticia, Delphine, Chris, Erica, and Preston. Special thanks to Mike Johnson for always being a fantastic listener and wise sage whenever I needed and to Jennifer Atlee who provided perfect balance to my thoughts and a sympathetic ear so often.

To my many friends in the Technology and Policy Program, you have made me think about everything in new ways. For the friendship, support, and conversations I will always be grateful. And to the woman who guides us all in countless ways, Sydney Miller. Thank you Sydney for your time, your guidance, and your encouragement, it has brought me so far.

To my friends from my journey through life – thank you for your continued support. Marcus, Denise, Sarah, Ann, Dan, Jill and Deena provide friendship in ways I did not think possible. You all have seen me through the most difficult times in my life and supported me with unconditional love. I am honored that you are my friends. Thank you Sue, for advising me from the first day you met me. I pray that my advisee status will continue forever. To Marty, I have come to rely on your consistent encouragement and care.

Finally, I would like to thank my parents for their continued love. From my earliest days they encouraged me to follow my dreams. Their continued support has always amazed me even during my roughest moments. I would not have made it through to today without them. And thanks to Kirsten for making sure I showed up at MIT at the right time.

Table of Contents

List of Figures

1. Background

1.1 Manufacturing Organizations Concerns Regarding a Skilled Workforce

With the increased complexity of manufacturing operations, employees need a range of skills from technical knowledge to general problem solving approaches. These skills are required by manufacturing organizations that seek the most efficient and productive environments.

Characteristics of a flexible or 'high performing' manufacturing facility is one engaged in continuous improvement and facilitates leadership by employees (MacDuffie 1995). A flexible workplace requires its employees to lead many aspects of production (MacDuffie 1995). Employees are to problem solve production issues, repair equipment, and examine for quality issues in addition to running the equipment (MacDuffie 1995). With this interest in 'high performing' workplaces, manufacturing firms are investing more in training (The Century Foundation). Most often the desired goals of the training are directly linked to performance improvements in the manufacturing plant (Burrow 2003).

In a survey of members of the National Association of Manufacturers more than half were investing in training for their employees (NAM 2001). These respondents indicated they were training primarily 'to keep pace with technology' (NAM 2001). Additionally, basic skill shortages were listed as a reason for companies to provide training to employees (NAM 2001).

Given the demands of modern manufacturing facilities, employees need a breadth of skills. Additionally some of those same employees need depth in particular skill areas.

1.2 Issues with Obtaining a Skilled Workforce

There are two primary methods for obtaining a skilled workforce. The first is to hire the necessary skills by having certain prerequisites for job applicants. The second is for a company to provide the necessary training to develop the skills. Given the uniqueness of some manufacturing processes, it can be nearly impossible to hire for the necessary skills.

Corporations utilize various approaches to obtain the skill profile needed for a manufacturing facility. Some specifically require certain skills as part of an employment posting.

However, not all companies take this approach. Many look for basic employee characteristics and then choose to train the individual on specific skills. This is a conscious decision by the employer on how to train its employees. For example, Miles Fiberglass & Composites, Inc., provides a mandatory training program for employees (NAM 2001). Miles hires employees with basic skills and trains them in the specifics of their manufacturing process.

Once training is decided to be an appropriate approach, additional decisions are required to determine the type of training. Two types of training exist in the manufacturing environment.   These are graphically represented in Figure 1, below. First, structured training achieves conceptual learning (Lapre et al 2000). This type of learning can be taught and leads to 'know-why' (Lapre et al 2000). Through this process employees are taught to understand things such as the manufacturing process.

The teaching process is not limited to classroom instruction. Structured training refers to a systematic approach to gaining skills. This approach involves identifying skills necessary for a task. After identifying skills, a skill assessment determines the gap between current employee skill level and the necessary skill level. Once training needs are identified, specific instructional approaches are developed. These approaches have specific objects and can include classroom training, structured on the job training and other methods. After training, employees are evaluated to ensure the training was successful. This full process is considered structured training.

The second type of training is experiential which leads to operational learning or 'know-how" (Lapre et al 2000). This type of learning occurs through experience and employees learn this knowledge by actually performing their manufacturing tasks (Sinclair 2000). This information can be learned, but requires time and production to achieve.

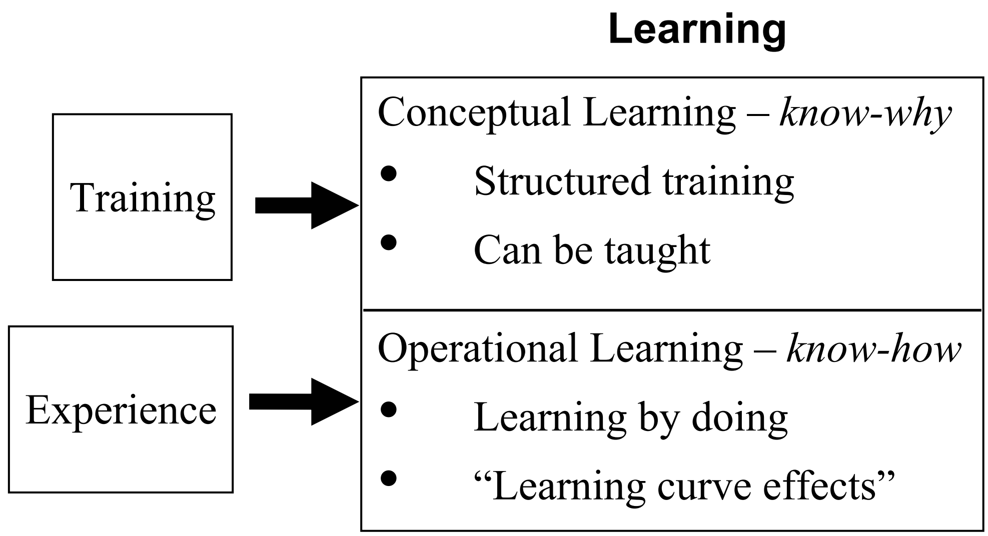

Figure 1: Manufacturing Training Types

Both types of training are required for the best benefits in manufacturing to be achieved (Lapre et al 2000). Eliminating either learning approach greatly diminishes the benefits that could be achieved by combining both mechanisms. More details regarding the benefits of training are discussed below.

One of the most substantive hurdles in achieving appropriate training is securing funding. To achieve the benefits of training, a significant investment in employees is required. Corporate budgets are tight and financial allocations must demonstrate results indicating a substantial return on investment. With few quantitative analyses to demonstrate the return on investment of training, securing funding for training is difficult.

The National Association of Manufacturers recommends employers spend at least three percent of payroll to train and educate employees (NAM 2001). This recommendation includes a range of programs that should be offered from literacy training to tuition reimbursement for higher education (NAM 2001). However, current spending on training is much less than the recommended amount, with actual spending in the range of one to two percent of payroll for survey respondents (NAM 2001). This is indicative of tension in achieving an appropriate amount of training. Without adequate financial commitment, gaining the most benefits from training will be unlikely.

1.3 Benefits of Training

A great variety of benefits are achieved by training manufacturing employees. Two specific benefits are examined in this research, improved quality (i.e. decreased reject rate) and improved equipment performance (i.e. reduced unplanned downtime). Previous research indicates both of these benefits as a result of training.

Providing training has been shown to improve quality. Training is regularly viewed as a 'critical factor of quality management' (Benson et al 1991). Other approaches t quality management exist, but training is always considered essential. This view is widespread, as indicated by one study where 94% of the forty-nine manufacturing units studied provided training in an effort to improve quality (Ittner 1996). The investment being made in quality training delivers results. For example, research has indicated that 'induced learning' (training) leads to quality improvement (Fine 1986).

Quality also improves by operational learning. Research indicates the existence of a 'quality learning curve' that develops over time (Levin 2000). This indicates that both learning approaches, structured training and experiential knowledge, contribute significantly to improved quality.

Linking training benefits to unplanned downtime is more difficult; limited research addresses this problem. One study links the benefits of expert systems and training to maintenance support (Stein et al 2003). This study indicates that improvements can be made to maintenance of equipment by providing particular information to employees (Stein et al 2003). This improved maintenance would then be translated into decreased unplanned equipment downtime. As this study indicates the link between training and unplanned downtime is not direct.

Beyond quality and maintenance, the effective usage of new technology occurs by developing and executing training (ASTD Research 2003). Training provides specific skills that increase the effectiveness of technology during implementation and in the long term. Furthermore, increasing the effectiveness of new technology aids in efficient ramp-up of manufacturing processes.

Training provides other benefits beyond improvements to manufacturing processes. Current research indicates that employees develop a ‘psychological contract’ with employers (Rousseau and Tijoriwala 1998). This contract exists when the employee believes that a ‘promise’ has been made by the employers in exchange for certain activities (Rousseau and Tijoriwala 1998). An employee will deliver their portion of the contract as long as they perceive the employer to be doing the same. A portion of the employer side of the contract includes providing training (Robinson 1996). Other research indicates that providing training increases job satisfaction and organizational commitment (Birdi et al 1997). Increased job satisfaction and organizational commitment provide substantial benefits to companies, but these benefits are difficult to quantify. Although this research only examines the financial benefits of providing training, it is critical to remember that training provides benefits that are not easily measured or quantified.

1.4 Optimal Manufacturing Ramp-Up

Manufacturing organizations have long sought to start-up new equipment along an optimal acceleration curve. By using an optimal curve, costly errors can be avoided. However, determination of this curve is difficult. Previous research has attempted to develop methodologies for determining ramp-up in other industries. In one study a methodology was developed to manage cycle time during the ramp-up (Haller et al 2003). This leads to more efficient use of time and resources during ramp-up. A similar approach is taken in this thesis.

Other research developed an analytical approach to evaluate production ramp-up. The study indicated the need for examining multiple trade-offs during the ramp-up process. The trade-offs examined include production speed and yield (Terwiesch and Bohn 2001). The approach presented by Terwiesch and Bohn helps manufacturing facilities achieve more efficient ramp-up, a goal similar to this research.

Additional research has indicated the importance of identifying production disturbances during ramp-up (Almgren 2000). Control of these disturbances allows for more efficient ramp-up (Almgren 2000). However, achieving that control is difficult, since often the disruptions are unique and uncontrollable.

Research indicates a need for production facilities to efficiently perform ramp-up. A variety of factors have been previously considered in various industries, the learning from that research contributes to the work presented here. However, the research in the production ramp-up field is limited and therefore many gaps exist.

1.5 Government Interest in Training

Both federal and state governments make significant investments into training. Generally the reasons are tied to providing appropriate skilled labor for industry which leads to economic growth. In an effort to combine and build on previous federal legislation, the United States Congress passed the Workforce Investment Act of 1998. Summaries of specific sections of this Act are provided in Appendix A.

One section of the legislation most directly applies to the research in this thesis. Title I creates a statewide Workforce Investment System. This workforce investment provides training for adults seeking specific skills for employability. It also provides qualification and potentially funding for organizations who wish to provide training. The legislation allowed states to create approaches to implement the WIA within certain guidelines.

States have implemented this legislation differently. Some states tied this organization to an existing executive department. For example, Connecticut added the work required under the WIA to the Department of Labor (www.ctdol.state.ct.us/wia/wia.htm). In other states, new organizations were created. The State of Ohio created the Office of Investment in Training (www.odod.state.oh.us/oitp.htm). Regardless of the implementation strategy, the purpose of these state systems was to provide a 'one-stop' delivery systems with career centers, job training and education to local areas (Landini 1998). Through these delivery systems, individuals can create individualized training programs to address personal skill needs. Employers can work with the 'one-stop' center to locate appropriately training employees. Employers seeking to fund training for existing employees can potentially work with the state for funding and other assistance.

The WIA and other associated federal programs represent a significant financial investment into the training of workers. In 1999 the federal government spent an estimated $11.7 billion on job training or job placement assistance (Policy Almanac 2001). This money was spent by approximately forty programs that listed either job training or job placement assistance as a primary goal (Policy Almanac 2001). It should be noted that not all of this training expenditure was directed towards manufacturing organizations. But, a significant portion of this spending does impact manufacturing.

The importance of government involvement in workforce development is reflected in a 2001 survey of members of the National Association of Manufacturers. More than half of the survey respondents thought that government's role in workforce development should be tax relief for companies that offer training (NAM 2001). Although other governmental roles are possible, it is clear from the NAM survey that manufacturing organizations favor some type of governmental involvement.

The government reaps the benefits of a trained workforce. Whether that training is provided by government sponsored programs or an individual company, the positive impact to the national economy is the same.

Training is an effective method for manufacturing facilities to obtain skilled employees. Currently the government is assisting in this training effort. Unfortunately, little work has been done to quantitatively show the benefits of training for a particular manufacturing process. The research presented in this thesis addresses this need.

2. Problem Statement

When introducing new manufacturing methods, companies are faced with a difficult dilemma. A production manager is forced to determine the best approach to starting up this new manufacturing process. It is unlikely that a production facility can start up at long-term optimal speeds on the first day of production without causing significant problems. Therefore, critical decisions must be made during the start-up process. Of particular concern are two issues: 1) what line rate, as compared to final line rate, is appropriate at different periods during of ramp-up and 2) what level of training is required for employees to achieve optimal costs.

During initial ramp-up serious complications occur if the line is run too quickly. These issues can include an increased number of rejected parts and more frequent unplanned equipment downtime. Therefore, a ramp-up plan, indicating the rate at which the cycle times can be reduced, shall be determined by balancing production experience and training should be determined. However, making these decisions requires significant analyses of the tradeoffs among multiple operation decisions. Among these are decisions concerning the amount of training to be given to the various types of workers.

A manufacturing workforce becomes skilled through two primary mechanisms. First, structured training assists workers in understanding the cause and effect relationships between their work and production performance. Structured training also provides basic knowledge of the manufacturing process and associated issues such as safety. Second, experiential learning, commonly referred to as learning by doing, describes the knowledge employees acquire over a period of time while performing the work. Combining these two approaches to learning leads to better results for manufacturing ramp-up.

These learning methods lead to the other interesting balance to be achieved during manufacturing ramp-up: providing the appropriate amount of structured training while gaining benefits by experiential learning. A new production method requires that employees understand both how the process functions and the impact between their work and production output.

By helping companies recognize the benefits of both structured training and experience, better decisions can be made during start-ups. Managers can predict the production cycle time that would be best for the process at various times during production. Based on these decisions a cycle time acceleration curve can be defined and steady-state performance can be achieved sooner. Knowledge of the acceleration curve leads directly to lower costs of ramp-up due to balancing cycle time and unplanned downtime and reject rate. Allowing longer cycle times improves the unplanned downtime and reject rate are improved, but this alternative is costly because slower cycle times translate into less efficient use of capital equipment and labor.

Furthermore, this study examines the optimal level of training from a cost minimization standpoint. A breakeven point for the investment in training is quantifiable. With the framework used herein, the point of greatest difference between production savings and the cost of training can be determined. Using the methodology presented in this thesis, the impact of various training levels can be examined for their benefits during the ramp-up process. It can also be determined if there is a point at which training no longer translates directly into financial benefits for the manufacturing operation.

Finally, a main objective of this work is to develop a framework for analyzing these decisions. Given the limited data available, an important contribution to this field is a re-applicable methodology for future analysis of various manufacturing processes. With minor changes the mechanisms developed for the analyses presented in this research can be applied to other manufacturing processes.

Two approaches are presented in this thesis. The first approach uses a ramp-up and structured training framework in conjunction with a generic cost model. This facilitates a more straightforward analysis to examine and understand the implications of training decisions without complications arising from more detailed models. The second approach uses a ramp-up framework with a detailed cost model to ensure consistent results when additional process details are considered.

A number of analyses using the two approaches were done. These analyses include key training investment points, the benefits of operational learning, the relationship between operational learning and structured training, and the implications of choosing one cycle time for an entire production run (only included in the generic process approach).

3. Methodology

3.1 Modeling the Cost of Production

Effectively modeling the cost of production provides a variety of benefits to manufacturing managers. Models facilitate better decision making, with more accurate projections of the impacts of production decisions. Models allow for a variety of scenarios to be run before critical financial resources are committed. By simulating potential situations, more data in available to be used in up front decision making.

Historically, rules of thumb have been used to analyze the cost of production (Busch 1987). Using this approach, managers with years of experience made production decisions based by reapplying knowledge gained in previous situations. This approach is limited by the scope of experience of particular individuals.

Other modeling approaches focus on using large quantities of data to predict future costs, modeling a manufacturing process abstractly, or using first principle physics. (Fixson 2002). Each of these approaches has limitations. For those relying on large quantities of data, the obvious limitations are the availability and accuracy of that data. Abstractly modeling manufacturing process creates mathematical calculations of the manufacturing process. These models are limited by the complexity of the process under investigation; a process that is overly complex is difficult to model (Fixson 2002). Using first principles to approach modeling allows for engineering information to be translated into manufacturing information. For a full discussion of the various cost modeling techniques, refer to Fixson 2002.

3.2 Process Based Cost Models

Process based cost modeling (PBCM) analyzes the various cost components of a production process. Through a mathematical transformation the magnitude of factors affecting cost are estimated (Kirchain 2001). These factors are set by the process being modeled (Kirchain 2001). PBCM was developed to provide cost estimates using engineering, technical, and economic knowledge with accounting principles (Veloso et al 2001). The importance of the model is not in producing a usable cost for manufactured items, but in examining how changes impact cost. Examples of changes that can be made are production volume, equipment type or material selection. The design of a PBCM allows for sensitivity analyses to be performed on gradual changes of a particular variable, for examples increases in material cost or energy rates. The scope of PBCM allow for a variety of changes to be examined across many aspects of the production process.

As discussed previously, various mechanisms exist for understanding manufacturing costs. However given the limitations of those methods, alternative approaches are required for this research. For three reasons the approach used in this thesis is a PBCM. First, PBCM can model manufacturing processes that are in various stages of development. Other approaches require processes to be fully operational for sufficient data to be gathered. Second, PBCM requires a limited number of process, operational, and financial inputs. By minimizing the number of inputs needed, model users are able to perform analyzes without every detail specified. Third, the calculation process of PBCM allows for changes to be made on the variables of particular interest in this research. PBCM provides the ability to analyze issues with real data while balancing the level of detail required.

A PBCM is built backwards, with cost elements identified first. Examples of cost elements are material, equipment, or energy. Next, the factors impacting these cost elements are determined. Finally, process operations are correlated to the cost factor (Kirchain 2001). In this particular case, PBCM uses variables that most impact the cost of fabrication.

PBCMs are actually three models functioning seamlessly: a process model, an operations model, and a financial model. The first step in a PBCM calculation is to determine specifics regarding a manufacturing process. The process model transforms basic part and process data into all the production variables needed to estimate cost. These include calculations on type and quantity of production equipment, steps in production process, materials required per product, and other production specific calculations. The operations model calculates information applicable to the manufacturing facility. This includes information such as the production time available based on employee work schedules, number of workers needed, and other operational considerations. Finally the financial model calculates the cost of the various determinations made by the process and operations models. Those calculations include the amortized cost of the equipment, employee wages, and items such as interest rate and overhead costs. These three separate parts of the model are not clearly delineated in the model, but function together to perform the full functionality of a PBCM.

3.3 Generic Process Based Cost Model

The analyses conducted in this research primarily used a generic process based cost model. This model is a stripped down version of a more detailed PBCM. However, this generic model took steps to reduce the number of inputs required and therefore computes fewer intermediate calculations. For example, all equipment was grouped into one overall charge and energy and materials were combined into one cost per part.

The generic model can be used for any process. For example, by using data appropriate for the stamping process, the generic model can be used to estimate the costs of stamping. First, cycle times are similar to stamping cycle times, ranging from four seconds to thirty seconds. Second, the capital investment is set at $5 million, the approximate cost of a mid-range stamping press line. Third, each line in the generic model has three workers dedicated to production. The cost of a piece calculated by this generic model is roughly equal to the cost calculated by the full scale stamping model, although some accuracy is presumably sacrificed using the simplified approach.

The generic model was used to analyze most questions discussed in this research. Since the simplified model is not process specific, input changes are all that is needed to emulate other manufacturing processes. Actual inputs and intermediate calculations of the generic model are reported in Appendix B.

3.4 Conceptual Operational Decision Making Model

3.4.1 Incorporations of Training Parameters into Cost Models

Choices are made early in the production development process that have an impact on cost. For example, technology choices are made that may include decisions on types of presses to be used. Additionally operating decisions are made regarding the specifics of how to manufacture the part. These can include decisions such as cycle time. Use of cycle time as performance indicator has been used elsewhere in modeling analyses (Womer 1979). Finally, choices are made regarding the level of knowledge required by workers to run the process. This knowledge can be achieved by training the employees. These choices then translate into a set of production characteristics. This includes performance metrics such as unplanned downtime and reject rate. From these production characteristics comes actual production. This impact of production choice on cost is graphically represented in Figure 2. As mentioned previously, production can be analyzed to determine a final cost of manufacturing through a PBCM.

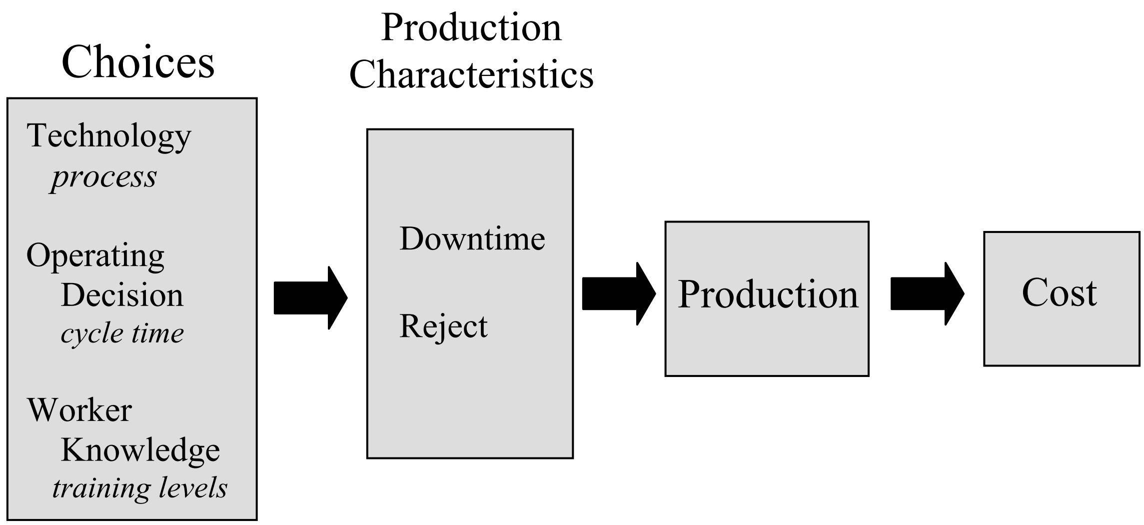

Figure 2: Production Choice Impact on Cost

The first step in evaluating the impact of the training and experiential learning in the manufacturing environment was to determine which production performance metrics are most impacted by learning. Through a series of interviews with experienced production managers, training experts, and manufacturing personnel two production measures were chosen for analysis: unplanned equipment downtime and reject rate. Other performance metrics were considered, but were eliminated because they are not impacted as much by training and learning.

In order to think about the various relationships considered in this research, connections between the various metrics were required. The general relationship is indicated in Figure 3. Cycle time (CT) and training are decisions that are made with direct impact on production. They are specific for the manufacturing process being modeled. From calculations in the generic process model, a reject rate (RR) and unplanned equipment downtime (DT) are determined for the specific manufacturing process being investigated. More details on the specific development of the RR and DT are provided below.

The generic model was used for operations and financial calculations, with the addition of the operating decision making framework to replace the process model. This framework provided a feedback loop for cumulative production through the concept of operational learning.

For this research, training was considered to be provided at various levels. A level is defined as a certain number of hours per each skilled trade employee, each production employee, and each salaried employee.

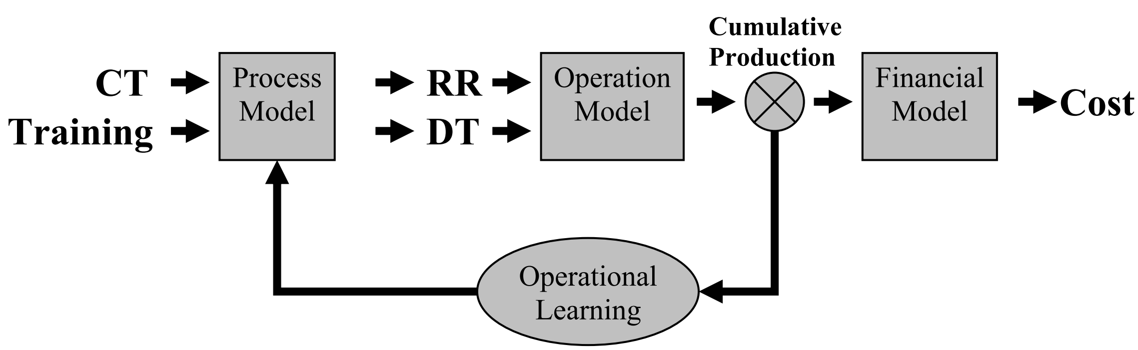

Figure 3: Conceptual Operational Decision Making (CODM)

3.4.2 Relationship between Cycle Time, Production Interval, Structured Training, Reject Rate, and Unplanned Downtime

The decision making framework consisted of relationships between cycle time and unplanned downtime (DT) and reject rate (RR) at various levels of experiential learning. To develop calculations for RR and DT, a quantitative relationship needed to be determined. The first step in this process was to determine a general functional form. Based on several studies, the general form of the relationship is shown in Figure 4 (Terwiesch and Bohn 2001). The research indicates a monotonic decrease in reject rate or downtime given increased cycle time at a single level of structured training.

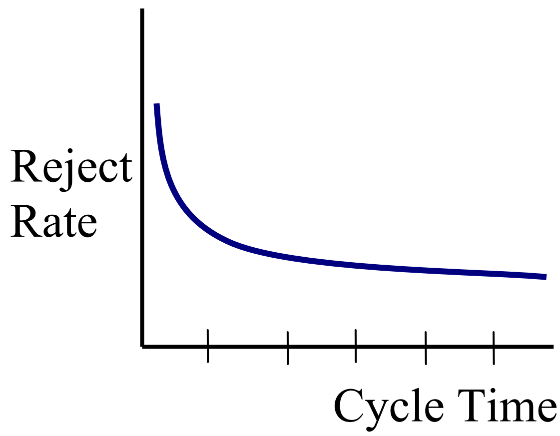

Figure 4: Relationship Between Reject Rate and Downtime

A monotonic mathematical form was chosen since this clearly resembles the expected behavior of these relationships. The form of the equation stays the same for both reject rate and downtime. These equations are listed **Error! Reference source not found.**.

(1) $$RR = \frac{A_{RR}}{CT^{b_{RR}}}$$

(2) $$DT = \frac{A_{DT}}{CT^{b_{DT}}}$$

The coefficient, A, and exponent, B, define the slop and magnitude of the curves holding constant all other variables, in particular training and employee experience. Different structured training and experience levels have different cycle time and reject rate relationships, but are modeled as always following the same exponential form. Accordingly, new values for A and b can be found for each level of training and experience. A sample of the data used to calculate these values is contained in Appendix C.

It was assumed that both the coefficient, A, and the exponent, b, also have an exponential relationship with the levels of training and experience. While it is more difficult to confirm the accuracy of this functional form, it is thought to generally represent production data and is a fairly flexible form able to represent a large range of data.

Applying this functional form one can write equations for the coefficient A and the exponent b in terms of the level of training (Tr) and the number of production intervals (N). These equations are given below.

$$A = C \times N^{d} \times Tr^{e} \tag{3}$$

$$b = F \times N^{g} \times Tr^{h} \tag{4}$$

3.5 Stamping Model

The stamping cost model has been developed and refined over a period of years by the Materials Systems Laboratory at MIT. It is a multiple step process that includes blanking, rinsing, stamping, and finishing to produce metal automobile parts. The accuracy of this model has been verified by data from various automobile manufacturers.

In keeping with cost modeling approaches discussed previously, the stamping model can be thought of as three seamless models, a process model, an operations model, and a financial model combined to produce one cost output. In this model more detailed inputs are required and more calculations performed as compared to the generic model.

The process component of the stamping cost model uses part geometry considerations to estimate the manufacturing requirements to produce the part. Input information includes length, width, height, and complexity of the part. The model then estimates a size and cost of the presses, the costs of the tools, and other process specific issues. The model selects a stamping press from a listing of available presses. Cycle time is an input that is generally considered to be the long term steady state cycle time. Traditionally this cycle time has not considered the optimal cycle time at different levels of training. This research changes that approach and includes training.

Operational inputs into the stamping model include worker wage, production days per year, production hours per day, and worker break information. Based on these inputs, a time is calculated that is required for production of the necessary parts. This is compared to the time available based on production days and time in each day available for production. Based on these operational considerations, additional equipment may be required to meet production demands.

From the process requirements and operational information, the final step in the stamping model is the determination of financial costs. Financial information inputted into the model includes, overhead rate, interest rate, and building costs. Costs are calculated using accounting principles, such as amortizing the cost of equipment over the equipment life or the cost of tools over the product life.

A significant change was made to the stamping model for use with the downtime and reject rate equations.   All calculations are based on production interval as opposed to on an annual basis. This was required because the decision making interval is a production interval and therefore changes to cycle could be made at every production interval.

3.6 GM Training Cost Model

Based on dozens of plant start-ups and production changes over many years, General Motors (GM) developed a training cost model. This model predicts the training investment necessary to appropriately educate plant personnel before a large project. The training cost model divides training between skilled trades (electrical and mechanical maintenance personnel), production employees, and salaried employees.

The determination of the amount of training required is correlated to the project complexity and size. Complexity is defined by a series of factors including:

- Extent of new process technology being implemented
- Extent of cultural change being implemented
- Changes previously implemented in other plants
- Quick change-over or major re-tooling

A more complex project will require additional training. Size is determined by the number of employees working in the manufacturing facility.

The training cost model requires more inputs to fully analyze all factors contributing to overall training cost. Additional inputs include:

- Average hours of training – This includes information on the three groups of employees: skilled trades, production and salaried. Different training hours are entered for each group of employees and for the five project complexity levels.
- Labor rates – These inputs provide information on the cost of fully-loaded instructors, course developers, students, and other employee hourly wages.
- Percentage of course delivery – Courses can be provided over a three year period and these inputs allow determination for what percentage of the training is offered during each of those years.
- Workforce deployment – This section creates specifics on the workforce make-up. The percentage translates into a number to of certain types of employees: skilled trades, production employees, or salaried workers.

- Class size and attendance rates – Classes can contain a certain number of participants and these participants have average attendance rates. Based on the attendance rates more classes may be required to achieve one hundred percent training, resulting in higher costs.

With all these inputs and information regarding the complexity of the project, a cost estimation is calculated for the overall training package. This cost can then be used in the budgeting process to allocate enough financial resources to achieve adequate training. The total dollar investment calculated by the training model was divided to provide an investment per employee required for the two models investigated here.   For the purposes of these analyses, all training was provided in one year. It was assumed that the training was actually provided prior to the start of production.   The complexity of the project was not correlated to the model, but instead complexity level one was considered to be training level of one. This level corresponds to seventy-three hours of training per skilled trades employee and thirty-eight hours of training per production employee. Levels two through nine were then determined by creating equally distributed training for all types of employees.

4. Analyses

The purpose of this project is to demonstrate the types of information that can be obtained by careful analysis of training and cycle time during manufacturing process ramp-up. The following set of analyses investigate the benefits of experience (production interval), structured training, and optimal cycle time. Two PBCMs were used, a generic model built for this research, and a fully detailed stamping model.

4.1 Generic Model

Using a generic process based cost model a series of analyses were conducted to understand the changes in manufacturing costs due to structured training and production interval. The operating decisions that were changed include the cycle time for the process given production interval and the training level to be provided to workers.

The analyses presented examined production intervals from one to one hundred in steps of five. A production interval was defined as making 1000 good parts. A decision was made at the beginning of each grouping of five production intervals, regarding what cycle time to run during the next five production intervals. Although, more frequent decisions could be made, that level of detail was deemed unnecessary for this work.

For these analyses, costs were estimated at a range of cycle times. Cycle times started at four seconds and ranged to thirty seconds. With increments of a quarter of a second for most cycle times within that range, more specific optimal cycle times could be determined.

4.1.1 Reduction in Cost Provided by Training

A key concept to be investigated by this research is what, if any, benefits in production costs are provided by structured training. To investigate this question, one automobile stamping was investigated at all ten training levels, with production interval being held constant. Reduction in optimal cycle time occurred for each of the ten levels. Between level one and level ten a reduction of several seconds is achievable. For the earliest production intervals it is three seconds, for the later production levels it is almost four seconds.

As indicated by Figure 5, increased training leads to a reduction in cost per part. The lowest point on both curves indicates the best cost obtained over a series of cycle times for a particular production interval. A savings of 7% was achieved by increasing the training amount by only two levels. Additional cost reductions can be achieved by continuing to increase the amount of training provided.

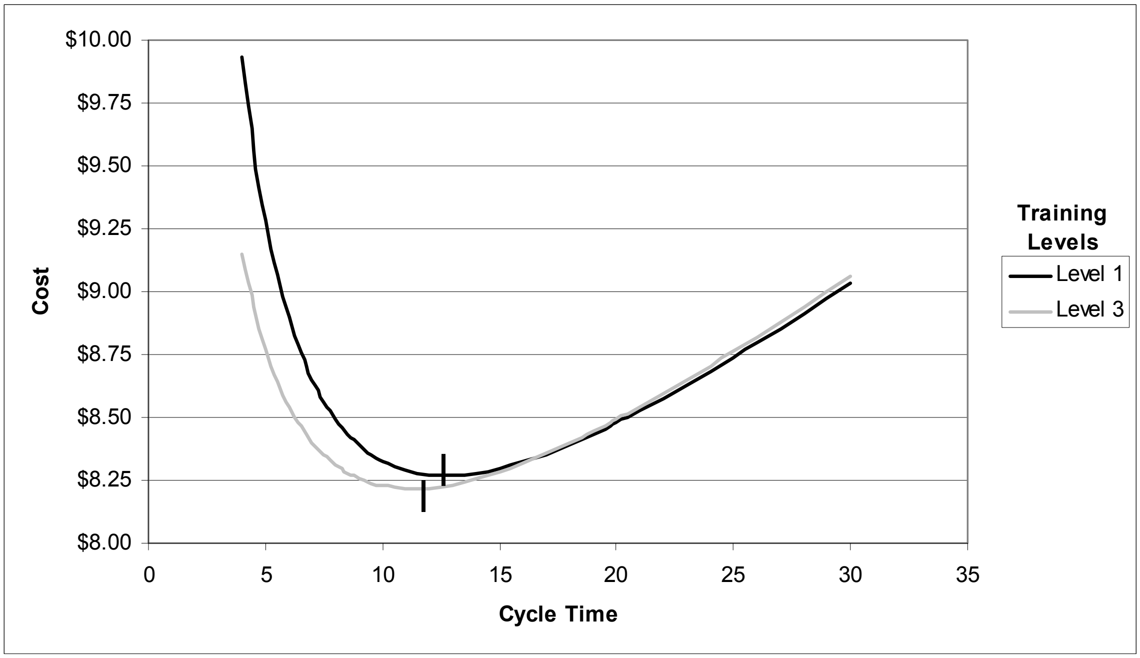

Figure 5: Reduction in Cost Provided by Training

4.1.2 Key Training Investment Points

By incorporating the cost information from the training cost model into the generic cost model, various investment levels for training were analyzed and compared with the benefits of training obtained at those levels. Again, the benefits from training are decreased unplanned downtime and decreased reject rates.

These analyses were run over the entire production volume of 100,000 parts. Because of this, the costs presented are for the entire production, as opposed to one individual part.

As indicated in Figure 6, the benefits of training continue to increase over time. This is indicated by the solid line continually rising. However, the training benefits curve shows diminishing cost savings as the training levels increase. The incremental cost of training indicated by the dashed line is linear because the difference in cost between any two training levels is the same. However, these benefits overlap the incremental cost of training at a particular level. The light grey line in the graph shows the difference between the training benefits and costs.

Two important points exists on the 'savings from training' curve. The first point is at training level four, indicated by a square marker. This point indicates an efficient training investment amount. By providing training at this level an efficient use of resources occurs. This is because it is the point where the most savings occurs compared with the amount of training provided. For this particular analysis that savings is over $5,600, which includes the cost of training.

The second point is at training level eight, indicated by a triangular marker. At this point, there are no more financial incentives for providing training. If more money is invested in training after level eight, there are still savings generated by the training, but the expense of training is more than the savings delivered. Basing investment in training on purely financial motives there would be no reason to invest in training beyond level eight.

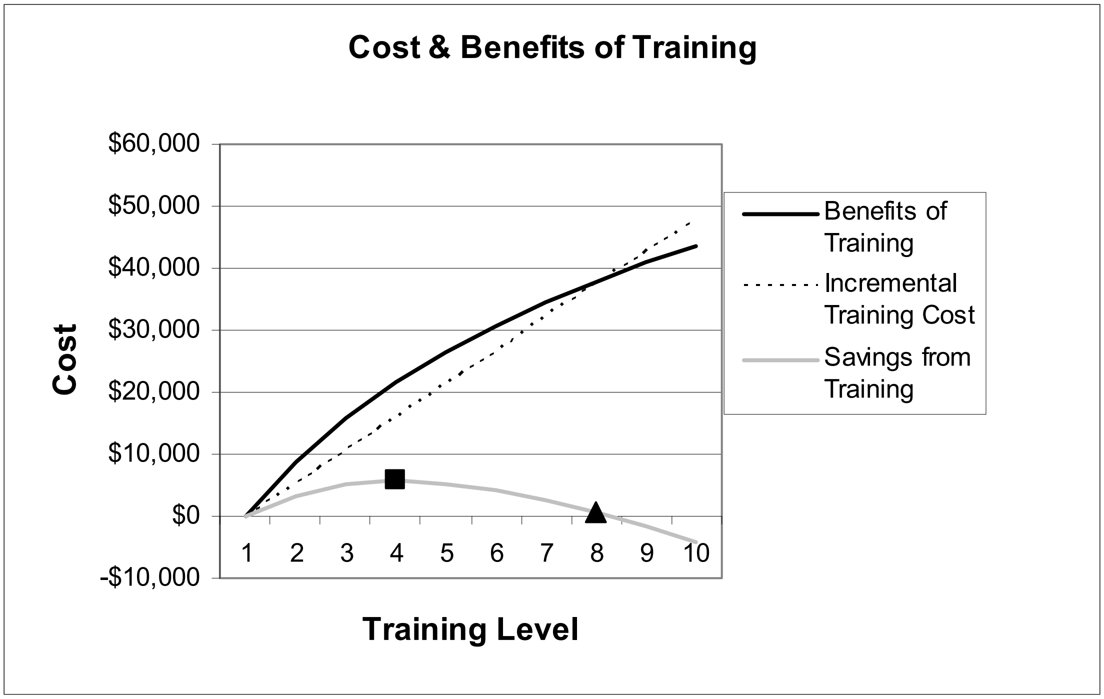

Figure 6: Key Training Investment Points

These two points are critical to consider for the financial investment made into training. Knowing these points prior to starting a manufacturing project provides more information into the optimal use of limited financial resources. However, as mentioned previously, reasons other than financial motives for additional training may exist. Based on this analysis a production manager may seek to train only to the most efficient point or choose to continue to train until there are no more financial benefits whatsoever.

4.1.3 Operational Learning

The next analysis examines the benefits of experience, without the influence of structured training programs. For this analysis, cost was estimated across a range of different cycle times for several production intervals. The training amount provided was held constant.

As shown in Figure 7, the cost per part decreases between each successive set of production intervals. There are greater cost decreases between the earliest production intervals. For example, between production interval twenty and production interval forty there is a $.25 cost decrease per part. But, between production interval eighty and one hundred there is only a $.06 decrease per part. The actual cost per part is not the important point. The difference in magnitude indicates that the most significant gains to be achieved from operational learning occur at the earliest intervals of manufacturing ramp-up. The difference of $.06 between production intervals sixty and one hundred still demonstrates the importance of operational learning through the production run. Even though larger gains occur at earlier production intervals, there are still operational learning gains at the later production intervals.

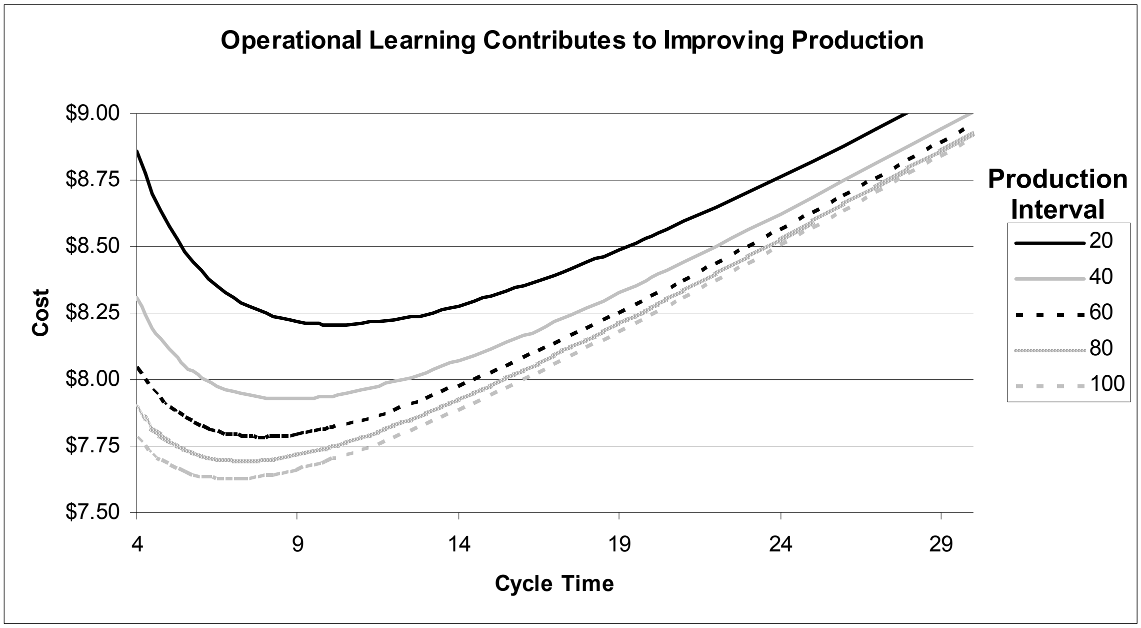

Figure 7: Operational Learning Contributes to Improving Production

Similar to the decrease in cost over a series of production intervals, a reduction in cycle time also occurs over those intervals. This is indicated by the lowest point on each curve in Figure 7 moving to the right as the production interval increases. Again, the most significant reduction in cycle time occurs during the first sets of production intervals. Nevertheless, reduction in cycle time continues even at the later production intervals.

This analysis indicates the benefits gained by operational learning. It also indicates that most of the benefits are gained at the earliest production intervals. But continued gains do occur at the later intervals.

4.1.4 Training and Experience

Based on the discussion of the previous two sections, both experiential learning and structured training provide benefits to manufacturing economics. The next analysis examines the interaction between these two processes. Figure 8 provides a graphical representation of the relationship between production interval, training level, and cycle time.

Several key points emerge from this graph. First, at the early production intervals, the impact of training is minimal. When one views the cycle times achieved across all training levels below production interval ten, it is clear that providing additional training does not yield improved cycle times. This indicates the critical nature of operational learning in the early stages of ramp-up.

However, when the higher production intervals are reached, training becomes absolutely necessary to achieve the best cycle times. The graph in Figure 8 indicates that the shortest cycle times can not be reached without a significant investment in training. The upper right side with the shortest cycle times are only possible when at least a training level of five is provided. This graph represents a need for the training investment to be made, even if the benefits are not immediately apparent.

At the middle of the graph in Figure 8, an understanding of the balancing that occurs between structured training and experiential learning is shown. With full training the minimum cycle time can be achieved after forty-five production intervals or 45,000 parts.

However, with the minimum level of training provided, seventy production intervals or 70,000 parts are required before the minimum cycle time can be achieved. This result demonstrates that training can shorten the ramp-up phase of production. This translates into 25,000 parts being made at slower cycle times due to reduced training amounts. The slopes of the curves on this graph indicate a generalized rate of substitution between structured training and operational learning. However, as previous graphs have indicated these two concepts are not directly interchangeable.

The connection between cycle time and cost has been made previously. When this graph indicates improved cycle times can be reached, the real indication is that with shorter cycle times, the cost per piece generally decreases.

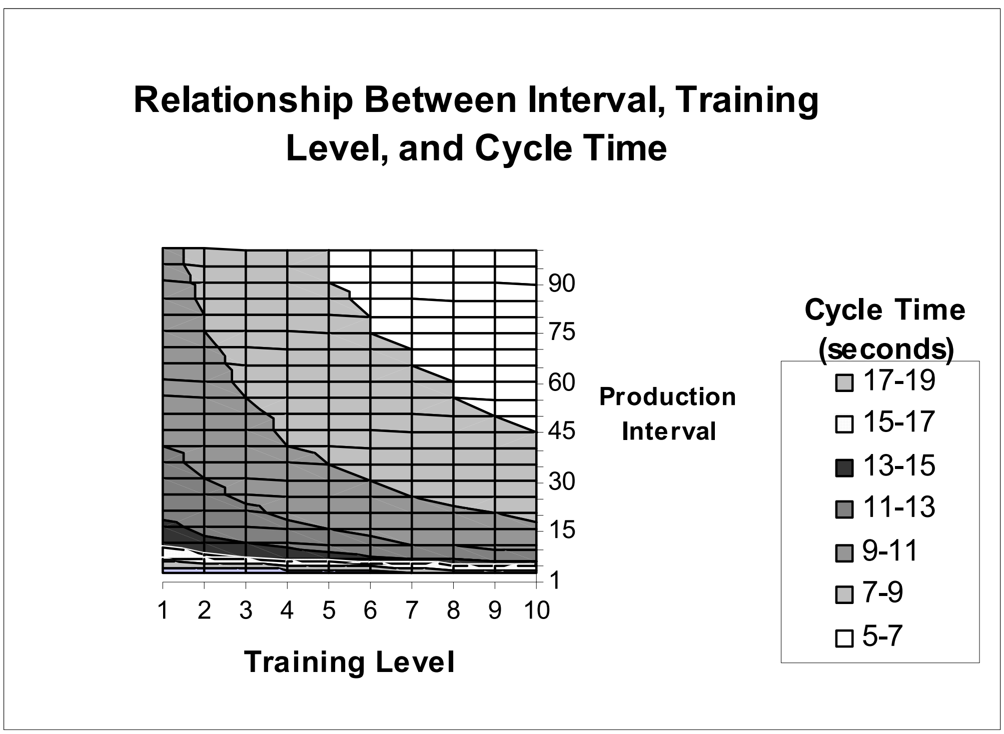

Figure 8: Relationship Between Production Interval, Training Level, and Cycle Time

4.1.5 Ramp-Up

Another benefit of the analyses conducted using this framework is determining an optimal cycle time for a given training level and production interval. Achieving optimal cycle time is important to effectively utilize investment made in equipment and labor. If cycle times are too slow, equipment and labor are more expensive then necessary, increasing the cost of a good part. If cycle times are too fast, rejects and unplanned downtime increase, adding to the cost of good part.

As indicated in Figure 9, least cost cycle time decreases over increased production intervals. The largest decreases to cycle time occur during the first production intervals. At later production intervals cycle time still decrease although less dramatically.

Additionally, cycle times plateau for a series of production intervals. This occurs once initial experiential learning has been achieved. Attempting to run faster than optimal cycle times creates increased rejects and unplanned equipment downtime.

The graph in Figure 9 also indicates that increasing the training amount will decrease the least cost cycle time at any given production interval. For example, at production interval thirty, providing only level one training yields an optimal cycle time of 12 seconds. But, with training level ten, at that same production interval of thirty, the optimal cycle time is 7.75 seconds. This is a difference of 4.25 seconds in cycle time at this one production interval a 35% reduction in cycle time. Additionally, the graph shows that at the highest production interval, training achieves a significantly faster cycle time by 3.75 seconds. As such, increased training also yields benefits in long-term cycle time reduction.

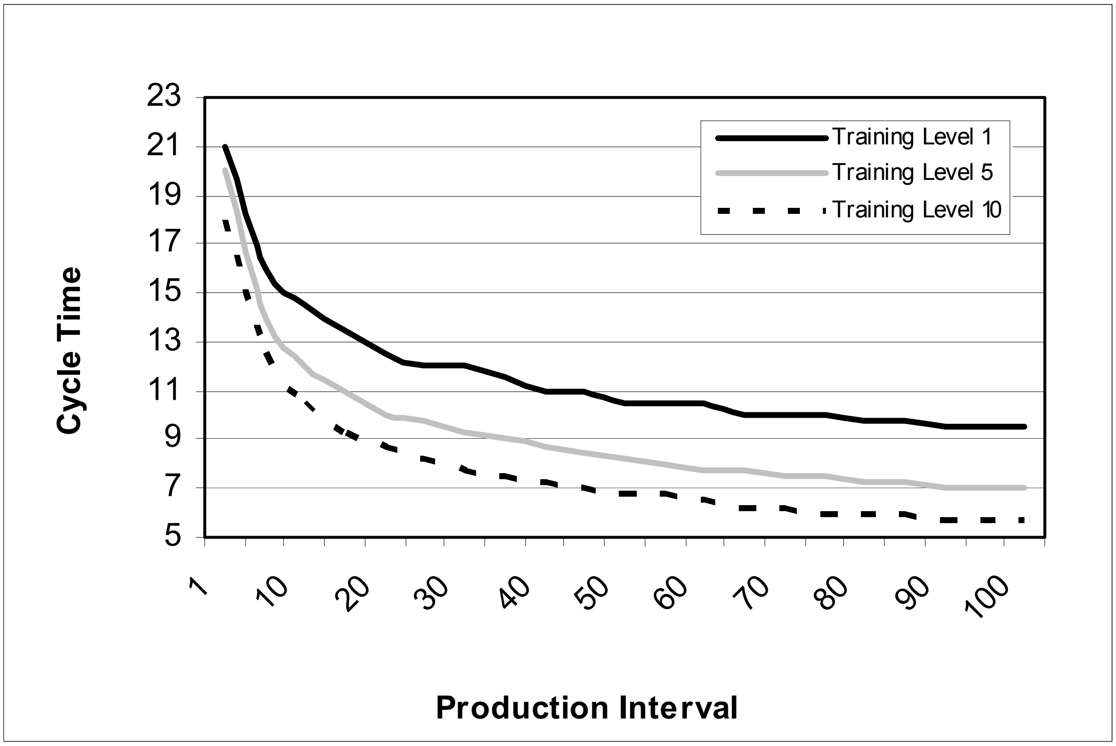

Figure 9: Ramp-Up Optimal Cycle Times

4.1.6. Single Cycle Times

Without quantitative analyses to determine the optimal cycle time, production managers may choose a single cycle to run a process from the first production interval through the last. When this occurs, there can be significant cost increase above the best achievable results. The results of this analysis are displayed below in Figure 10.

If the single cycle time is too slow, at the earliest production adverse consequences relating to unplanned downtime and reject rate are reduced, but this has a minimal impact. At the later production intervals that same slower cycle time creates additional cost based on inefficient capital and labor usage. When this cycle time is viewed over the entire production run, it produces a cost higher than that achieved with optimal cycle times throughout ramp-up.

At the opposite extreme, if a cycle time is chosen that is too fast, the earliest production intervals experience tremendous rejects and unplanned downtime. These two adverse consequences increase the cost per piece. At the later production intervals this same cycle time may produce few consequences since the knowledge needed to run at these faster times has been obtained by employees.

Another important concept represented on the graph is that the width of lines represent the range where costs increase. Providing training increases the width of the 0-1% cost increase range. This means that even if a poor decision is made regarding cycle time, the cost increase is not as significant. For lower training levels, choosing the wrong cycle time and continuing to operate at that speed for the entire production volume has more substantial consequences.

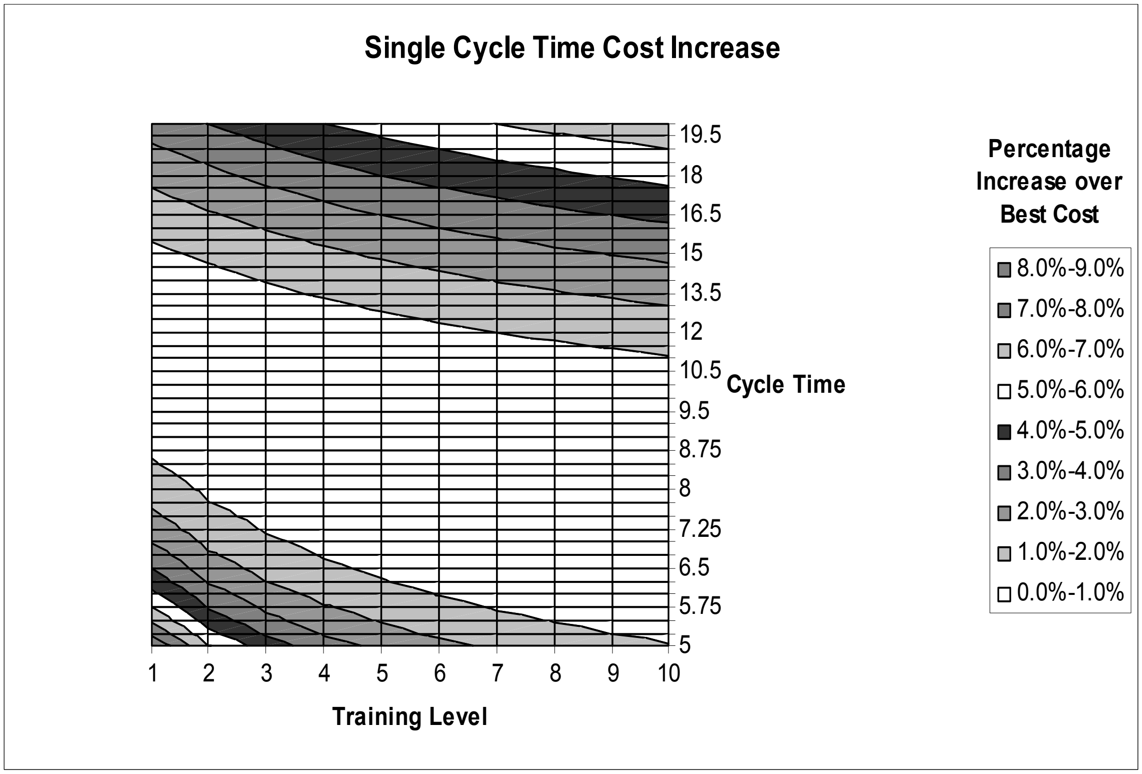

Figure 10: Single Cycle Time Cost Increase

4.1.7 Additional Process

By changing key inputs to the generic cost model, other detailed process based cost models can be emulated. A variety of changes can be made from material and energy costs per piece to number of works required. For these analyses the cost of capital was changed, but other production variables are similar to other analyses. This allows the generic process based cost model to be representative of other manufacturing processes with various capital investments. The optimal cycle time is determined, but the relationship between cycle time and downtime and unplanned equipment downtime are unchanged from the previous analysis. By varying the cost of capital the training level variation can be determined for other processes. Therefore, the next set of analyses indicates the changes to training level for a set of manufacturing processes with various capital investments.

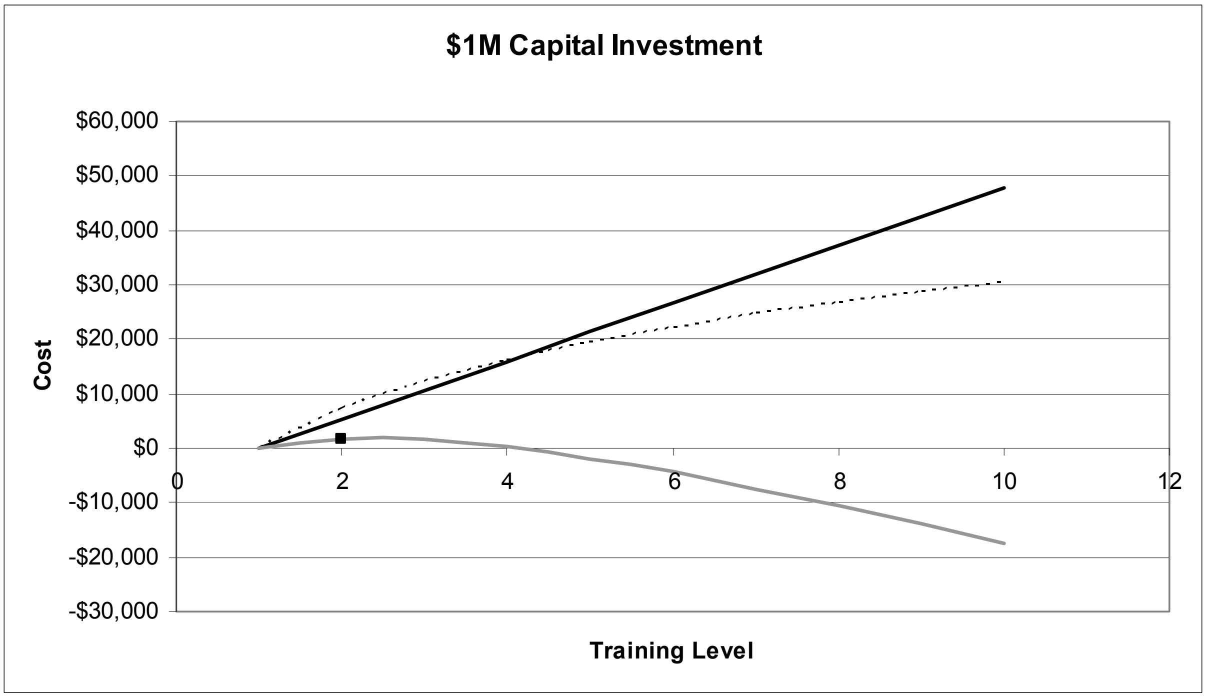

Figure 11: Key Training Investment Points for $1 Million Capital Investment

First, when the cost of capital is decreased to $1 million, the efficient level of training decreases as well. This is shown in Figure 11. For the previous analyses when the capital investment was $5 million, the efficient amount of training was level four. In this situation, the efficient training level decreases to level two.

Similarly, the point of limited financial incentives for additional training occurs at level four. For the previous analyses, this training level was eight. This occurs because the decreased cost of capital changes the benefits that can be obtained from training. With less costs associated with manufacturing, the cost of training becomes a larger percentage. Therefore more savings are required for the training to deliver before it becomes a financially unwise decision.

On the opposite side of the spectrum, when the capital investment is increased to $10 million, the key training points shift. The graph for this analysis is contained in Figure 12. With a capital investment of $10 million the efficient training investment level is eight. Of interest is that the savings from training never crosses the x-axis. This indicates that for the training levels examined here, there never is a point where training ceases to provide financial benefits. A point at a training level above 10 may occur which financial benefits are no longer achieved. The points shift because as the cost shifts, the opportunity for training savings also shift. With increased capital costs, efficiently running the equipment with better cycle times is more important. Those better cycle times are only achievable through training.

Again, given that the cost of capital is such a greater percentage of overall costs as compared to the cost of training create more opportunity is available for savings provided by the training. This causes the points to shift to greater levels of training due to increased capital costs.

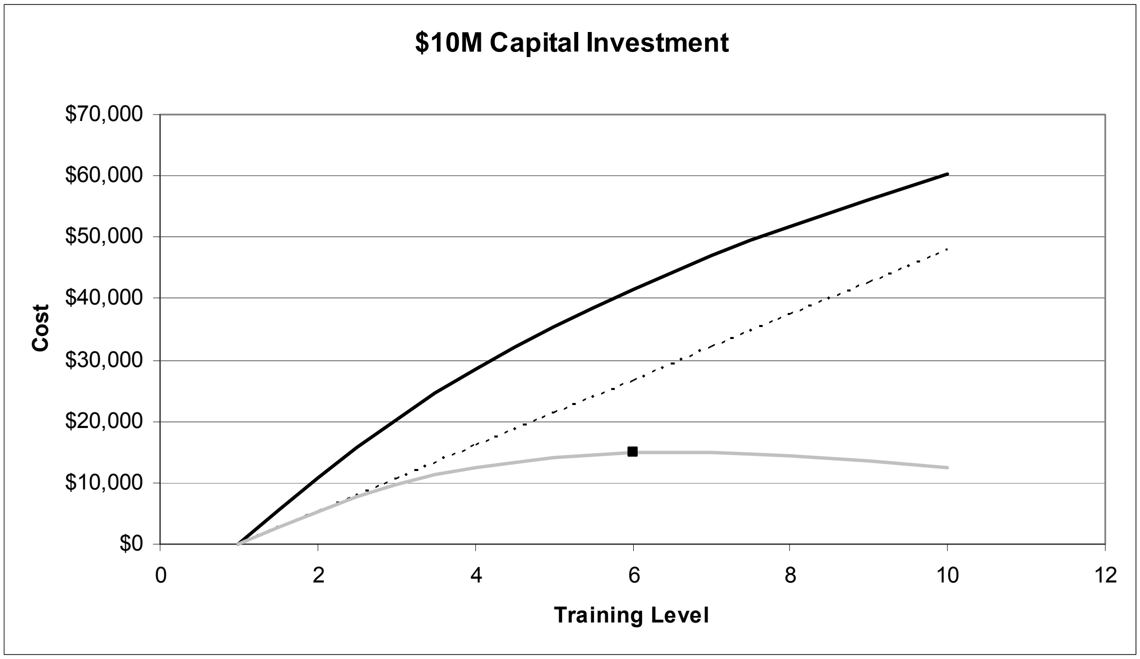

Figure 12: Key Training Investment Points $10 Million Capital Investment

The optimal level of training changes depending on the capital intensity of the process. The key investment points shift based on the relative cost of capital to the relative cost of training.

4.2 Stamping

The next analysis was conducted using the previously described stamping model. These analyses were run to expand the understanding provided by these relationships by incorporating more of the details of the stamping process. This fully detailed stamping model contains additional inputs and calculations, beyond those in the generic model. For example, more specifics around material cost and usage are provided. Additional information regarding equipment cost and type is also calculated.

Again cycle time ranged between four seconds and thirty seconds, with time steps broken down to a quarter of a second. Ten training levels were also analyzed, with training costing the same amount by incremental level as the cost applied to the generic model.

4.2.1 Key Training Investment Points

The next analysis investigated the same critical training investment points as the second analysis performed with the generic model. An interesting result was obtained. The incremental cost of training for this process was always considerably less than the savings achieved by this training. At no point was there a diminishing financial return on investment made in training. The difference between the two models is predominately the treatment of variable costs. The detailed stamping model had greater costs for material and energy than were calculated by the generic model. Because of these differences in variable costs, reductions in reject rates became critical. Reductions in reject rates occur through more training. Another possible explanation is that the cost of training was too small given the manufacturing operation investigated.

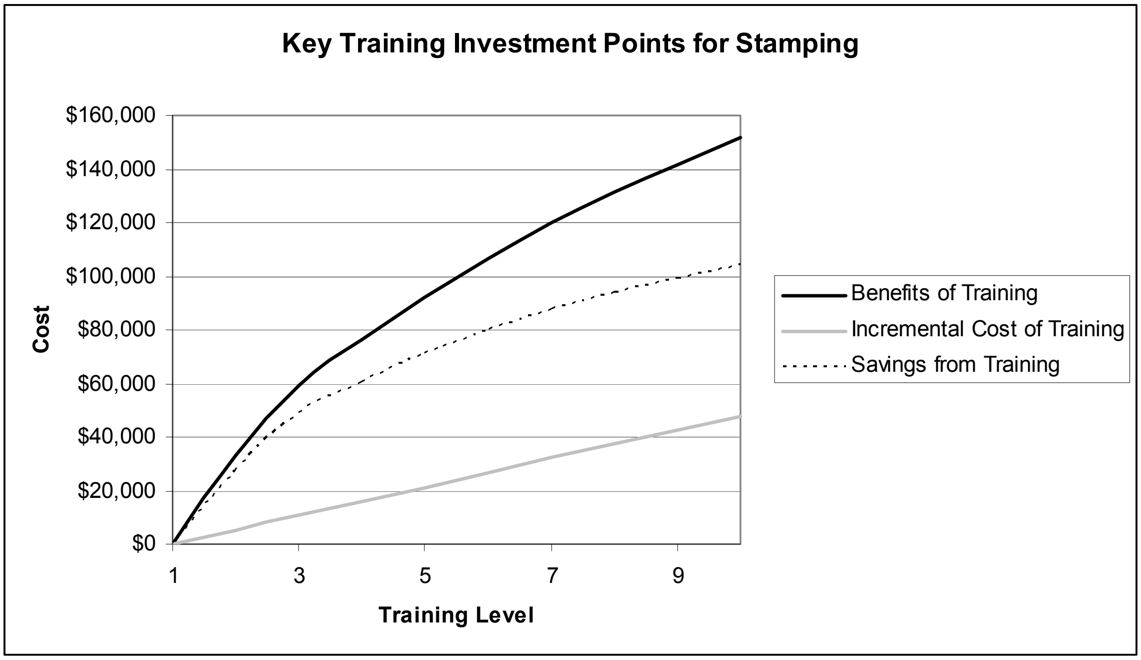

Figure 13: Key Training Investment Points for Stamping

4.2.2 Relationship Between Operational Learning and Structured Training

An overall look was done at the stamping model to understand the relationship between the training level, production interval and cycle time. This was done to examine the similarities between the stamping results and the results obtained by the generic model discussed previously.

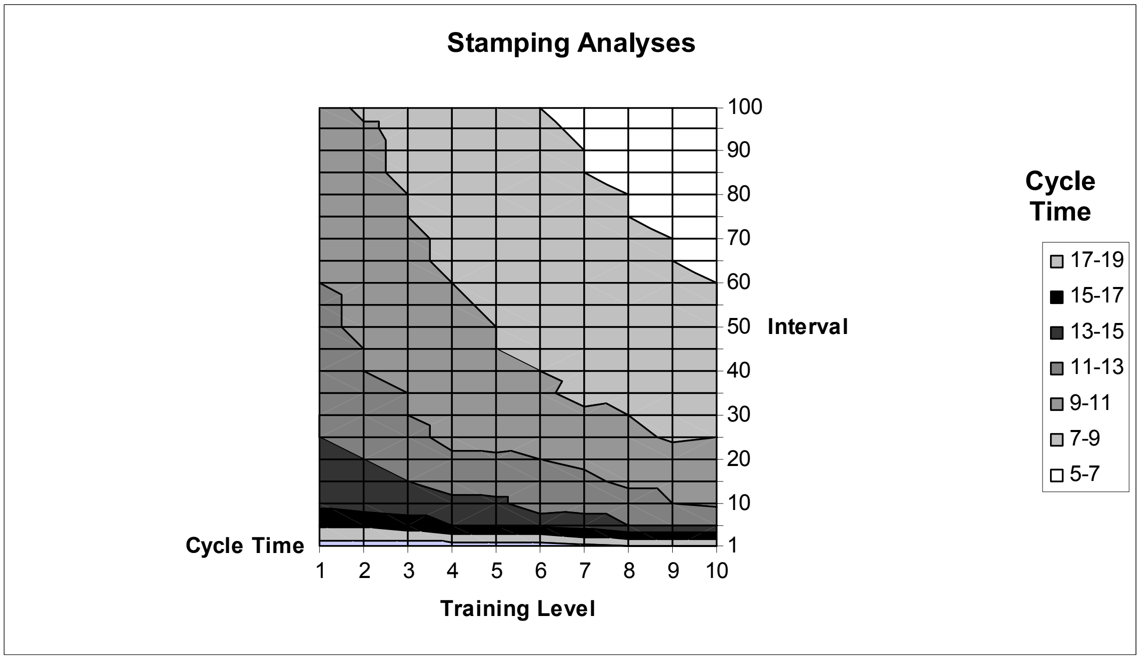

Figure 14: Application of Operational Decision Relationships to Detailed Stamping Model

The graph above in Figure 14, is similar to the graph in Figure 8. As such, similar conclusions result as well. At the starting production intervals, increased training provides no substantial benefits to achieving faster cycle times. During these first production intervals, experiential learning is the key contributor to better cycle times. This is because across the entire spectrum of training levels, no appreciable difference is noted in cycle time at the earliest production intervals.

Again at the highest production intervals, training is required to reach the shortest cycle times. Without a significant investment in training, the shortest cycle times are unreachable. This time the requisite training level is six. To achieve these best cycle times training of at least level six and significant production experience must occur.

The slope of the boundary lines between cycle times, balancing the benefits of training become steeper at the higher production intervals. At the lower intervals, the slope is less steep and therefore indicates the importance of operational learning at these times.

These analyses represent the scope of information provided by the methodology developed for this research. Additional analyses are possible given the models developed and the information available.

5. Conclusions

5.1 Training Investment

The previous analyses demonstrate the importance and impact of training for a manufacturing workforce. An obvious, but critical point, is the conclusion that providing structured training translates into financial benefits. By providing structured training on the manufacturing process, problem solving skills, and other information, that manufacturing process improves its performance on important metrics. In this particular research, the benefits translated into reduced rejects and reduced unplanned equipment downtime.

An efficient training investment point exists, where the highest return on investment can be obtained. To maximize the use of limited financial resources, the methodology presented here determined the efficient training point. As indicated through various analyses this point can shift depending on process specifics. This shift indicates the need for quantitative analysis of the benefits of training to be most helpful.

Additionally, there is a point at which continued investment in training does not yield additional financial benefits. This point of no financial benefits indicates the upper most training investment when monetary benefits will be achieved by investing to a particular training level. Similar to the efficient training level, the point of no financial benefits changes based on particular process conditions. Again this indicates the need for quantitative analyses of training benefits to achieve the best return on investment.

As mentioned previously, the benefits of training investigated here are purely financial. Many other benefits of training are discussed in other research, including employee dedication and loyalty (Birdi et al 1997). Although financial benefits are a chief consideration in deciding how much to invest in training, there are other issues that manufacturing managers must weigh. The conclusions here should not be an indication that management should cease to train above a certain level, but that financial incentives change.

5.2 Benefit of Production Experience

As many of the previous analyses discussed, there is a distinct benefit gained through production experience. The operational learning occurs more distinctly at the earliest stages of production. However, the learning continues to occur through the entire production runs considered in this research. Therefore two conclusions are reached based on production experience.

First, at the earliest production intervals, experience outweighs the importance of structured training programs. Through production experience the two variables examined, unplanned downtime and reject rate, are both impacted to improve production capability. The initial gains of operational learning decrease both the optimal cycle time and the cost of production. Furthermore, the analyses indicate that structured training provides limited benefits in these early production intervals. It appears as though this early production experience provides a foundation on which the structured training can build.

Second, benefits based on production experience still occur even at the latest production intervals. The benefits to reduced reject rate and unplanned downtime taper off at the later production intervals, but the analyses indicate that continued reduction still occurs in both variables. This is critical for manufacturing organizations at the end of production cycles to still know that appreciable benefits based on operational experience still occur.

The analyses indicate that experience is critical for a manufacturing process to achieve optimal running times and costs. A need for ample operational experience for training to become most beneficial also exists.

5.3. Benefits of Both Structured Training and Production Experience

Although the two previous sections discuss the benefits of structured training and production experience they do so independently. The analyses indicate the benefit of combining structured training that leads to conceptual learning with production experience that leads to operational learning. The combination of the two leads to the best cycle times and least expensive costs. Relying solely on one learning mechanism puts a manufacturing process at a significant disadvantage.

As mentioned previously, a foundation of operational learning appears to provide better results for structured training. Even at the later production intervals, when experience does not provide as much benefit, the combination of structured training and operational experience becomes evident.

5.4 Selection of Cycle Time

A significant contribution of the framework in this research is the determination of optimal cycle time. This methodology allows for the calculation of an optimal cycle time based on process decisions such as production interval and training level. The calculation of this optimal cycle time takes the guesswork out of one decision made during ramp-up by production managers. The model determines the cycle time at each point during ramp-up and, therefore, generates an optimal rate at which the ramp-up process can occur and reach steady state. The ramp-up curve is a critical approach for manufacturing managers to use during process start-ups.

Additionally, several analyses presented indicate the significance of selecting a cycle time at each production interval and training level. If comprehensive analyses are not performed and a production manager selects an inappropriate cycle time, costs increase. The cycle time selection becomes critical in achieving optimal cycle times and best costs for a production process.

This determination of an optimal cycle time is achieved based on the specific approach taken in this research. Using cycle time as a variable, allowed for analyses of this important decision to occur.

6. Policy Implications

The policy implications of this research fall into two categories: those which apply to corporate strategy and those which apply to government policy. The first set of recommendations impacts corporate strategies involving manufacturing ramp-up. The second group of recommendations applies to government policymaking. These results suggest ways that government policy making in the area of worker development can be made more effective.

6.1 Corporate Changes

The research conclusions point to specific areas of improvement. Within the area of corporate policy recommendations, two strategic approaches are most important to implement. The first is an increased emphasis on and use of quantitative analyses of manufacturing process ramp-up. The second strategy is to optimize investment in structured training programs, based on results provided by quantitative analyses.

6.1.1 Quantitative Analysis of Manufacturing Process Ramp-Up

These results suggest that the operators of manufacturing facilities should examine process ramp-up more quantitatively. Frameworks, such as the one presented in this thesis, provide mechanisms for information to be more effectively used both before and during ramp-up. As the results indicate, the use of these analyses can translate into financial savings.

As discussed in Section 4.1.5, the analyses quantify the benefit of an optimal cycle time over the course of production ramp-up. By selecting the optimal cycle time, inefficient use of capital equipment and labor and increased reject rate and unplanned downtime can be avoided. Without the quantitative analyses of cycle time, costs can increase by as much as 9%. Further discussion of the impact of cycle time is available in Section 4.1.6.

To perform these analyses, a significant change may be needed in manufacturing facilities. Frequently, decisions are made by individuals with years of experience based on their acquired knowledge. A shift to more mathematical analyses can be perceived as a threat, to these individuals and their accumulated experiences. To minimize the potential of losing their involvement, employee experiences must be built into the relationships between cycle time, production interval, structured training and unplanned downtime and reject rate. To effectively use these models, experience and data from previous ramp-ups should be included. For the models to be used most effectively, accuracy confirmation is required. Effective implementation of the models depends on integrating the experiences of knowledgeable employees. Additionally, upper levels of management should insist on quantitative analyses to assist in decision making.

Given the benefits of modeling and analysis, production decisions should be made early enough to give ample time that these analyses can be done. The results presented here take time to build. A model for the process must either be created, or modified, to meet the specifics of the particular manufacturing process being investigated. Therefore, companies need to build time into production development schedules for this work to be done. Traditionally, production ramp-up schedules are tight and non-essential work is eliminated as the schedule slips. The results of this research indicate there is a real price to be paid for not systematically examining production ramp-up.

All of these recommendations can be implemented. Companies must make the decision to promote and use quantitative analyses of manufacturing ramp-up strategies. The added difficulty of committing to this decision with appropriate resources throughout the production development process may prove more difficult. When schedules slip and financial resources become constrained, implementation of these decisions will be challenging.

6.1.2 Investment in Training

As discussed in Chapter 3, the data linking training to manufacturing performance metrics is limited. In spite of this limited data, the results of this research should encourage corporations to continue investment in training. Initial analyses indicate that training benefits a manufacturing process during ramp-up. Training improves two key manufacturing performance metrics: unplanned downtime and reject rate. Decreases in both of these metrics translate into financial gains for the company, and the research suggests that there is a level of training that optimizes these gains.

Although some analyses discussed in this thesis indicate there is an efficient point and a point of no financial benefit for training, these only reflect the financial benefits obtained by training. Even when accounting for only financial benefits, the key investment points may even be a higher training investment level than those currently being provided. For several of the analyses the key investment training points are at the higher levels of training. These levels represent a significant investment in training. Therefore, it is unlikely that the current investment in training reaches optimal levels.

6.2 Government Investment

The conclusions of this research suggest that the government has two main responsibilities:

1. Government must continue to invest in training programs for manufacturing workforces.
2. Government should be actively encouraging methodologies which quantitatively support the benefit of training.

6.2.1 Continued Investment in Training Programs

The analyses indicate that an investment in training has substantial benefits. The government, both federal and state, has correctly chosen to allocate resources to training of workers. Continued support for the Workforce Investment Act (WIA) of 1998, including reauthorization, is recommended. As discussed in Chapter One, the WIA is the first comprehensive legislation to address worker training in the United States.

The need for manufacturing employee training to improve production performance has been demonstrated by this research. Without some support of the government, continued investment is unlikely. The WIA creates state organizations to manage training approaches, within legislated guidelines. The state organizations can delegate the work further into local agencies. Local organizations are in a better position to determine the training needs of a particular community.

The WIA is certainly a positive step for training investment. However, this research indicates that modifications to the approach of the WIA are required. First, a requirement on specifics of training investment data should be required. With better data, better analyses, similar to those done in this work, can be performed. Better analyses leads to more efficient use of constrained resources, including resource allocation to training.

Second, the WIA should increase resources to offset training costs for employers. Currently, up to fifty percent of training costs can be reimbursed by governmental organizations for companies training employees (http://www.odod.state.oh.us/oitp.htm). This amount should change based on several factors. First, target industries should be able to obtain increased reimbursements. Each locale can identify the target industries based on industries the community is looking to attract, grow or maintain. For some communities, this will likely include manufacturing facilities. Second, smaller companies should be able to recoup larger amounts of training costs. Due to limited resources, smaller companies have historically invested less in training (NWAC).

A third modification to the WIA should be expansion of Title I to specifically describe involvement of employers. Currently, the WIA describes assistance to employees, but little is said regarding employers. Expansion of the WIA to include a requirement for employer involvement would more actively engage the business community in the development of governmental approaches to training needs and results. The WIA should require local 'one-stop' agencies develop outreach programs to inform local industries of the services available through the WIA. Details regarding the outreach program should be decided by the local WIA agency.

Governmental organizations providing training resources should be requiring companies receiving money to track the benefits of training more aggressively. Measurement is key for both the government investing the money in training and the company investing the time. This is discussed in more detail in Section 6.2.2.

6.2.2 Call for Quantitative Data on Training Analyses

With the quantity of resources devoted to the various training programs, ensuring return on that investment is critical. As part of the grant for training programs, government agencies should require that implementing organizations collect data. This data can be translated into analyses that demonstrate the importance of structured training programs.

The framework presented here begins to quantify the results of training. Other approaches are possible for training analyses. Organizations should not be limited to the approach taken here, but should explore other mechanisms for quantitative methodologies to analyze training benefits.

Organizations that fund training should expand their funding into quantitative analyses of training benefits. This includes developing methodologies to analyze the return on investment for training to expanding to improving training assessment. Analyses detailing the benefits of training provide better justification for the allocation of governmental resources.

7. Future Work

Although this research is a contribution to quantitative analyses of training in manufacturing environment, there is continued work to be done. Two primary areas require further exploration. The first is additional data collection and analyses with that data. The second area is the creation of additional methodological tools to explore training benefits.

7.1 Additional Data Collection and Analyses

As mentioned previously, data on actual production start-ups is not readily available. With the controlled chaos of equipment start-ups, organizations are not able to gather the data necessary to determine the full relationships between cycle time and training and unplanned downtime and reject rates.

Specific data required would require tracking information from multiple manufacturing process start-ups using the same production process. First, information about the training approach taken at the plant would be required to understand the level of training provided to employees. Then during the process ramp-up, actual data on the reject rate and unplanned downtime would be collected. This data, once pooled, could more explicitly define the relationship between production interval, cycle time, structured training and reject rate and downtime. This more defined curve would yield even more practical results for use in actual manufacturing ramp-ups.

To extend this data collection to other manufacturing processes provides growth in the analyses performed. This growth leads to refinement of the ideas presented here and a continued systematic methodology of analyzing training benefits. Similar data would need to be collected. Several manufacturing operation ramp-ups would need to be analyzed. Specific information on their structured training approach and cost would be required. Then actual data on reject rate and unplanned downtime for various cycle times and production intervals would be collected.

Complete analysis of other manufacturing processes allows for comparisons to the research presented here. That comparison confirms the research conducted.

With continued research in this field, manufacturing as a whole is improved through better ramp-ups and continued operation. Data will be required for the next step of moving academic research into practical applications.

7.2 Further Quantitative Analyses of Training

Collectively, companies spend billions of dollars a year training their workforces. In the last few years, the spending has been approximately $100 billion a year within the business community (Eisen 2004). Unfortunately there is very little data linking that investment with quantitative results. For those who work in the training and development field, the benefits are understood qualitatively. Training specialists have seen the impact of developing training programs and so continue to advocate for additional training investment in the future. Unfortunately, in tighter fiscal environments more concrete analyses are required. There is a gap in the research that indicates the return on investment of training in most industries, and manufacturing in particular.

The methodology presented in this research is one approach to examining the issues of structured training and operational learning in the manufacturing context. Other methodologies most certainly exist. Continued work in developing and refining methodologies ensures that the best approaches are taken when starting up a manufacturing process.

Of particular interest is the impact of structured training and operational learning in an ongoing manufacturing operation. The balance between these two learning mechanisms may be rarely achieved in manufacturing facilities. Through continued research, the relationship between the two will be expanded.

Expanding quantitative analyses to view continuing operations provides additional help to the manufacturing industry. The research performed here investigates the ramp-up process. But, for manufacturing operations currently in full production, an understanding of where best to invest training resources would be helpful. Further research will need to explore these issues.

There is a tremendous realm of possibilities to examine in the structured training and manufacturing area. Any research that continues to analyze these relationships is the most important work to be done in this field.

Appendix A

Select Sections Summary of the Workforce Investment Act of 1998

Title I: Job Training

- Requires use of individual training accounts through which a participant chooses from among qualified providers.
    - Exceptions:
        - On-the-Job and Customized Training
        - Insufficient number of qualified providers
        - Programs provided by Community Based Organizations

Funding

- 85% allocated to local areas
- 15% for state-wide activities: incentive grants, management information systems, evaluations, incumbent worker projects.

Appendix B

Generic Process Based Cost Model

Inputs into the Generic Model

Volumes	Annual Production Volume	100000	
	Production Volume Each Cycle?	1,000	
Costs	Material & Energy Cost	$3.50	per piece
	Capital Cost	$10,000,000	
	Tool Cost	$1,000,000	
	Training Cost	$75,652	
Production Information	Cycle Time	12	sec
	Training Amount	9	level
	Production Interval	10	
Worker Information	Days Per Year	250	
	Hours Per Day	20	
	Paid Breaks	1	hr
	Unpaid Breaks	1	hr
	Number of Workers	3	
	Labor Wage	$40	per hr
Exogenous	Interest Rate	8%	
	Equipment Life	30	yr
	Fixed Overhead Rate	35%	
	Building Costs	$1,500	$/sqm
	Product Life	5	yrs
	Building Life	25	yrs
	Maintenance Percent	10%	

Particular Intermediate Calculations

Strokes that result in line stoppage	1.74%
Reject Rate	3.68%

Summary Output Table

	Per Interval	Per Part	Percent
Material & Energy	$3,629	$3.63	38.15%
Labor	$775	$0.77	8.14%
Capital Cost	$1,274	$1.27	13.40%
Maintenance	$127	$0.13	1.34%
Overhead	$446	$0.45	4.69%
Tools	$2,505	$2.50	26.33%
Training Cost	$757	$0.76	7.95%
Total Cost	$9,513	$9.51	100.00%

Appendix C

Data Points for Reject Rate and Unplanned Downtime Equations

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Reject Rate	19.0%	16.5%	7.5%	4.5%	15.0%	11.0%
Cycle Time	6	12	6	12	6	12
Production Interval	1	1	60	60	1	1
Training Level	1	1	1	1	10	10

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Downtime Event Percent	12.0%	5.0%	2.2%	1.0%	7.5%	4.5%
Cycle Time	6	12	6	12	6	12
Production Interval	1	1	60	60	1	1
Training Level	1	1	1	1	10	10

References

Almgren, Henrik (2000). "Pilot Production and Manufacturing Start-Up: The Case of Vovlo S80." International Journal of Production Research **38**(17): 4577-4588.

ASTD Research (2000). American Society for Training and Development http://www.astd.org/astd/Resources/performance_improvement_community/trends.htm

Benson, P. George, Jayant V. Saraph, and Roger G. Schroeder (1991). Management Science **37**(9): 1107-1124.

Birdi, Kamal, and Catriona Allan, and Peter Warr (1997). "Correlates and Perceived Outcomes of Four Types of Employee Development Activity." Journal of Applied Psychology **82**(6): 845-857.

Burrow, J. and P. Berardinelli (2003). "Systematic Performance Improvement – Refining the Space Between Learning and Results. The Journal of Workplace Learning **15**:6-13.

Busch, John Victor (1987). "Technical Cost Modeling of Plastics Fabrication Processes." Doctoral Thesis. Materials Engineering, Massachusetts Institute of Technology, Cambridge, MA.

The Century Foundation, "Corporate Investments in Workers." www.tcf.org/TaskForces/retraining_workforce/Corp_Investment.html

Eisen, Phyllis (2004). "Skills for a 21st Century Workforce: Can We Meet the Challenge?" The Manufacturing Institute.

Fine, Charles H (1986). "Quality Improvement and Learning in Productive Systems." Management Science **32**(10): 1301-1315.

Fixson, Sebastian K (2002). Linking Modularity and Cost: A Methodology to Assess Cost Implications of Product Architecture Differences to Support Product Design Doctoral Thesis. Technology, Management, and Policy, Massachusetts Institute of Technology, Cambridge, MA: 123-132.

Haller, Martin, Andreas Peikert, and Josef Thoma (2003). "Cycle Time Management During Production Ramp-Up." Robotics and Computer Integrated Manufacturing **19**:183-188.

"Job Training and Vocational Education." *Almanac of Policy Issues*. June 1, 2001.

Ittner, Christopher D. (1996). "Exploratory Evidence on the Behavior of Quality Costs." Operations Research **44**(1):114-130.

Kilbridge, Maurice (1962). "A Model for Industrial Learning Costs." Management Science **8**: 516-527.

Kirchain, R.E. (2001). "Cost Modeling of Materials and Manufacturing Processes." Encyclopedia of Materials: Science and Technology.

Landini, Michael (1998). " Workforce Investment Act of 1998." U.S. Department of Labor Employment and Training Administration.

Lapre, Michael A., Amit Shankar Mukhergee, and Luk N. Van Wassenhove (2000). "Behind the Learning Curve: Linking Learning Activities to Waste Reduction." Management Science **46**(5):597-611.

Levin, Daniel Z. (2000). "Organizational Learning and the Transfer of Knowledge: An Investigation of Quality Improvement." Organization Science **11**(6): 630-647.

MacDuffie, John Paul (1995). "Human Resource Bundles and manufacturing Performance: Organizational Logic and Flexible Production Systems in the World Auto Industry." Industrial and Labor Relations Review **48**(2): 197-221.

National Association of Manufacturers (NAM) (2001). "Skills Gap 2000." National Association of Manufacturers.

National Workforce Assistance Collaborative (NWAC) "Collaborative Demand for Training Loans." http://www.ed.psu.edu/nwac/document/train/demand.html

Robinson, Sandra L. (1996). "Trust and Breach of the Psychological Contract." Administrative Science Quarterly **41**:574-599.

Roussea, Denise M. and Shenal A. Tijoriwala (1998). "Assessing Psychological Contracts: Issues, Alternatives, and Measures." Journal of Organizational Behavior **19**(4): 679-695.

Sinclair, Gavin, Stephen Klepper, and Wesley Cohen (2000). "What's Experience Got to Do With It? Sources of Cost Reduction in a Large Specialty Chemicals Producer." Management Science **46**(1): 28-45.

Stein, Eric W., Mark C. Pauster, and David May (2003). "A Knowledge-based system to improve the quality and efficiency of titanium melting." Expert Systems with Applications **24**: 239-246.

Terwiesch, Christian and Roger E. Bohn (2001). "Learning and process improvement during production ramp-up." International Journal of Production Economics **70**: 1-19.

Veloso, Francisco (2001). Local Content Requirements and Industrial Development: Economic Analysis and Cost Modeling of the Automotive Supply Chain. Doctoral Thesis. Technology, Management, and Policy, Massachusetts Institute of Technology, Cambridge, MA.

Veloso, Francisco, Chris Henry, Richard Roth, and Joel P. Clark (2000). Global Straegies for the Development of the Portuguese Autoparts Industry. Instituto de Apoio as Pequenas e Medias Empresas e ao Investimento.

Womer, Norman Keith (1979). "Learning Curves, Production Rate, and Program Costs." Management Science **25**(4): 312-319.