Low Volume Manufacturing Strategies for the Automotive Industry: A Global and Emerging Economy Perspective

by

Luis David German

Licenciado en Ciencias Fisicas
Universidad de Buenos Aires, 1992

S.M. Materials Science and Engineering
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Signature of Author: ____________________________

Department of Materials Science and Engineering
May 1, 1998

Certified by: ____________________________
Joel P. Clark
Professor of Materials Engineering
Thesis Supervisor

Accepted by: ____________________________
Linn W. Hobbs
John F. Elliott Professor of Materials
Chairman, Departmental Committee on Graduate Students

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Luis David German

Submitted to the Department of Materials Science and Engineering
on May 1, 1998 in Partial Fulfillment of the
Requirements of the Degree of Doctor of Philosophy in
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ABSTRACT

Low volume manufacturing has become increasingly important for the automotive industry. Globalization trends have led automakers and their suppliers to operate in developing regions of the world were economies of scale can not always be achieved. Niche markets for the performance/sport cars and some luxury sedans have been gaining economic importance, further fueling the need for developing more economic efficient low volume manufacturing operations. While low volume manufacturing has been the subject of much research, this has largely focused on flow optimization, inventory reduction and logistics improvements. Less attention has been paid to the subject of process technology choices. Identifying and employing optimal processing technology for low volume applications can reduce costs significantly.

This thesis presents technical cost modeling as an effective methodology for examining low volume manufacturing cases and identifies typical areas of concern for low volume producers. General strategies for reducing the cost penalties associated with low volume production are also presented. Four cases are analyzed; Argentine engine valve manufacturing, Thai steering wheel manufacturing, automobile radiator manufacturing, and sheet metal stamping. These cases exemplify three of the most common issues affecting low volume manufacturing; the selection of optimal alternative manufacturing technologies, tooling related issues such as the optimal investment levels and the choice of tooling technologies, and the choice of automation levels.

Results show that alternative process technologies may address low volume problems associated with long set-up times, poor equipment and tooling utilization and high tooling investment. The use of alternative tools which are less expensive, but have a shorter life are also potential solutions. Automation level optimization can be used to target the required output levels as well as affect the labor capital balance.

Thesis Supervisor: Joel P. Clark
Title: Professor of Materials Engineering
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To all of them my deepest gratitude.
1- INTRODUCTION

1.1. The Importance of Low Volume Manufacturing in the Automotive Industry

The current trends towards globalization have led the major automakers to begin vehicle production in far flung corners of the world. Local production offers advantages in terms of reduced logistics costs and access to otherwise protected markets. However, the increasingly decentralized nature of production is not without its difficulties for both the automaker and its suppliers. Labor conditions, access to capital and market size can significantly affect the cost of manufacturing the same parts in different regions. Generally speaking, labor wages tend to be lower, access to capital more restricted and market sizes smaller in developing regions, which are now experiencing the highest rate of growth in automobile production.

The strategy for succeeding in gaining market share in these developing regions is, in some sense, quite simple; offer high quality and large varieties of products to the market at a lower prices than those of the competitors [Hayes & Jaikumar, 1991]. Achieving this goal is not simple at all. Developing markets present a more difficult operating environment for the automakers due to highly uncertain growth rates, relatively low demand volumes, highly volatile market conditions, and higher capital costs, among other factors. In this complex market scenario automakers have to achieve the goal of quality products at a competitive cost by defining an appropriate manufacturing strategy. Local parts suppliers face similar issues as those faced by the automakers. In order to satisfy local content requirements, automakers must find local suppliers which can meet their product demands in terms of quality, reliability of delivery and price. Local suppliers must figure out how to offer quality parts at a comparable price, often under conditions which are quite different from those of their counterparts in fully industrialized economies.
A common challenge shared by the automakers and part suppliers is how to provide the quality and cost competitive products in this low volume demand environment. To define a coherent strategy for their operations, an better understanding of low volume manufacturing is needed.

Cost efficient low production manufacturing is also important for a completely different niche market segment; the performance/sport cars and some luxury sedans. Over the last decades, this niche market has been gaining in importance as the demand for these vehicles increases. It has been shown that as societies become wealthier, so does the desire of individuals to possess specialty goods different form those of others increases. As a consequence, the demand for specialty products increases, while the life cycle of these products decreases [Hitomi, 1995]. This fact is particularly true for the most affluent segments of societies in developed economies.

Production of most performance/sport cars and some luxury sedans are constrained by low demand volumes. Traditionally, the nature of this market segment allowed the automakers to pass on to the consumers the extra costs generated in the manufacturing operation by inefficiencies resulting form low volume production. In this market segment, consumers have exhibited low price elasticity and profits have been achieved through increased prices rather than manufacturing cost savings. However, as the performance/sport car and luxury sedan markets have grown and more automakers are competing in this niche market, the situation has become more competitive and cost reduction more important.

While the high end niche market and the low volume general use market seen in developing economies are very different, there are clear similarities between them. A common theme links these two automotive industry markets; how to remain cost competitive despite the seeming disadvantage of producing lower volumes. If auto makers and part suppliers are to succeed in these markets they must develop methods that help improve low volume manufacturing operations in order to overcome some of its intrinsic economic disadvantages.
1.2. Changing the Economics of Low Volume Manufacturing

To remain cost competitive at low volumes, changes have to be introduced to the manufacturing operation. The use of high volume manufacturing and process technologies in low volume manufacturing operations (often accompanied by large product mixes) has proven to be economically inefficient. Classic manufacturing operations theory provides a good basis for examining general process alternatives and their implications for production economics.

![Diagram of production volume and process structure]

Figure 1: The Hayes-Wheelwright product/process matrix

Manufacturing operations theory organizes processes by production volumes and product mixes. This organization ranges from batch to continuous flow processes depending on the level of the production volume and product mix. Batch processes involve the flow of parts through the process steps in groups, while continuous processes consist of parts flowing
through in an uninterrupted sequence. Traditional mass production techniques using transfer lines or continuous flow operations are cost effective for large volumes of parts. Alternatively, a job-shop or batch flow environment organized in cells which usually requires a higher labor component is far more flexible and can better handle low manufacturing volumes, but is less productive. One way of visualizing this situation was introduced by [Hayes-Wheelwright, 1984] and is shown in figure 1.

This approach provides a very broad picture, which is more helpful at classifying processes than at improving a manufacturing operation. Nevertheless, there are critical issues known to be associated with each type of process, and that information can lead to an early identification of areas that would affect the economics of low volume manufacturing. Over time, specific manufacturing strategies for low volume operations have been developed. Figure 2 represents the general areas at which an engineer designing and optimizing low volume manufacturing operations should concentrate his effort.

Most of the intensive work done around operating more effectively at low volumes has focused on work flow optimization, inventory reduction and logistics improvements. Several techniques were introduced to improve these aspects. Techniques such as Group Technology, Part Oriented Production, Material Requirements Planning, Lot Scheduling, Modular Production [Star, 1965], Flexible Automation, Flexible Manufacturing Systems, Computer Integrated Manufacturing, On-line Production Management, and Just in Time [Ohno, 1978] [Monden, 1983] have proved useful towards addressing some of the problems. A time base evolution of these techniques is presented in figure 3.
Figure 2: Key areas affecting the competitiveness of low volume manufacturing

Figure 3: Evolution to high-mix, low-volume manufacturing [Mahoney, 1997]

These techniques can be combined to achieve even greater results. For example, the use of flexible manufacturing systems FMS, in a facility operating with group technology GT, involves the implementation of high levels of automation to achieve both flexibility and
productivity at low volumes. The integration of these highly automated operations is done under what is commonly termed CIM, computer integrated manufacturing [Mesina, 1993]. This may be a suitable compromise for some manufacturers [Parrish, 1990] under certain scenarios. The objective of these technologies is to be able to efficiently manufacture batches composed of only a minimum number of parts, reducing the overall cycle time. Although these technologies provide very efficient ways of operating at low volumes, their implementation requires high levels of capital investment and may not be the best option under other circumstances.

Usually neglected in the operations literature, the processing technology choice (see figure 2) should be the cornerstone of any low volume manufacturing analysis. Even in the absence of any other consideration, choosing the right processing technology can reduce costs significantly at low volumes. If alternative processing technologies, better suited for low volume manufacturing, are not analyzed, the manufacturer may have an unnecessarily high cost structure. Further, the previously presented techniques targeting work flow optimization, inventory reduction and logistics improvements could always be applied to the process after the most cost effective technology has being determined. For example, a high volume producer use impression die forming in a line flow process structure to force a piece to acquire the shape of the die cavity. A low volume producer may rather use lathes and milling machines implemented in a cell manufacturing operation to make a part with similar characteristics. By doing so, low volume producer can effectively reduce dedicated capital investment and thus reducing cost at low volumes.

This thesis focuses on low volume manufacturing and what can be done in terms of identifying the most effective processing technologies rather than logistics or flow optimization concerns. This document is divided into ten chapters. Chapter 2 provides an overview of the broader issues involving low volume manufacturing. Also, it defines the goals of the work; providing a methodology for analyzing low volume manufacturing, identifying typical problems, and proposing general strategies for reducing the cost penalties associated
with low volume production. Chapter 3 provides details concerning the methodological approach. This includes a discussion of technical cost modeling and the case study method and their relevance to this work. Chapter 4 presents the research hypotheses used to define the cases to be analyzed in this thesis. It details a set of cost related low volume manufacturing research questions such as; the effect of large product mix on low volumes, the relevance of set up times for competing manufacturing processes, the impact of automation, and the labor-capital tradeoffs. Chapters 5, 6, and 7 detail three individual cases designed to provide in-depth analyses of low volume manufacturing situations of a single critical issue. Each individual case includes a case description, results and conclusions. Chapter 8 discusses the case of sheet metal stamping in which multiple critical low volume manufacturing issues are combined. This chapter exemplifies a problem involving combinations of factors requiring simultaneous analysis and understanding. It demonstrates the applicability of the analytical framework to the analysis of complex low volume manufacturing situations. Chapter 9 summarizes this thesis findings and chapter 10 presents the main conclusions in a concise way. Chapter 10 Chapter 11 notes several limitations of this thesis and suggests opportunities for continuing research.
2. PROBLEM STATEMENT

2.1. Low Volume Manufacturing

Low volume manufacturing is a product specific concept. Depending on the particular characteristics of a part and the manufacturing process used to produce it, a manufacturing volume would be referred to as "low" when substantial cost improvements can be achieved by increasing this volume. For a particular industry such as commercial bakeries, a production volume of a few hundred thousand units (bread) per year would be considered very low, but the same volume would be considered extremely high for a machine tool manufacturer.

Generally speaking, the term "low volume manufacturing" only makes sense when there is a production volume point that can be referred to as the counterpart "high volume manufacturing". The idea of high volumes is linked with concepts developed late in the 19th century about mass production. Mass production and mass consumption became a goal for most corporations in America during the first half of the 20th century. A prime example was Ford's model T car, of which 15 million were produced from 1908 to 1927. The general idea was that the per unit cost of producing a good decreases as the number of units being produced increases. This phenomenon is referred to as economies of scale. Mathematically, a cost function, \( f(x) \), with economies of scale is generally expressed as:

\[
f(x) = a + bx^k \quad k < 1
\]

where \( a \) is the fixed cost, \( b \) is the variable cost and \( x \) is the number of parts to be produced. In the linear case, when \( k = 1 \), and \( x \to \infty \); \( f(x)/x \to b \). When \( k > 1 \), there is a optimum production scale at which the unit manufacturing cost is a minimum [Maxcy & Silberston, 1959]. In the real world, the behavior of the cost function is more complex and the concept of minimum efficient scales should be defined. The minimum efficient scale is the minimum production volume after which there are no significant economic benefits in producing larger quantities. At low volumes, those much smaller than either the optimum production scale or
the minimum efficient scale, the per unit cost would be higher than at high volumes. Understanding the cost changes with production volume means understanding the shape of the cost function $f(x)$.

There are several aspects contributing to higher unit costs at low volumes. Those aspects are related to the work flow, inventory, logistics, and processing technology. This thesis will concentrate its effort on aspects related to the process technology. At low production volumes there may be a cost penalty associated with the low capital utilization, particularly for dedicated equipment. Furthermore, if large product mixes or smaller batches are needed at these volumes, there can be cost penalties arising from the increased set up times and material loses at start ups. An in-depth discussion of these issues is provided in chapter 4.

2.2. Thesis Objective

The objectives of this thesis are to provide:

- A method for examining specific low volume manufacturing cases.
- The identification of typical low volume problems and solutions for several industries of interest.
- Some general strategies for reducing the cost penalties of operating at low volumes.

To achieve these goals, this dissertation will identify specific aspects of manufacturing technologies which could be adjusted to better suit low volume production. The proper adjustment of manufacturing parameters related to these aspects will be presented in order to illustrate how to improve the competitiveness of low volume manufactured goods. It is the goal of this thesis to help the reader to better understand these issues and to provide a methodological framework for the analysis of the economics of low production volume manufacturing. More specifically this thesis will also look at external issues (not directly related to the process technology) such as labor cost, capital cost, and demand conditions that
can have profound effects on the manufacturing cost, and are important considerations when evaluating the competitiveness of low volume manufacturing.
3- METHODOLOGY

3.1. Introduction

The work developed in this thesis employs two methodologies, the technical cost modeling and case study approaches. Technical cost modeling is used to analyze costs which arise directly from the manufacturing process. This method facilitates the understanding of the relationship between part cost (model output) and variables such as production volume, labor cost, and equipment performance (typical model inputs), allowing the study of the cost implications of different manufacturing strategies and business conditions.

Different low volume operations may require different types of strategies to improve their competitiveness. This thesis will use the case study approach to address some of the most relevant manufacturing issues since an understanding of factors common to a variety of manufacturing situations can only be obtained through the investigation of actual production operations.

The combination of these two methodologies will allow this work to identify typical drawbacks of low production volume manufacturing and to show the effects that some proposed solutions will have on the overall economic performance.

3.2. Technical Cost Modeling

Technical cost modeling will be used throughout this thesis to simulate and study the cost behavior of manufacturing operations. Building these models and applying them to real and virtual manufacturing situations allows one to understand the low volume manufacturing cost behavior under a variety of conditions. Cost models will be the main tools used to understand the cost drivers for different process technologies and the influences of external factors on these costs. Also, cost models will be used to study the cost response of a manufacturing operation to changes in production volume, lot size, capital investment level,
equipment utilization, automaton level, labor productivity and others. The models will allow a comparison of the use of different processing technologies for the fabrication of the same parts. Models will facilitate the comparison of using two competing technologies and the study and optimization of alternative technologies.

3.2.1. Technical Cost Modeling Background

While many cost estimation techniques exist, few offer significant depth of analysis or the ability to investigate the effects of changes in input variables on the manufacturing cost. The technical cost modeling (TCM) technique overcomes these disadvantages [Poggiali, 1985], [Nallicheri, 1990], [Roth, 1992], [Han, 1994], [German, 1996].

The traditional approach to estimate manufacturing cost has always been based on "rules of thumb" and accounting empiricism. These rules include factors which lead to oversimplification and other specific weaknesses. Important issues such as processing variables, production volume, part geometry, and others do not play any role on such simplistic approaches [Sims, 1995]. Even more, the part cost is extremely sensitive to some assumed factors such as machine rent, even though machine rent does not factor in important effects like economies of scale, part geometry, and others. Examples of these traditional "rule of thumb" cost estimates are presented in Table 1.

<table>
<thead>
<tr>
<th>Rule Name</th>
<th>Part Cost ($/unit) =</th>
</tr>
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<tbody>
<tr>
<td>Multiplier</td>
<td>Multiplier Factor x Material Cost</td>
</tr>
<tr>
<td>Rent</td>
<td>Material Cost + (Cycle Time x Machine Rent)</td>
</tr>
<tr>
<td>Burden</td>
<td>(Material Cost + Labor Cost) x Burden Rate</td>
</tr>
</tbody>
</table>

Table 1: The "rules of thumb" for manufacturing cost estimate
These approaches lack the key ingredient necessary for analyzing changes on the manufacturing process, the ability to understand the dependence of the output (cost) on changes in the input parameters, such as production volume, lot sizes, etc.

On the contrary, TCM is specifically designed to investigate the interactions between process variables and cost. TCM breaks down the different cost elements and estimates each one separately. This is done from basic engineering and physics principles of each of the manufacturing processes involved in the overall operation. Clearly defined economic and accounting principles are then applied to these cost elements. These elements are then classified as either fixed or variable costs.

The division of cost elements into variable and fixed categories is a widely accepted accounting and engineering classification [Sims, 1995]. The basic difference is that variable costs are a function of the annual production volume while fixed costs are not. The elements use in under these categories are presented in table 2.

<table>
<thead>
<tr>
<th>Variable Cost</th>
<th>Fixed Cost</th>
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<tbody>
<tr>
<td>Material</td>
<td>Main Machine</td>
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<tr>
<td>Direct Labor</td>
<td>Auxiliary Equipment</td>
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<td>Energy</td>
<td>Tooling</td>
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<td></td>
<td>Maintenance</td>
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<td></td>
<td>Overhead</td>
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<tr>
<td></td>
<td>Building</td>
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</tbody>
</table>

Table 2: Cost elements used in TCM for both variable and fixed cost

Central to the goals of TCM has been the development of a tool for analyzing the manufacturing cost implications of different manufacturing strategies, business conditions and materials selection. This methodology has been used to evaluate not only the competitive implications of conventional materials and materials forming technologies, but also
developmental and research alternatives, quantifying the strengths and weaknesses of these alternatives as well as pinpointing the critical factors (both engineering and economic) which contribute to this competitive position. TCM is designed to work with so-called "zero-stage" design data, making it possible to take advantage of this information in the critical early phases of product and process development. This is particularly important since the firm's strategic intent must be decided prior to the selection of an appropriate process technology. For example, in an early stage of a process design, TCM can be used to specifically analyze the effect of changes in parameters such as production volume on the overall cost.

3.2.2. Computation of the Cost Elements used in TCM

Understanding time utilization is critical in developing reliable cost models. Accounting for every fraction of time used in the manufacturing operation allows the models to accurately allocate costs to a given part. The models built for this thesis share a common analysis of the use of time and is based on a full account of a 24 hour day. Before going into the workings of the models it is first important to understand the basics of operating a manufacturing facility with respect to time.

Expected overall volume, together with information about worker breaks, line breakdown rates, and the need to set aside extra time for routine maintenance, determines the total line-hours planned for a year. Establishing an operating schedule for the day then fixed the size of the plant as well as the planned labor time for the year. Union contracts and other restrictions on the use of labor often mean the plant can not operate with fewer labor hours even if less time is required to achieve the actual production in practice. If the firm had complete information about the overall production volume, downtimes, actual running rates, as well as complete freedom regarding the availability of labor, they would make sure that the planned labor time and the total required operating time were equal. However, since they can not do this there is usually some gap between these two times.
The time distribution presented in Figure 4 summarizes the allocation of time used in technical cost models for this research.

Figure 4: Time distribution used in this thesis TCMs

Figure 4 shows several time components that are specifically tracked by the technical cost models. These components are listed below with a brief explanation of their meaning:

- **Planned labor time**: Is the total operating time needed based on the expected overall production volume. It includes all times needed for worker breaks, line breakdowns, and maintenance.

- **Expected idle time**: Time when no workers are present to operate the lines.

- **Total required operating time**: Is the total operating time needed to produce the actual overall production volume. It does not include the time spent on maintenance, since this is assumed to occur during idle time.
- **Idle time:** Any remaining daily time left unused after the total required operating time. This may include time during which workers are paid, but no production occurs.

- **Time required for the part specific production:** Is the required operating time employed in the manufacture of a specific part.

- **Time required for the remaining production:** Is the total required operating time employed in the manufacture of all other parts beside the specific part under study.

- **Set-up times:** Is the time spent in preparing the line to run new parts or batches.

- **Production time:** Is the time when the line is actually running and producing parts, and is calculated as the product of the manufacturing cycle time and the production volume.

- **Loading and unloading times:** Is the time spent loading and unloading pieces for the line.

- **Running time:** Is actual time the pieces spend in the line undergoing physical transformations.

- **Worker breaks:** The time the line is stopped due to labor requirements.

- **Unplanned breaks:** The time the line is down due to unexpected breakdowns.

- **Planned maintenance:** Time usually during the otherwise idle hours, used for preventive or other maintenance of the line.

From the above time breakdown, labor and equipment utilization can be defined. Labor utilization is the ratio of the amount of time workers spend operating the line to the amount of time workers are paid. These are represented by the total required operating time and the planned labor time in figure 4. Similarly, the line utilization is the ratio of total required operating time to the maximum available time. The maximum available time (not shown in figure 4) consist of the 24 hours day minus the time needed for maintenance. Both labor and line utilization can play a significant role in low volume production costs. Many factors can cause the total required operating time to be smaller than the maximum available time,
resulting in reduced labor and equipment utilization and increased costs. The exact amount of the per part cost increase will depend on the individual contributions of labor and capital.

When the line is non dedicated, the total required operating time is split into the portion used to produce the specific part under consideration and the time needed to produce all other parts on this line. For simplicity, the models assume that all the different parts manufactured in the same line have similar characteristics leading to an identical time structure, though in reality, parts requiring different fabrication times may be produced in the same line. This simplification reduces the models input to the part specific yearly production volume and the overall production volume. Without this simplification, a complete description of all the parts manufactured in each line (including production volumes, cycle times, lot sizes, set up times, etc.) would be needed. This is reasonable provided that the same assumptions are used when comparing the cost outcome from all manufacturing scenarios.

Models assume four major aspects of the operating time; set-up time, production time, workers breaks, and unplanned breaks. Planned breaks are assumed to be scheduled during the idle time.

Setup accounts for the time needed to prepare a line for starting the manufacturing of a different part or batch. Setup times include tooling changes, equipment preparation, material changes, etc. The total number of setups is determined by the ratio of the effective production volume to the typical lot size.

Production time is composed of the time needed for loading and unloading a part and the time the part spends on the line while being transformed. The combination of these two times is usually referred as the production cycle time (or the inverse of the running rate). Some models treat these two factors as separate issues while others deal with them simultaneously. The approach depends on the process characteristics. These times are estimated by the models in different ways. Sometimes models will use regression data to estimate the cycle
time, in other cases engineering and processing physics will be used, and in others the model user will have to provide these numbers based on observed cycle times.

Workers breaks account for interruptions in the line operation related to breaks such as lunch breaks. These times are obtained by reviewing regional labor regulations.

Unplanned breaks account for those interruptions in the manufacturing operation mostly related to unexpected breakdowns on the line. Different technologies have different expected breakdown rates. These expected rates were obtained by interviewing the engineering staff in charge of the manufacturing operations. Also, quite often the production of different parts has different breakdown rates, however models will assume for simplicity that all parts lead to similar breakdown rates.

Planned maintenance is usually scheduled for the idle portion of the day. The amount of time needed for maintenance can be estimated by interviewing equipment suppliers to learn the recommended maintenance schedules or by collecting statistical data from existing manufacturing lines.

The manufacturing time analysis is a key factors for the models to yield meaningful and realistic results. The time analysis is then used in the models for the evaluation of manufacturing cost. This cost is composed of nine different elements. Table 2 provided a list of these elements divided in two categories, variable and fixed costs. The next sections present a brief explanation of how each of these elements are calculated including the use of the time considerations already discussed.

3.2.2.a. Material Cost

The cost of material can be estimated directly from the design of the piece and the price of the raw material, but the part design weight may not always be an accurate measure of the total amount of material used. An accurate treatment of the amount of material to be consumed should include scrap losses in the form of engineering scrap and rejected parts.
Further, it should be kept in mind that in many cases the listed material market price and scrap price may be different from the actual transaction price. It is not possible to capture such differences in a model given that they involve managerial decisions and different transfer scenarios.

3.2.2.b. Direct Labor Cost

Direct labor cost reflects the number of man-hours required to produce a given part. It is a function of the wages paid, the time required to produce the part, the number of workers needed for the process, labor productivity and the total amount of operating hours per year. As explained in section 3.1.2, the number of paid workers hours per year depends on the labor flexibility of the company. Strictly speaking the labor requirement is equal to the man-hours required to produce the parts. However, union contracts or other factors which limit labor flexibility may dictate payments for labor beyond the physical requirements of production. For example, workers contracts often do not allow employers to pay for only partial shifts even if there is no planned production for the remaining time. The total number of hours will then be split by the fraction of time allocated to the specific part production. The hourly wage should represent the cost of a worker-hour to the company, not the salary perceived by the worker.

3.2.2.c. Energy Cost

Ideally, the energy cost can be calculated by using a detailed energy balance for each process and the cost of the energy source. However, this is extremely complex since it involves all possible energy losses, energy efficiencies and considerations of heat, mass and momentum transfer. Because in most cases the cost of energy is a small portion of the total piece cost, it is reasonable to estimate it as a function of the equipment energy consumption per hour. Only in some processes, such as heat treatment, does the cost of the energy merit treatment in greater detail.
3.2.2.d. Main Equipment Cost

The cost of the equipment is in most cases a function of the equipment capacity, degree of automation and the number of lines required to achieve the planned overall production volume. The equipment capacity can be related to a large number of design parameters. Knowing the design parameters and therefore the required equipment capacity the machinery cost can be obtained from vendors.

For a given level of investment in equipment, an annual cost must be derived. It is assumed that the investments are paid for by loans over the estimated period of life of the equipment at a predetermined interest rate. The annual payment, \( R \), is calculated using the standard amortization equation given below.

\[
R = P \cdot \frac{(1 + i)^N \cdot i}{(1 + i)^N - 1}
\]

Where \( i \) is the interest rate, \( N \) is the number of periods (years) over its life, \( P \) is the total investment.

The next step is to distribute the cost over the production volume to obtain a cost per piece base. If the equipment is dedicated to the manufacturing of a particular part, the annual cost is then divided by the total production volume to obtain the per piece cost. Otherwise, the annual cost of the equipment is allocated to the parts by the ratio of the time required to finish the specific part over the totally required operating time.

3.2.2.e. Auxiliary Equipment Cost

Typically auxiliary equipment for material fabrication includes compressors, storage equipment, conveyors, etc. A simpler way of estimating auxiliary equipment cost assumes that the ratio of the auxiliary equipment to the main machine is constant. For many fabrication processes this assumption is good enough to yield valid results. In some cases, an automation
level input will trigger the use of different auxiliary equipment investment ratios, as well as a change in cycle times and a modification on the component of direct labor required. In these cases, line automation is treated by the models as a discrete variable, usually allowing a fairly limited number of automation levels (in the stamping model four automation levels can be analyzed; no automation, automatic loading, automatic unloading, and full automation). The choice on a particular automation level triggers other (discrete) model parameters changes. These changes are usually determined by regression analyses from data collected that correlates to different automation scenarios.

3.2.2.f. Tooling Cost

Calculating a tooling cost per part can be very complicated. Estimating both the investment in a set of tooling and the number of parts it will produce during its life span is very difficult. It would involve variables such as the material, design and size of the part, the automation level, and the tool quality. Further, tools are usually dedicated to the production of a specific part. The per part tooling cost for a dedicated set of dies such as those used in forging is calculated in a different way than for non-dedicated items such as non-part specific cutting inserts.

Estimating the cost of a tools set which may not exist is difficult provided that the each tool set is uniquely design for the production of a specific part. A regression analysis of data for the cost of existing tools provides a good mechanism for estimating tooling cost. Historical tooling data is collected and analyzed to evaluate correlation between tooling physical characteristics and investment. The number of tooling sets is calculated based on the over-the-life part production volume and the number of parallel lines used in manufacturing.

It is assumed that the total amount of tooling is bought at the beginning of the production life. Like the investment in equipment, the tooling investment is paid for by loans over the estimated period of product life at a predetermined interest rate.
3.2.2.g. Maintenance Cost

Maintenance cost is difficult to quantify precisely. There are two types of maintenance, scheduled and unscheduled. Unscheduled maintenance is done in response to problems as they develop. An accurate estimation of the occurrence of problems requires prediction of probabilistic events. Instead, a simple calculation is done by estimating maintenance cost as a fixed percentage of machinery cost and building cost.

3.2.2.h. Overhead Cost

Overhead accounts for laborers and other costs not directly involved in the manufacturing. Nonetheless these elements are necessary in the production process. This group includes personnel working in supervisory, managerial, janitorial, security, and accounting positions. The overhead cost is usually classified as a fixed cost and can be estimated as a fixed percentage of the total capital investment.

3.2.2.i. Building Cost

The cost of building space is relatively straightforward to estimate, given the amount of space required and the price per unit surface area. The space required is determined by the quantity and size of the equipment which must be installed. The price per surface area can be obtained from real estate agents or industry sources. Once the data has been obtained and the investment established it can be distributed over the entire production volume using a similar allocation method as the one explained for the equipment cost analysis.

3.3. Case Study Approach

There is no single solution on how to operate at low volumes. Using mass production processes at low volumes may yield costly results. An examination of the common denominators that improve the competitiveness of low volume manufacturing under different situations is required. Why is a particular processing technology better suited to a particular
industry under a given scenario than others? How can one select the most appropriate process technology for the low volume manufacturing scenario under consideration? An understanding of factors common to a variety of manufacturing situations can only be obtained through the investigation of actual production operations. The aim is to determine general strategies that can be applied to other cases by means of in-depth analyses of issues involved in specific cases.

In general, case studies have been criticized as a poor basis for generalization. A few and unique cases can not determine general trends is argue. Arguments in favor of the case method claim that through an in depth analysis of only a single or just a few cases insight can be gained into certain activities, problems, or responses which come up again and again, making it possible to draw some meaningful generalizations [Stake, 1995].

The strength of the case study approach is the ability to examine a manufacturing scenario in sufficient detail to get a full picture of the economics of a process across a spectrum of external variables, in particular production volume. Therefore a strong effort was placed on gaining a detailed understanding of each industry an firm to be examined. In all cases this starts with a literature review followed by a visit to factories producing equivalent products at different production volumes. The goal of these visits is to learn and become familiar with the manufacturing processes. The interaction with engineers and the in-depth discussions about technological issues help the development of questionnaires directed at collecting the data needed for the case analyses and the building of technical cost models. These models and analysis results are validated by running simulations for parts that are currently being manufactured. These results are then presented and discussed with industry experts, and the feedback received is the applied to improve the models until a final, reliable version is achieved.

The selection of the cases to be presented in this thesis reflects the research hypotheses discussed in the next chapter. The original objectives and design of the case studies is based on such propositions, which in turn reflect the set of research questions aimed at providing
new insight into low volume manufacturing issues. The combination of the case study methodology with the development of technical cost models provided a powerful analytical tool to develop this research.
4- RESEARCH HYPOTHESES & CASE SELECTION

4.1. Research Hypotheses

There are two main goals for this thesis; to help improve the competitiveness of processing at low volumes through the choice of the optimal processing technology, and to understand characteristics of different manufacturing scenarios that are better suited to low volume manufacturing. Clearly defined research hypotheses will lead to the selection of suitable cases studies, and therefore to the achievement of the thesis objectives.

The research hypotheses of this thesis concentrate in three areas; the selection of optimal low volume alternative manufacturing technologies, effective decision making regarding tooling investment levels and the choice of tooling technologies, and the choice of optimal low volume automation levels. In some cases there is more than one technology available for making equivalent products. In others, where alternate processes are not available, different levels of automation can be used to change the relationship between fixed and variable costs. Tooling can also be a critical issue in low volume manufacturing. In those cases specific trade-offs between tooling investment and the consequence of using different tooling technologies could become a critical factor. These are fundamental issues in defining a competitive, low volume processing operation. An in depth look at these issues will follow in the next section.

It is also the objective of this thesis to integrate into the manufacturing analysis some of the most relevant economic factors that can significantly affect cost at low volumes. Understanding critical characteristics of manufacturing scenarios that are better suited to low volume manufacturing is fundamental as well. The cases presented in this thesis will look at different manufacturing scenarios and the effect they have on the core concepts discussed in the research hypotheses.
4.2. Manufacturing Issues

What effect does a large product mix have on the economics of low volume manufacturing? To address this question this thesis explores the economic impact behind the relationship between parts specific production volumes and the overall production volumes. Further, utilization issues may prove to be the limiting factor under some low volume manufacturing scenarios. For some processes, where capital investment is a major cost driver, it becomes critical to achieve high capital utilization levels. In these cases, the production volume of specific parts is less important than the overall production volume for the factory. A manufacturing line that produces low individual part volumes but has a large product mix, can achieve a large overall production volume and thus effective levels of capital utilization. This may not always be the case, and for some processes (i.e., where setup times are long relative to the line running time) large product mixes may also carry with them a major economic disadvantage. Understanding the relationship between product mix at low volumes, and the consequence on capital utilization becomes critical at low volumes.

What is the impact of different set up times on the selection among competing processes? Short cycle time processes may be better suited for low volumes and small lot sizes even when they demand larger cycle times. High volume manufacturing processes are usually developed with the idea of achieving short cycle times. In some cases, in order to achieve this goal, these processes demand complicated setup operations. Even if long set up times are required, this may not be a major cost penalty for high production volumes processes. However, at low volumes this is not the case. Under these circumstances, alternative processes with shorter set up times may prove to be more economical, even if these processes appear to be less effective due to factors such as longer cycle times, higher reject rates, and lower materials yields. Exploring the tradeoffs between competing processes is an integral part of this thesis.

How can large product mixes be used to reach large enough volumes (and thus achieve economies of scale) to justify the use of highly automated lines? How does the automation
level change the labor capital balance? How can a manufacturer use automation to minimize production cost? This thesis illustrates how different levels of automation can be used to change the relationship between fixed and variable labor costs, and the scenarios where these changes become critical for low volume competitiveness. Low labor cost regions may be well suited to low volume production which relies on labor intensive operations, but low volumes also may be produced economically in expensive labor regions through the use of automation. Balancing the pros and cons of automation implementation is crucial at low volumes as this thesis will show.

The research hypotheses of this thesis concentrate in three particular areas; alternative technologies, tooling related issues, and optimal automation level. These are fundamental issues in defining a competitive low volume processing operation and play a critical role in the definition of the case studies to be used throughout this dissertation.

4.2.1. Alternative Technologies

It is well documented that different processes have different cycle and setup times. Even more, they have different economies of scale, even when used to manufacture the same product. Therefore, choosing a suitable technology to manufacture a competitive product becomes an essential issue in the definition of a manufacturing strategy. As an example, large product mixes can be achieved either through conventional means, such as an increased investment in automation, or through the choice of a manufacturing process which more easily lends itself to product changes.

As Hayes-Wheelwright illustrated (figure 1), a manufacturing process flow would be organized according to the targeted production volume. For example, continuous process flows are better suited to high volume operations. Furthermore, the choice of a process technology is dependent on the type of process flow. Therefore, it is reasonable to expect a different process technologies at different levels of production volume. The processing technology choice should be the cornerstone of any low volume manufacturing analysis. Even
in the absence of any other consideration, choosing the best processing technology could reduce costs significantly at low volumes. If alternative processing technologies, better suited for low volume manufacturing, are not considered the manufacturer could end up with an unnecessarily high cost structure.

In some cases there may not be any alternative processing technology, but if there is, it is always advised to look for the technologies that could be better suited for low volume operations. In particular, low volume manufacturing could benefit from technologies with reduced set up times, lower capital investments, less dedicated tooling requirements, better material utilization, etc.

A simple and yet informative type of analysis used to evaluate alternative processing technologies is called crossover analysis [Marinich, 1997]. Crossover analysis begins by modeling a manufacturing operation or constructing an analytical cost function for each specific processing technology. By plotting these technologies simultaneously as a function of a particular variable (production volume, line utilization, etc.), one can identify which technology is better suited at a given value of the input variable. Figure 5 demonstrates the use of crossover analysis.
Figure 5: Crossover analysis applied to a three competing technologies situation

At the crossover points, any two alternatives are equal. To the sides of the crossover point one alternative is less expensive at lower volumes while the other is less expensive at higher volumes. When changes (or fluctuations) are expected (or forecasted) in the input variable, deciding on the best technology can be more complex. For example if there is expected market growth which will push the production volume past a crossover point, the analysis will indicate a change in the optimal process choice. This selection will then be dependent on the growth rate assumptions which are subject to error. The probabilities of different growth rate or in general other scenarios could be included in the analysis using decision analysis techniques [de Neufville, 1990].
4.2.2. Tooling Related Issues

Tooling investment can be a major factor in the competitiveness of low volume manufacturing. This is particularly the case when expensive dedicated tooling is needed. Tooling cost is spread over the part production volume, and when that production volume is low, the cost of each part produced includes a larger fraction of the tooling investment. Therefore, it is always a goal to try to use tooling as effectively as possible. On the other hand, when technologically feasible, specific measures should be taken to adjust the tooling technology to better serve the needs of low volume manufacturing economics. For example, one way for achieving this goal is by using less lasting but cheaper tooling, or another way is by reducing tooling complexity even if that requires slowing down the line running rate. Dedicated investment is allocated to a part by dividing that investment over the yearly part specific production volume times the life of the product.

Non dedicated investment like machinery, and building is allocated to a part cost by dividing that investment over its expected life and adjusting it by the fraction of the totally required operating time used to finish the part specific work. Therefore the cost implications of non-dedicated investments depend on this manufacturing times ratio and are independent of the part specific production volume.

Because at low volumes, dedicated cost, such as those arising from tooling investment, are spread over fewer parts, they have a more profound effect on the per piece cost than non dedicated costs. Therefore, even when tooling accounts for only a minor part of the overall manufacturing investment, it is often a major cost factor when the parts specific production volume is low.

To overcome this obstacle to low volume manufacturing, alternative tooling options should be considered. Alternative tooling may have consequences for both the part quality and the useful tool life (as measured by number of parts). However, tooling choices which significantly alter the product quality are not considered in this thesis since the resulting
products are not directly substitutable. There are several different options to reduce tool costs, usually at the expense of tool life. These alternatives usually include: the use of less expensive materials, alternative manufacturing processes, alternative tooling manufacturing technologies and tooling design simplifications (usually at the expense of an increase in the number of manufacturing steps). It is generally true that these alternative tooling options have a higher tooling cost to tooling life ratio. Any of these alternative technologies for which this is not true would be the technology choice at all production volumes. That is because in order to produce the needed parts over the production life it would be less expensive to use multiple tool sets (each with shorter lives than the reference) with a lower cost to life ratio than the reference tooling technology. This ratio usually limits the use of these alternative technologies at high production volumes, and constrains their use to manufacturing volumes of the order of the tool life.

Even in cases where no alternative tooling options are available, these issues should be carefully considered. Optimizing the tooling investment (and thus the number of tool sets) for a particular target production volume may not be an easy task. This is particularly true when there exists large cost differences between tooling and equipment. It may seem logical to improve the utilization of expensive equipment through the use of multiple, simultaneous operations. However, careful optimization is needed if the simultaneous operations require multiple tool sets which may be otherwise unnecessary. Simultaneous operations will reduce the overall required manufacturing time and thus improve the line capacity. When constrained by demand (production volume), the tradeoffs should be carefully analyzed. On one hand, savings may be reached in terms of equipment investment and labor content, but on the other hand, it tooling investment will increase and tool utilization will decrease.

4.2.3. Optimal Automation Level

In cases where alternate processes are not available, different levels of automation can be used to change the relationship between fixed and variable costs. Using less automation
reduces the initial investment at the expense of increased labor costs. The cost penalty for operating at production volumes that are below minimum efficient scales may thus reduced. This strategy is more generally applicable than a complete change in the processing technique. But defining an optimal automation level can be much more complicated that this relatively simple tradeoff. In some cases it may not be economical to replace automation by labor, even in low labor cost regions, as discussed in section 4.2. The investment in automation level should be carefully studied in a case by case basis [Meredith & Hill, 1987].

A major issue in automation choice involves the match between the competitive strategy of the firm and the proposed manufacturing system. This can be achieved through a careful study of the different automation options. These options include several levels of automation and several areas to which automation can be applied, such as the process technology, the materials handling system, the tool handling, and the quality assurance system.

It is recognized in the literature that justifying a decision on an economically optimal automation level is very complicated [Chakravarty & Bijayananda, 1994]. This requires the identification of all the costs and benefits associated with that decision. Besides the obvious equipment cost there are other costs and benefits arising from auxiliary equipment implications, labor requirements, and cycle time changes. Technical cost modeling has proven to be a particularly useful method to account for these changes and will be used throughout this thesis.

4.3. Case Selection

The design of the case studies is based on the research hypotheses discussed in section 4.1. Also, this thesis aims to integrate into the processing analysis relevant economic aspects that can meaningfully impact the cost behavior at low volumes.

In order to achieve these goals this thesis will include four case studies. Argentine engine valve manufacturing, Thai steering wheel manufacturing, automobile radiator
manufacturing, and sheet metal stamping. In each case at least one of the previously mentioned issues is relevant to the manufacturing competitiveness at low volumes.

The Argentine engine valve industry provides an excellent example of the use of a more appropriate manufacturing process to yield the flexibility needed to be a valuable industry supplier in the low production volume niche market. By employing a processing technique that has shorter set up times and lower fixed costs, the Argentine valve makers are able to compete on the basis of cost in the market for lower volume engine valves.

The Thai steering wheel manufacturing case illustrates the importance of tooling investment optimization and the use of an alternative manufacturing process to yield a cost competitive product for the domestic low volume market. For one part of the process they employ a technique that has shorter set up times and avoids the expense of dedicated tooling. For the remaining process steps there is the need to optimize the unavoidable tooling requirements.

Radiator manufacturing represents a situation in which there is essentially only one process route available to obtain the final product, but a continuum of automation possibilities. This case illustrates the capital-labor tradeoffs which can be used to reduce costs.

Finally, the sheet metal stamping case provides an excellent opportunity to simultaneously explore multiple issues affecting the competitiveness of low volume manufacturing. This case will analyze the potential for the use of "active hydorforming", an alternative to the traditional stamping technology. Further, it will explore the potential alternative tooling technologies that can significantly reduce the cost of conventional stamping at low volumes. This dissertation will look into the possibility of combining the active hydroforming technology with less expensive alternative tooling technologies. The use of various degrees of automation at different production volume levels will be studied as well.
All these cases will be discussed in the context of operating in the US versus other regions such as Argentina and Thailand. This allows one to study and understand the relationship between critical macroeconomic characteristics and the effects they have on the competitiveness of low volume manufacturing operations.
5- ARGENTINE ENGINE VALVE MANUFACTURING

5.1. Introduction

The Argentine engine valve manufacturing case illustrates the effectiveness of using an alternative manufacturing process to produce valves for a low volume niche market. This alternative process characterized by has shorter set up times and lower fixed costs, yield the flexibility needed to be a valuable industry supplier in the low volume engine valve market. By using this process they obtain a competitive edge that allows them to compete on cost basis in this particular market segment.

In some cases there is more than one technology available for making equivalent products. Setup and cycle times changes form process to process, even when used to manufacture the same product. As a consequence alternative processes have different economies of scale. This is the case for automotive engine valve manufacturing. Forging, the traditional valve manufacturing process, involves high equipment and tooling costs, but is very efficient at producing large volumes of valves. An alternate method, forge-extrusion requires a lower investment, but has a slower cycle time, thus making it less expensive at low production volumes. This case demonstrates how the Argentine engine valve suppliers chose a process technology which was more appropriate to their situation in order to remain competitive in their market niche.

5.2. Case Description

The worldwide engine valve industry is dominated by two main competitors (TRW and Eaton) who control approximately 90% of the more than 1 billion units consumed annually worldwide. These two companies target high volume products and use the low cost structure resulting from economies of scale to compete. The remaining 10% represents a substantial market, consisting of a large variety of low volume products. This product mix is difficult to produce in a cost effective manner using the mass production techniques of the two main
producers. This market consists of engine valves for low production volume automobiles, motorcycles, buses, aircraft, off-shore boats, grass trimmers, pumps and specialty automobiles, such as race cars. Staying competitive requires the ability to produce low volume or custom made parts in relatively small lots. Success is determined mainly by the manufacturer's ability to cope with variability in demand (both volume and product mix) and still produce a cost competitive valve.

The Argentine engine valve manufacturers started operations during the mid 1950's as suppliers to a protected local market. Their cost structure made it difficult to export and thus they were subject to the very high level of volatility in demand for automobiles in Argentina over the last two decades, which has varied between 100,000 and 400,000 units/year [ADEFA Reports]. To deal with these large volume fluctuations, the valve manufacturers targeted Argentina's after-market as well. By doing this, they expected to stabilize slightly the fluctuations in demand for new vehicles, but they faced the complicated task of having to manufacture even smaller volumes and larger product mixes. This market situation is considerably different from the large and relatively stable market demand faced by the two large global competitors. To survive in this highly volatile market, these companies had to be flexible enough to accommodate wide swings in orders from year to year. Their difficulties were further compounded by a fluctuating macroeconomic situation. In particular, this meant there was little access to the capital needed to acquire flexibility through the purchase of expensive automation equipment. Their solution was to find a more suitable manufacturing process, one that would sacrifice speed for lower equipment investment and shorter set up times when switching to a new product.

The selection of a suitable manufacturing process was central both to the early success of the Argentine valve manufacturers in their closed domestic market and to their competitiveness in the low volume niche of the global market. Valve production can be accomplished by two techniques, forging and forge-extrusion. The Argentine producers
chose to use the low volume, highly flexible process of forge-extrusion instead of using forging, which is a very cost effective production process at high production volumes.

The high volume producers typically use forging [Kalpakjian, 1992] to produce valves. The forging process is based on plastically deforming a material cylinder into a near net shape part. A schematic of this is given in figure 6a. In addition to the forging step, other processes are required to produce the final part. Figure 7 contains a flow chart for the process typically used to produce engine valves. The forging process requires a large investment in equipment and tooling, but has short cycle times and low variable costs, and is typically associated with high volume producers [Ludema, et. al., 1987]. Its main drawback is that the set up times for changing from one product to another can be quite substantial. This long changeover time limits its usefulness when manufacturing a large mix of products. Furthermore, the high level of capital investment means that large production volumes are essential in order to recover the fixed costs.

Figure 6 a & b: A schematic of the forging step used in the "forging" and in the "forge-extrusion" process.
Figure 7: Valve manufacturing flow chart

The forge-extrusion process is similar to forging, but only involves plastic deformation to form the valve head, rather than the entire valve body (see figure 6b). As a result, the tooling does not need to be as precise, and the forging press can also be less expensive. However, this saving comes at a price. The forge-extrusion step results in a part which requires more extensive machining to achieve the desired final valve geometry. Since more material is removed in the post-forming steps, the forming itself is less critical to the final quality. Thus, the forge-extrusion step can be done with less expensive equipment and tooling. Further, the set-up time for this process is greatly reduced. While the final steps, such as machining and grinding are more critical and have a longer cycle time than in the forging process, their costs can be reduced through the introduction of computer numerical control (CNC) systems, further increasing the flexibility of the production line.
The short set up times and lower capital investment mean that the forge-extrusion process is far better suited to producing smaller lots, and the process is more flexible with regard to both product mix and total production volume. Larger product mix can also be used to mitigate the effects of volume fluctuations in a single product line. Furthermore, the lower investment costs mean that idle time is less expensive, and thus demand fluctuations do not impose as great a cost penalty. These features are significant if the manufacturer operates in a market with a high degree of demand variability.

5.3. Case Results

In general, the forge-extrusion process is less expensive when supplying to relatively small markets or to markets with a large product mix, while forging should be used for the high volume markets. At intermediate volumes, technical cost modeling can be used to estimate the conditions under which one process is more cost effective than the other. For the purpose of comparing these two processes, costs were estimated for a generic intake valve for a mid size automobile engine. This valve has a simple design made out of standard HNV3 steel [Larson, et. al., 1987]. Figure 8 shows the cost distribution for producing a valve by both processes at a crossover production point (show later in this chapter). That crossover point corresponds to a production volume of 300,000 valves per year and an average lot size of 75,000 pieces.

There are three major differences between these processes. First, the forge-extrusion option has a larger labor component, 30% compared to only 18% for the forging case on a cost basis. Based purely on a man-hour basis (that is, if the differences in wages between Argentina and USA are eliminated), the forge-extrusion process has nearly eight times the labor content of the forging process. Second, machinery and tooling represent a smaller fraction of the total cost of forge-extrusion than forging (20% compared to 32%). This reflects the fact that the forge-extrusion process is less capital intensive. The third difference
is the material cost. The steel rods needed in the forge-extrusion process are more expensive than those used in the forging process.

Figure 8: Cost breakdown for producing a valve using the forging & forge-extrusion process

The cost models were also used to observe the sensitivity of the manufacturing cost to variations in the production volume and lot size. Results, in the form of three dimensional graphs, are presented in figures 9 and 10. Each graph shows the per piece cost as a function of the production volume and lot size.
Figure 9: Manufacturing cost sensitivity to production volume & lot size for the forging process.

Figure 10: Manufacturing cost sensitivity to production volume and lot size for the forge-extrusion process.
These graphs indicate that the cost associated with forging process exhibits a stronger dependence on both the production volume and lot size produced. This is due mainly to two penalizing factors. The reduction in tooling utilization at low volumes, and the large amount of time spent in setup operations when lot sizes are reduced. At low volumes and small lot sizes the forge-extrusion process offers considerable savings over the traditional high volume forging process.

A comparison of the two techniques can be seen by analyzing the intersection of the two surfaces shown in figures 9 and 10. This defines two feasible regions in the "Lot Size-Production Volume" space (it is infeasible to have lot sizes greater than the annual production volume). Each region is characterized by the more cost effective process for that particular set of inputs and is shown in figure 11.

Figure 11: Regions of dominant cost-effectiveness for the two competing processes
Figure 11 indicates that the forging process yields a lower manufacturing cost in the region where production volumes are larger than approximately 300,000 valves per year and lot sizes are larger than approximately 75,000 valves. For the rest of the "Lot Size-Production Volume" space the cost effective choice is the forge-extrusion process. This overall behavior is mainly due to the much smaller set up time needed to run the forge-extrusion process. Only when the production volume is large enough to diminish the cost penalty resulting from longer set up times does the forging process become the choice.

Near the boundary between the processes the overall manufacturing costs are similar. Nevertheless, the set up time of the forge-extrusion process is still much smaller than the set up cost of the forging process. On the other hand, the manufacturing cost, excluding set up for the forge-extrusion process is higher at this point. This is presented in figure 12, where it can be seen that the cost due to set up is approximately 10 cents for a valve made by the forging process compared to only 2 cents for one produced by the forge-extrusion process. This was calculated at a production volume of 300,000 and a lot size 75,000 and corresponds to a point in the crossover boundary. Relatively small uncertainties in the demand variables could lead to a change in the selection of the optimal process. Consequently, it is especially important to understand the demand variability near this boundary.
Figure 12: Cost break down by process steps, material cost, and set up for producing a valve using the two competing processes

5.4. Case Conclusions

The costs of forging, the standard high production volume technology, are very sensitive to reductions in production volume or lot size. In order to be cost competitive at low volumes, an alternative process technology, forge-extrusion, can be used. Even though valve manufacturing requires an almost identical processing flow for these two technologies, changes in the way the forging step is done have major consequences on the product cost. The use of forge-extrusion, a less precise process, demands more complex downstream processes, increasing the overall manufacturing cycle time and thus eliminating the chances for using forge-extrusion for high volumes applications. At the same time, it does not require expensive tools and has a much simpler (and thus less time consuming) setup operation.
Forge-extrusion is a clear case in which low volume manufacturing benefits from technologies that have reduced set up times and require lower tooling investment than that of the standard high production technology. It is important to note that, even though the forging process uses more expensive equipment, the short cycle time makes the use of that equipment very cost effective at high volumes.

The determination of the crossover line (and thus the regions of dominant cost-effectiveness for the two competing processes) is nonetheless affected by external factors. The forge-extursion process uses almost eight times more man-hours per valve. This is partially compensated by the fact that the Argentinean labor cost is about one fourth of the American. Furthermore, operating these processes in a different environment could significantly move the crossover line since labor is in all cases a major cost component.
6- THAI STEERING WHEEL MANUFACTURING

6.1. Introduction

The Thai steering wheel manufacturing case illustrates both the importance of tooling investment optimization and the use of an alternative manufacturing process to yield a cost competitive product for the domestic low volume market. Thai companies employ a slightly modified version of the conventional high volume manufacturing process. One process step employs a technique that has shorter set up times and avoids the expense of dedicated tooling. For the remaining process steps there is the need to optimize the unavoidable tooling requirements.

The use of this modified manufacturing process has allowed Thai suppliers to maintain a dominant role in their local semi-protected market. Still, if the Thai local market becomes more open [Panichapat, 1996], and the local OEMs adopt steering wheel designs already in use in other regions, Thai suppliers may not be able to compete with the large volume importers. Success will likely depend on achieving sufficiently large volumes to remain cost competitive. The necessary minimum volumes vary for each step of the production process and will be closely associated with the process step cycle time. The manufacturer can then make strategic choices such as the decision to outsource steps where the minimum efficient production volumes in unattainable. Alternatively they can supply rims, hub structures or other welded parts to other manufacturers as a way to fully utilize their equipment.

6.2. Case Description

The Thai automotive industry was established in 1961 with the help of a strong investment promotion plan established by the government. With the establishment of a minimum local content requirement of 25% in 1974, most Japanese firms set up affiliated supplier companies, giving rise to locally produced parts. These parts were mainly peripherals
such as alternators, filters, exhaust pipes and radiators. The local content level was raised to 45% in 1978 and then to 54% in 1983 [Office of The Board of Investment, Royal Thai Government, 1995]. This introduced a big incentive for local companies to expand production of auto parts to other, non-peripheral parts.

After a sharp increase in vehicle demand from less than 80,000 in 1986 to 300,000 by 1990, in what is called "the golden years of Thailand's automotive industry", pressure started to build to drop the local content requirement. In 1995, with automotive production at almost 600,000, the Thai government decided to embark on a liberalization process and eliminate local content regulations by the year 2000 [Panichapat, 1996], in accordance with GATT regulations and international trade trends. This liberalization process was furthered by the creation of the Asian Free Trade Area (AFTA) among the ASEAN (Brunei, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam) countries that allow free commerce of goods among member countries, creating a market of 375 million individuals.

By 1995 the economic perspectives for the region could not look better. Japanese car companies that already had a 90% share (mainly Toyota, Isuzu, Nissan, and Mitsubishi in Thailand) of the market in the four major ASEAN countries (Thailand, Malaysia, Indonesia and the Philippines), were already expanding their investment in the region by 1996. At the same time, automakers without ASEAN operations were scrambling to establish foothold. Though to a lesser extent than the Japanese firms, the American Big Three have also made ASEAN countries a priority investment target. In 1996, GM decided to invest US$750 million in Thailand to build a factory to produce 100,000 cars per year [The Economist, August 17, 1996]. Thailand obtained the GM investment over other ASEAN countries by moving forward to 1998 the date by which the local content provisions would be eliminated.

Though this region only represents 3% of the total automotive world demand, remarkable economic growth (during the late 1980's and early 1990's) and a population in excess of that of the European Union make it a very attractive market. By 1996 the ASEAN automotive manufacturers were planning sharp increases in production capacity.
current high growth rate an increase in present automotive capacities in the region would lead to a serious oversupply problem. In general ASEAN countries, automobile markets are generally in the range of 100,000 to 500,000 cars a year. There are more than 10 automakers competing in the region. Their typical platform production volumes are only between 10,000 to 30,000 units a year [Tokyo-Mitsubishi Review, 1996]. Production levels in the 150,000 - 200,000 range are required to enjoy minimum efficient scales. In other words, no auto maker in the region has yet to achieve the required scales and nor is the necessary ten fold increase in volumes likely to occur in the near future. Further, this situation could potentially get even worst due to the financial crisis affecting South-East Asia since the end of 1996 [Business Week, December 2, 1996]. Automotive OEMs are not the only ones to suffer from a lack of volume. This same over capacity situation also affects the parts supply industry. The auto parts industry has been trying to increase volumes through exporting. However, so far exports have not helped the situation since they represent only a small percent of the parts produced in Thailand.

Like many other part suppliers in Thailand, the steering wheel industry grew under a governmental protective umbrella, competing mainly among themselves. They were concerned with their ability to supply cost competitive, quality products, but their benchmarks were the other Thai manufacturers which faced similar low volume limitations. In this environment, steering wheel producers did their best to optimize their processing capabilities for the low volume market. While they are not currently competing with imports, the decision to remove local content requirement and lift major import taxes, is forcing local producers to start looking at possible threats from imports.

The manufacture of steering wheels is limited to one basic process route for which there are multiple process steps which are capital intensive. These steps (principally the wheel structure making and the injection molding) require the use of some automation in order to produce quality parts. Furthermore, these steps are the main cost drivers. Process variation can occur in the remaining steps, particularly with regard to additional automation of the
manual assembly processes but, as these steps do not contribute dramatically to the overall part cost, they are not likely to have any significant effect.

Figure 13: Process flow chart for the steering wheel manufacturing process

Figure 13 shows a typical process flow chart for making steering wheels. The steering wheel manufacturing process starts with the making of the wheel structure. Traditional high volume manufacturers use die casting to produce this structure. The die casting process [Kalpakjian, 1992] requires expensive tooling but allows the production of large quantities; thus efficiently spreading the tooling cost over all the parts to produced. The wheel structure can also be made by another process better suited for low volume manufacturing. This process is actually the combination of four steps; the making of the rim, the making of the hub structure, the assembly of these two, and a final cleaning and glueing in preparation for the injection molding operation. By employing these processes, Thai producers avoid the
expensive dedicated tooling investment otherwise needed for the die casting operation. However, this saving comes at a price. The cycle time for these operations is longer and thus these alternative processes yield smaller throughputs. Also, these processes require the input of more elaborate and expensive materials.

Following the making of the wheel structure, both high and low volume producers follow similar manufacturing strategies. They both employ an injection molding process followed by several assembly intensive steps. The injection molding step has a long cycle time of approximately 4 minutes and is a likely bottleneck in the process. Multiple individual presses can share the same injection molding equipment (tanks, heaters, pumps, etc.), therefore increasing production capabilities and eliminating this potential bottle neck. For each extra press, another injection molding tool set is required.

The total equipment investment in a line is approximately $2M, of which the press costs less than $6,000, and each tool set costs between $50,000 to $100,000. The cost of an extra injection molding die and press is much smaller than the line equipment cost. Therefore it may seem logical to use multiple presses and tool sets to improve the overall productivity of the equipment, and at the same time, reduce the labor content. However, the cost penalty from the extra presses and tools must be carefully considered. The next section will explore these alternatives and their effect on the overall part manufacturing cost.

6.3. Case Results

This thesis will compare the economics of a high volume US operation and a low volume Thai operation. A typical polyurethane wheel with no air bag compartment for the use in pickup trucks will be used for this study. Technical cost modeling will be used to quantify cost differences among the manufacturing steps and to identify the main cost drivers. This thesis will look at four different manufacturing situations as well as two possible production volumes. The two previously mentioned process routes each can be evaluated using two operating environments, one represents the US and the other Thailand. Hereafter the name
"high volume process" will refer to the process route which uses die casting to produce the wheel structure. Since this is generally better suited to high volume situations. The name "low volume process" will be refer to the process which assembles the wheel structure from smaller parts. Operating in the US and Thailand differ in the assumptions about the labor wage, working days per year and the cost of capital.

The first analysis represents the current manufacturing situation and compares the "low volume process" in Thailand with the "high volume process" in the US. In this case the low volume/Thai operation was analyzed for the current typical Thai production volume of 5,000 units per year, while the high volume/US operation was analyzed at a more typical US production volume of 200,000 units per year. Figure 14 shows the cost breakdown by process step for these two scenarios.

Figure 14: Steering wheel cost breakdown by process step
There are two major differences between these processes. First, the low volume process uses parts and material inputs that are almost five times more expensive than the high volume process. This cost gap is due mainly to the different materials and parts requirements of the wheel structure making process step. While the low volume wheel making process uses steel tubes and other pre-formed parts, the high volume die casting process uses plain carbon steel with a lower cost per weight unit. An even larger gap can be observed in the injection molding step (the most expensive one in both scenarios). The remaining process steps are of minor importance to the overall cost competitiveness. Figure 15 is shown to further explore the cost drivers for these differences.

![Graph showing cost breakdown]

**Figure 15: Steering wheel cost breakdown by cost element**

While there is still a gap between input materials and parts, this figure indicates that tooling is the major cause of the cost difference. This is caused by the low tool utilization.
achieved at only 5,000 parts per year. Differences between labor and equipment cost cancel each other out. While labor costs are smaller in Thailand mainly due to the cheaper wages, equipment costs are higher due to lower process yields. Extending the analysis to include the costs for the US firms if they only produced 5,000 parts per year yields Table 3.

<table>
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<th>Case #</th>
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<th>2</th>
<th>3</th>
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<td><strong>Cost Categories</strong></td>
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<td><strong>High volume process</strong></td>
<td><strong>Low volume process</strong></td>
</tr>
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<td></td>
<td><strong>US scenario</strong></td>
<td><strong>US scenario</strong></td>
<td><strong>Thai scenario</strong></td>
</tr>
<tr>
<td></td>
<td>PV = 200,000</td>
<td>PV = 5,000</td>
<td>PV = 5,000</td>
</tr>
<tr>
<td>Parts/Materials</td>
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<td>$0.92</td>
<td>$3.36</td>
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<td>Wheel structure making</td>
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<td>$29.85</td>
<td>$2.15</td>
</tr>
<tr>
<td>Injection molding: Tooling</td>
<td>$0.96</td>
<td>$28.02</td>
<td>$10.78</td>
</tr>
<tr>
<td>Injection molding: Others</td>
<td>$1.57</td>
<td>$2.33</td>
<td>$2.57</td>
</tr>
<tr>
<td>Other steps</td>
<td>$0.85</td>
<td>$1.15</td>
<td>$0.59</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$5.81</strong></td>
<td><strong>$62.27</strong></td>
<td><strong>$19.42</strong></td>
</tr>
</tbody>
</table>

Table 3: Summary of the main key cost differences

Table 3 summarizes the cost breakdown for the five most significant categories for the three scenarios; the two previously discussed (cases #1 and #3) in figure 14 and 15 and case #2, the high volume process in the US operation at only 5,000 parts/year. The first row shows that for the high volume process, better material and input parts utilization is obtained when producing larger volumes. This is caused by a relative reduction of engineering scrap in start up operations as production volumes and lot sizes get larger. The main material disadvantage for the low volume process is caused by the use of the alternative wheel structure manufacturing steps that require the input of more expensive parts and materials. Nevertheless, this material disadvantage becomes less relevant when compared to the large manufacturing cost savings in the wheel structure making.
The die casting manufacturing step used by the high volume process presents significant economies of scale, going from $1.74 at 200,000 parts per year to $29.85 at 5,000. The alternative process technology (see process flow chart in figure 13) employed by the low volume process for the structure making costs $2.15, only $0.41 more than the die casting operation used by the high volume process. The cost of the wheel structure including the materials is $5.51 for the typical Thai situation (case #3). This is more expensive than the current US situation (case #1) but much cheaper than it would be for US manufacturers if their volumes dropped to only 5,000 units per year. The third and fourth rows show that injection molding tooling dominates the overall part cost at low volumes for the Thai scenario. This is directly related to the inefficient tooling utilization. The high volume process (case #1 and case #2) is assumed to use simultaneously four tool sets, while for the low volume process (case #3) only two tools are used. Coincidentally, at a production volume of 200,000 parts per year the optimum number of tool sets needed is four. As case #1 shows, when four tooling sets are used, the per part tooling cost is $0.96. When the same process is run at a production volume of only 5,000 parts/year (case #2), the per part tooling cost increases to $28.02, because an excess number of tool sets are being used. In the case #3, the number of tool sets used is two, which is better suited for the low volume of 5,000 parts per year, and thus the per part tooling cost is reduced to $10.78. Even when optimized, 5,000 parts per years is not high enough to achieve full utilization of even a single tool set. Therefore the low volume operations tooling cost will always be much higher than the $0.96. The cost differences observed in the other injection molding factors is due to the equipment utilization and changes in labor content and cost.

Altogether, the high volume process used in US has a cost of $5.81 per part at a production volume of 200,000 parts/year. When the same process is used for only 5,000 parts/year the part cost increases ten fold to $62.27. Using the low volume process in Thailand for 5,000 parts/year can cut that cost to $19.42. This is because the low volume process uses a more appropriate wheel structure manufacturing operation and two injection
molding tooling sets instead of four. This cost could be further reduced if tooling utilization were improved by using only a single tool.

Figure 16 shows the cost sensitivity to the number of injection molding die sets, and illustrates how important it is to optimize for tooling investment. This figure presents four different scenarios; cases #1 through case #3 (as presented in table 3) plus a fourth case showing the cost behavior of the low volume process, operated in the Thai scenario, for a production volume of 200,000 parts per year. The curves for the production volume of 5,000 parts (indicated with square markers) should be associated with the y axis on the left side of the figure, while the curves for the production volume of 200,000 parts (indicated with star markers) with the y axis on the right hand. The circles point out the optimal number of tool sets (minimum achievable cost) for each case.

![Cost sensitivity to the number of injection molding die sets](image)

Figure 16: Cost sensitivity to the number of injection molding die sets
At 200,000 parts per year, the cost is minimized when four dies sets are used for both the US (case #1) and Thai (case #4) scenarios. Before that point, the cost is higher due to an underutilization of the equipment investment. By using more than four dies, the equipment utilization would be improved further, but at that point, the marginal gains would be lower than the marginal costs incurred from having underutilized tools. At 5,000 parts per year, the cost function only increases from its minimum at one tool set. This is because even a single tool is poorly utilized. Therefore, as the number of dies increases, the marginal gains from equipment sharing are offset by the losses from even lower tooling utilization.

The case study found that the Thai company operating with two injection molding die sets was not manufacturing at its minimum cost. This company assumed that they could benefit from improving the utilization of the equipment which cost $2 million by spending an extra ~$75,000 on a second die set. Figure 16 shows that the optimal solution is to have only a single die set. This would reduce their manufacturing cost to $14.98 from its current $19.42 (see table 3), a cost savings of 23%. Tooling investment optimization is essential at any production volume, but it is particularly important at low volumes where tooling makes up a larger percent of the total piece cost.

A comparative analysis reveals the economic boundaries between the low volume process operating in the Thai scenario and the high volume process operating in the US scenario. Figure 17 presents a break even analysis for these processes as a function of production volume. The Thai operation is cost effective up to volumes of ~92,000 units/year. Economic externalities can affect its value. In this case, the break-even point is very sensitive to currency fluctuations, which became significant early in 1997 when the Thai Baht started a sharp decline in value. In general, when currency fluctuations occur, equipment and material costs do not change in real terms since they usually are linked to global prices. However costs such as labor and building change with currency fluctuations, while others such as energy or tooling must be addressed on a case by case basis. The cost models built for the study of the
manufacturing of steering wheel track changes generated by currency fluctuations. Figure 17 presents results for three currency exchange rates; 25, 32.5, and 45 Baht/Dollar.

![Graph showing comparative sensitivity analysis to production volume with three currency exchange rates: 25 Baht/$, 32.5 Baht/$, and 45 Baht/$. The graph indicates production volume on the x-axis and manufacturing cost on the y-axis.]

Figure 17: Comparative sensitivity analysis to production volume. Three currency exchange levels considered: 25 Baht/$, 32.5 Baht/$, and 45 Baht/$

6.4. Case Conclusions

The high production volume process employed by US steering wheel manufacturers relies heavily on the economies of scale of the die casting process used in the wheel structure making and on high utilization of the injection molding tooling. In order to be as cost effective as possible at low volumes, Thai companies introduced modifications to the high volume manufacturing process. The replacement of the die casting process by an assembly (welding) intensive operation mitigates some of the low volume cost penalties in the wheel
making operation. The Thai alternative is a comparatively slow cycle time process that requires more expensive materials but reduces cost penalties by eliminating the need for expensive tooling. The labor content in this step is much larger than that required for die casting, but comparatively cheap wages make the overall manufacturing labor cost smaller in the Thai case. There is no process alternative for the injection molding step, but, tooling investment optimization is critical. In many cases the simultaneous use of multiple tooling leads to improvements in equipment utilization. Nevertheless, the cost of additional tool sets may offset the savings achieved by equipment sharing. Identifying the optimal number of tool sets demands a careful study. Usually this number will depend on the production volume, the cycle time, the equipment / tooling cost ratio, the tooling life, and the labor cost among others.

The assembly intensive manufacturing strategy has allowed Thai steering wheel suppliers to remain competitive in their local semi-protected market. However as the liberalization moves forward in Thailand, the low volume process may not remain competitive with the high volume US process. Because there is little opportunity to further improve the low volume manufacturing process, Thai suppliers may need to achieve larger production volumes or limit their activities to specialty low volume niche applications.
7- THAI RADIATOR MANUFACTURING

7.1. Introduction

Radiator manufacturing represents a situation in which there is essentially only one process route available to obtain the final product, but a continuum of automation possibilities. The comparison between a Thai and a US operation illustrates the capital-labor tradeoffs which can be used to reduce costs.

The radiator manufacturing process does not heavily penalize low volume operations, provided that the automation level is optimized for the overall production volume. Investing in automation has two main effects on the manufacturing operation; it speeds up the line running rate and thus increases the line capacity, and reduces the labor content. Cost inefficiencies arise when the overall production volume is lower than expected, resulting in underutilized lines. Better original estimates of the overall market demand would have led to different optimal automation levels.

7.2. Case Description

Since the Thai automotive industry was established in 1961 it has gone through several stages of protection for the industry and its suppliers. Nowadays local content requirements are at 54% but the industry is moving in the direction of a free and open market. Section 6.2. provides a more complete description of the Thai automotive market evolution.

The Thai radiator industry, like other part suppliers in Thailand, developed under protective governmental regulations. Local radiator suppliers have been operating at the optimal level of automation for their demand, minimum to no automation. Particular characteristics of the radiator manufacturing process, such as its assembly intensive nature and the relatively low Thai labor cost, allow the industry to supply radiators to the local OEMs at competitive prices. The main industry concern is how to determine the optimal automation
level given the likely fluctuations in production volume and the industry growth. This requires fully understanding the effect of the automation level on the manufacturing cost in order to minimize inefficiencies associated with departures of the overall production volume from the expected volume used to determine the automation investment. This is critical to remain competitive when faced with the threat of import products.

Thai radiator suppliers produce standard cooper-tin radiators (the reminder of this chapter will focus on this type of radiator). These type of units get their name from the main materials used in the key cooling mechanism. Hot water from the engine circulates through brass tubes coated in a tin-lead bath in direct contact with cooper fins. These fins conduct the heat from the tubes (thus cooling the water) and dissipate that heat by convection to the air. There is essentially only one process route available for producing cooper-tin radiators. In general, the radiator structure is assembled, welded and goes through a variety of chemical and heat treatments. Various automation levels are possible. The end tanks are added and then tested for leaks before being washed, painted and re-tested. A detailed process flow chart is given in figure 18.

This process requires a limited capital investment and, if necessary, most steps can be done manually. The main fixed costs are in the tube and fin making steps, and from the oven in the baking steps. Therefore, it is most important to achieve high levels of equipment utilization in these steps. This is quite easy in the tube and fin making steps since each radiator requires dozens of these parts. Even low production volumes for entire radiators require high production volumes for tubes and fins. In the case of baking ovens, high levels of equipment utilization are also easily achieved since the required bake times tend to be quite long. Therefore, even at low production volumes, either multiple batch ovens or long lines through continuous ovens are necessary. Consequently the key issue is to have the optimal automation level that leads to the necessary throughput. The use of automation, then becomes strictly a choice between producing fewer parts at slower rates manually, or
Investing in equipment to increase the capacity of the plant. The choice between the two depends on whether capacity increases will be fully utilized.

Figure 18: Process flow chart for radiator production

In almost all of the process steps indicated in figure 18, the labor cost can be reduced through an increased investment in automation equipment. For example, automated soldering of the end tanks would result in faster cycle times and a decrease in the number of workers required, but would require an initial capital expenditure. Similarly, automated washing could result in a more efficient use of the cleaning tanks and can probably be done with little direct labor. However, increasing the investment in automation equipment increases the minimum efficient scale of the plant. Expenditures for automation without full utilization of the increased plant capacity is not cost competitive.
To address these issues, cost models are being developed to analyze the economics of the radiator manufacturing process. These will be used to determine the right mix of automation for given production volumes and other operating conditions. The effect of increased automation on the flexibility of the line will also be examined. The current low technology approach used by the Thai companies allows production in small lot sizes with only minor adjustments to the process and very short downtimes associated with the switch to another lot of radiators of different size or type. The addition of automation may reduce this flexibility, carrying with it a cost penalty resulting from longer set-up times.

High production volumes for radiators are typically on the order of 500,000 units per year, while a single fully automated line can produce up to 1,000,000 units per year. These are common volumes for US manufacturers. A typical Thai market part production volume is around 50,000, and the average overall volume for a Thai company is 200,000. A labor intensive line with the minimum automation possible (necessary to yield quality products) can produce up to ~330,000 radiators yearly.

7.3. Case Results

The radiator manufacturing analysis will be based on a cooper-tin standard radiator designed to cool a 3,000 cc pickup engine. This represent one of the most common radiators produced for Thai OEMs, and is average in size, as well as technical characteristics. Results presented in this section for the analysis of this part can be easily extended to other radiators. Even more, as this chapter will demonstrate, it is not specific radiator, but overall operation characteristics that determine optimal processing parameters.

Technical cost models were developed to simulate the radiator manufacturing process as described in figure 18. These models are used to identify and understand the cost drivers for this manufacturing process. More specifically, these models facilitate the understanding of the role played by automation in the fabrication process. Figures 19 compares the cost
breakdown by process step for the high volume, fully automated, US operation and for the low volume, labor intensive, Thai operation.

![Bar chart showing manufacturing cost by process step]

Figure 19: **Radiator manufacturing cost breakdown by process step.** Fully utilized lines

As figure 19 shows, no one process step is significantly more expensive than the others. For both scenarios, the materials and input parts account for roughly two thirds of the total part cost. The remaining third is the actual processing cost.

The cost breakdown shown in figure 20 indicates that all of the cost elements are roughly equal for both scenarios. Labor, followed by main machinery are the two most important elements contributing to the processing cost.
Figure 20: Radiator manufacturing cost breakdown by cost elements

The high automation operation, capable of producing 1,000,000 parts per year, required an total fixed investment of $12.0M, while the labor intensive operation requires an investment of $2.6M but can only produce 330,000 parts per year. On the other hand, the high automation process, uses only 0.16 man-hours per radiator compared to the labor intensive process which employs 0.95 man-hours, almost six times the labor content. This is particularly important in the US where labor costs are $15/hour and is less important in the low labor cost environment in Thailand where wages are only $4/hour. Fully automated operations have 4.5 times higher capital investment in automation and equipment. However, they have only three times the line capacity, and thus the investment in automation equipment is not justified by the increased capacity. However, fully automated lines have a labor content which is six times lower than their low automation counterparts. Therefore, the capital investment in automation is justified by the reduction in labor requirements. In general,
operations with high labor content (see figure 20) like assembly, could benefit from automation by reducing this amount. The net advantage of the use of automation in US operations is the reduction in labor content.

The relationship between part cost and production volume shown in figure 21 reveals that when manufacturing lines are fully utilized by means of producing several different radiator designs (thus the line is using the optimal automation leading to the necessary throughput) the radiator manufacturing process does not heavily penalize low volume operations.

![Diagram showing cost vs. production volume]

**Figure 21:** Sensitivity analysis to production volume. Fully utilized lines

Further, figure 21 shows when using the same process, operating in an inexpensive labor environment is always preferred, provided the process is done at full utilization and the same
productivity can be achieved in this environment. This is of particular importance for the low automation, labor intensive operation, which is evident by the large gap between the US and Thai scenario, low automation cost curves in figure 21. For the high automation operation, since the labor content is less significant, the low labor cost market provides only a small advantage over the expensive labor cost market with manufacturing costs of $15.60 and $14.20 per radiator, respectively.

It seems natural to expect that the Thai radiator producers would automate their lines and expand their sales. This would in fact be the best strategy if they could achieve full utilization. However, since there is a huge penalty in implementing an automated line, and not achieving full utilization, this strategy may not be appropriate given the small domestic market in Thailand. One possible solution is to obtain large markets through exports. However, this strategy is also flawed since the use of automation would only save $1.40 per radiator which may not be enough to offset the additional cost associated with exports.

At less than full utilization the use of highly automated lines may not be justified. This would be the case of using highly automated lines is Thailand where there is insufficient demand to maintain full line utilization (in other words, the full line utilization assumption used in developing the curve representing high automation - Thai scenario in figure 21, does not apply). In that case it is important to look at the effect of overall production volume on part cost. Figure 22 shows the cost sensitivity of the high automation operation to both part and overall production volumes. Again, this chart shows that the manufacturing process is not very sensitive to the part production volume presenting, an almost flat behavior. However, at low overall production volumes a sharp increase in part cost can be seen.
Figure 22: Cost sensitivity to part & overall production volume. High automated operation

The intersection of the surface defined in figure 22 and an equivalent surface generated by the labor intensive operation defines the dominant operation in the "Parts production volume-Overall production volume" space shown in figure 23. Each region represents the most cost effective process for that particular combination of part and overall production volumes. An infeasible region in the chart exists whenever the part specific production volume is higher than the overall production volume.
Figure 23: Regions of dominant cost-effectiveness for the manufacture of radiators employing a high automation and a labor intensive operation

The current average Thai producer has a part production volume of 50,000 radiators in lots of 1,000 units, reaching an overall production of 200,000 radiators per year. For these volumes, Figure 23 shows that the preferred process is the labor intensive operation. Model results show that the manufacturing cost for each radiator would be $20.08 using the labor intensive operation and $27.77 using the high automation process. The automated operation carries a higher cost due to the low capital utilization level.

This research compared the two extreme situations of fully automated and labor intensive operations, which more or less describe the demand characteristics of the US and Thai markets. It is important to note that for other markets with different demand and labor characteristics, and different costs of capital, the optimal amount of automation could lie somewhere between these two scenarios. For those cases, the optimal level of automation can
be defined by the method demonstrated this chapter. As in the previous examples, cost penalties will be suffered whenever the line utilization is not be the optimal.

7.4. Case Conclusions

To produce cooper-tin radiators there is only one manufacturing process available. This process involved basic operations such as assembly, welding and several heat and chemical treatments. This processes step required short set-up times and low tooling investment. Therefore, radiator manufacturing does not heavily penalize the manufacturing of low volumes or small lot sizes.

The role of automation becomes a matter of choosing to produce fewer parts at slower rates manually, or to produce more parts at a faster rate by investing in automation equipment. That investment increases the capacity of the plant and allows for the reduction of the labor content. For example, capital expenditure on automating the leakage inspection step would result in faster cycle times (thus a higher line capacity), and would decrease the labor content. The critical factor is whether the capacity increase would be fully utilized. In other words, any increase in capital expenditure without full utilization of the resulting increased capacity can offset cost reductions achieved through labor content reduction.

The Thai radiator manufacturing companies do not face major threats from competitors with higher production volumes, provided they select the process automation best suited to their market demand low labor cost environment. As demand and labor conditions change with time, local radiators suppliers will have to re-establish the new optimal automation investment. Fortunately, the process allows the introduction of automation in a gradual way without having to completely change their facilities.
8. SHEET METAL STAMPING

8.1. Introduction

There are numerous opportunities to improve the low volume competitiveness of sheet metal stamping processes. Among these options are the use of complex process technologies, different levels of tooling investment, alternative tooling technologies, and various automation levels. All these issues play an important role in low volume stamping and will be addressed in this chapter.

Low volume sheet metal stamping has been gaining importance over the last fifteen years. On one hand, auto makers are still operating in traditional low volume markets such as Australia, South Africa, and Argentina, while on the other hand, rapidly expanding vehicle demand is driving their entrance into new developing markets such as Thailand, India, and the Czech Republic. Many of these markets do not have the volumes automakers typically produced in their traditional markets. Furthermore, cost efficient low production manufacturing has also been gaining importance in the performance/sport cars and some luxury sedans niche markets. These vehicles are usually targeting markets in developed areas of the world where automakers have been traditionally producing at high volumes. The combination of these two markets has forced automakers into looking at low volume stamping solutions that can work in two very different economic environments. This has created the need for automakers to overcome their resistance to change what is their mainstay of parts fabrication methods and develop new techniques which directly address the needs of producing at low volumes.

8.2. The Conventional Stamping Approach

A typical sheet metal stamping process consists of a sequence of operations such as blanking, forming, trimming/piercing, and flanging, performed on either tandem press lines or transfer presses. Press characteristics such as tonnage and sizes depend upon the part
characteristics, such as its dimensions, the press operations required, and material mechanical properties. Tandem press lines usually consist of up to six sequential presses which may have automation equipment for loading the blanks, transporting the partially formed parts between the presses and unloading the final product. The presses in the line are usually identical except for the first press which may have two actions. These double action presses have two independent rams, a blank holder and an inner punch which produces the deep draw. Tandem press tonnages typically vary from 350 to over 1,000 tons for automotive applications.

The presses themselves represent non-dedicated investment in that they are not part specific. Rather, the forming characteristics are delivered to the blanks through the dies which are interchangeable components used in the presses. Figure 24 shows a schematic of a press without a die installed. The lower part of a die set is placed in the fixed press bed and the upper part on the press ram which moves up and down.

![Schematic representation of a stamping press](image)

**Figure 24: Schematic representation of a stamping press**
Transfer presses consist of a single, entirely self contained unit capable of providing all of the necessary forming strikes, usually using two rams capable of holding up to three dies each. The unit is fully automated and has a coordinated system for advancing the parts and raising and lowering the rams. This permits the transfer press to operate at speed far greater than that of tandem lines, up to 1000 parts per hour even for the largest presses (typical tandem presses can produce less than 500 large parts per hour).

Each step in the stamping process requires an individual die customized to the desired forming activity. The expense of the die set is related to the size and complexity of the final product. Among the most expensive are those used to form parts with deep draws since they require additional components in the form of independent punch. A schematic of a typical die is shown in figure 25.

Figure 25: Components of a drawing die set
The most common stamping steps are blanking, forming, trimming/piercing, and flanging. The blanking operation is basically a shearing process. In some cases, starting from a rectangular sheet of metal, a punch cuts a silhouette and the remaining material becomes engineering scrap. In some others, the blanking operation does not use a die but rather a shearing edge to cut a blank with a regular shape.

Depending on the shape and complexity of the formed part, one or more forming steps may be needed. Forming can be done by stretching or drawing the blank. Usually the most complex forming step is the so called deep drawing. In deep drawing, the blank is formed into a cylindrical or box shaped part. Restriking may be needed when the shape to be drawn is too complex to be done in a single step. Figure 26 Illustrates the draw die operation.

![Figure 26: Schematics representation of a drawing operation](image)

The first stage involves closing the press to allow the blank holder to grip the outer edges of the blank. The outer ram stops, while the inner one continues to descend. In the second stage the inner ram forces the punch into contact with the sheet metal, stretching it and forcing it to wrap around the punch. Finally, in the last stage, the sheet of metal is formed
around the punch which has now been driven all the way down into the die. Afterwards, the press opens and the part is released.

In trimming and piercing, material is removed form the blank. Piercing is used to remove small areas from within the blank and to make holes that in most cases are needed in future assembly operations. Trimming is generally used to remove material from the edges of the part, and thus leave the part within tolerance of design. This step is usually needed since forming operations tend to leave uneven part edges.

Flanging, usually one of the latest steps to be done, is used for bending the edges of the part. To perform this process, dies are needed with the capability of applying pressure to the part in horizontal directions. This is done by including moving cams in the die design. Sometimes a re-strike step is added to ensure part geometrical accuracy.

8.3. Low Volume Stamping Alternatives

A traditional automotive stamping operation shows a behavior for which a minimum efficient scale is observed. The literature usually estimates this minimum efficient scale at about 150,000 to 250,000 parts per year. Additional cost savings beyond 200,000 parts per year are limited and are usually lower than 10%. At low stamping volumes, those much smaller than the minimum efficient scale, the per unit cost of stamping is much higher than at high production volumes. As this thesis will later show, the relationship between cost function and production volume is mainly due to the tooling utilization.

The goal of any low volume stamping manufacturer is to find processing options to help reduce the cost disadvantages generated by the lack of economies of scale. This thesis will analyze three basic areas that can potentially improve low volume manufacturing economics; the automation level choice, the use of alternative tooling technologies, and a change to a new process technology.
8.3.1. The Automation Level Choice

Chapter 7 discussed the potential implications of the use of automation on the economics of manufacturing at different production volumes which result from changes in the line yield. These same issues apply to sheet metal stamping. In order to analyze the manufacturing economics of stamping, a cost model was built. The model was designed to capture the consequences of various automation levels on part cost. For the purpose of this study only tandem press lines were considered. High speed transfer lines are typically aimed at large production volumes and thus are less appropriate for low volume scenarios. However, the same cost modeling methodology used in this thesis could be applied to this technology as well. This thesis identifies three areas that are directly affected by the investment in line automation; the cycle time, the labor content, and the tooling cost, which in turn affect the part manufacturing cost.

The more automated the line, the faster the running rate, and the lower the process cycle time. Determining the actual relationship between the line running rate and the automation level is not easy. While presses with specific automation levels are generally rated to run at specified speeds, these are maximums and do not reflect the actual rates achieved when producing parts. Further complicating the situation is the fact that press line running rates are highly dependent on the size and geometry of the part. Data collected for an International Motor Vehicle Program benchmarking study of automotive press shops [Roth, 1997] has been used in a regression analysis to link the line running rate to the automation level. Three different automation categories were used for this analysis; no automation, automated unloading from the presses, and full automation, in other words automated for loading and unloading at each press. Line running rates (in parts per hour) were collected in stamping facilities throughout the world for five different large part types; rear floor pan, mid floor pan, quarter panel inner, quarter panel outer (body side), and door frame opening. Figure 27 shows the results from that regression analysis. Each asterisk is the average line running rate for a given part type and automation level. The squares mark the average of these asterisks.
The stamping model uses these numbers as estimates for the line running rates at each automation level.

![Diagram showing the effect of automation on line running rate]

**Figure 27: Effect of automation on the line running rate**

Automation also affects the direct labor content. Part transfer between the presses is the most common area in which automation is applied, and thus automation replaces the otherwise required labor that would have performed these operations. The other direct impact of automation is on tooling investment. Generally, tooling cost increases as the line automation gets more intensive. For the automation to work properly, dies must include specially designed moving parts (like ejectors) that increase the manufacturing cost of those dies. Interviews with die manufacturers and press shop managers reveal that a die set can be up to 10% more costly when built for a fully automated line than when it is built for a manually operated one. All these changes triggered by the selection of the automation level...
are included in the technical cost model used throughout this thesis to simulate the operation of a stamping line.

Four different scenarios are used to study the effects of automation on the stamping process. Full automation and labor intensive (no automation) operations are each considered for two economic situations, one for the US with a high labor and low interest rate, and the other for Thailand representing the opposite conditions. Figure 28 shows the part cost as a function of the part production volume for these four manufacturing conditions. The part used for this analysis and for all the following analyses in this chapter is an average mid-size sedan roof. This part was chosen since it provides an easy basis for comparison and the data (used in this dissertation) provided by the different sources of information can be easily normalized.

![Graph showing cost as a function of part production volume with different scenarios](image)

*Note: Full line utilization

Figure 28: Sensitivity analysis to part production volume
Figure 28 shows that at any part production volume, the use of automation seems to be the most economically effective alternative, provided that the line is fully utilized. At volumes lower than about 20,000 parts per year, there are no significant cost differences between the scenarios, but at higher volumes, the use of automation yields a lower per part cost. Surprisingly enough, most low volume operations throughout the world (particularly in low labor cost regions) rely heavily on the use of labor rather than automation. It should be noted that the analyses in figure 28 assumes a full line utilization. That is, other parts are being produced on the same line to achieve full utilization. The result is the same even at low overall production volumes? Similar analyses to the one performed in the radiator case were done for the stamping operation. Contrary to the findings in that case, for stamping automation is an effective alternative even at very low overall production volumes (thus low capital utilization).

Figure 28 also shows the presence of significant economies of scale for a stamping operation. In order to identify the main reason for this behavior a cost sensitivity analysis to production volume is done for all the different cost elements contributing to the part cost. Figures 29a and 29b present these results for a fully automated operation in the US and a labor intensive operation in Thailand. The product life for this analysis is assumed to be four years.
Figure 29a: Cost breakdown as function of production volume. Fully automated line

Figure 29b: Cost breakdown as function of production volume. Labor intensive line
Each row in the figure represents a different production volume. The front row shows the cost breakdown at a production volume of 250,000 parts per year and the last one at only 5,000. The height of each bar represents the cost of that particular category at a given production volume. Both figures 29a and 29b show that the main cost driver at low production volumes is tooling. In fact, a typical tool set for the roof under consideration costs approximately $1,000,000. At low production volumes this investment is spread over few parts resulting in a high per piece cost.

8.3.2. Alternative Tooling Options

Alternative tooling options provide a possibility to reduce the high costs associated with tooling when producing low volumes. Lower cost tools usually accompanied by a reduced tooling life, may provide the solutions. Typically a standard tool set made of cast iron with or without steel inserts can last for up to 5,000,000 strokes. A tool with a shorter life is not necessary bad, since in most low volume cases dies are used for far less than one million strokes (probably 50,000 to 250,000) over the entire life of the tool. Several different options are available to effectively reduce tool costs. These include one or more of the following strategies; the use of cheaper materials, the use of alternative tooling manufacturing technologies, the simplification of the tool design, and the use of alternative manufacturing processes with less stringent tool requirements.

Several alternative tooling technologies are currently under study by different companies throughout the world. This thesis will specifically discuss three of the most promising alternative die technologies; kirksite, epoxy, and nickel shell/reinforced concrete. Ceramic dies [Automotive News, 1998], Tin-Bismuth dies, STAMP epoxy technology [GM Research and Development Center, 1998], opposite shell dies, special steel alloys cast into near net shape dies [Australian Automotive Technology Center, 1994] and various hard coating techniques, are among some of the other technologies not specifically addressed in this work.
Kirksite tooling has been used for prototyping dies for many decades. The use of this material under actual manufacturing conditions has been suggested but never really implemented. Kirksite is a zinc based alloy that typically contains 4% aluminum and 3% copper with or without small amounts of magnesium [Morrow & Lynch, 1986]. This alloy has a tensile strength of 210-280 MPa [Eastern Alloys Inc., 1997], much smaller than that of the 400-1200 MPa of cast irons, and therefore deteriorates much faster than a standard die. With careful design of the stamping process and the use of steel inserts in critical sections, it is believed that a Kirksite die would last ~100,000 strokes. Floor repairs would be needed more frequently due to the higher wear rate of the die working surfaces (particularly true at the end of the die life). Also, a production kirksite die would be more massive and complex to design the required room to accommodate all the needed tool devices in the die. On the positive side, a softer kirksite die would be easier to machine and therefore faster to produce. More important is that it can be cast to a near net shape since it has a low melting point of about 400 °C (allowing it to be cast over a negative of a die model directly) and a much lower shrinkage coefficient (1.2%) than steel.

An important material characteristic is that it can be fully recycled, that is, an old Kirksite die could be melted and cast again into a new die. Kirksite is an expensive material that costs ~$1.48/kg, much more than the ~$0.07/kg cost of cast iron. In order for Kirksite to be a competitive alternative it is assumed that most of the material value is recovered at the end of the tooling life by recycling an old die into a new one. The recycling costs are mainly generated by the expenses incurred in breaking the die apart and removing inserts and other parts made from different materials. Standard cast iron dies are generally not recycled in this way, since the recovered value of the material is insufficient to offset the recycling costs.

Resin or epoxy (usually phenolic) dies have been used for prototyping as well as for very small and series production [Zharkov, 1995]. In general these dies have several components; artificial resins for bonding all the other components, hardeners used for curing resins by transferring them into a high molecular compound, softeners to reduce fragility and increase
elasticity after hardening, and fillers (inert solid substances) introduced mainly to improve mechanical properties. With these materials, mechanical strengths of 60-250 MPa can be obtained depending on the type of filler. A low shrinkage coefficient of 0.1 to 0.2 % allows accurate die surfaces to be produced. Low wear resistance significantly affects the life of these dies, but with proper lubrication, a life of 10,000 strokes can be expected. Epoxy dies have to be massive to maintain mechanical integrity, and therefore there is a serious concern about the possibility of incorporating actuators such as extractors and limiters into the die. The use of web like metallic structures to increase mechanical stability and allow the incorporation of actuators is currently under study.

Nickel shell-reinforced concrete dies are currently being tested by an Italian company. This is really the combination of two different technologies. An electroforming process using nickel is employed to create a thick shell over a model of the component to be tooled. Expensive machining is then fully eliminated from the process. The shell needs then to be mounted into a suitable structural frame. A special welded high strength steel frame is built and cylindrical tubes are added to provide room for the incorporation of actuators. The frame is filled with fiberglass reinforced concrete that will provide the mechanical rigidity needed for the die. Although the nickel shell should last quite long, the die as a whole faces serious problems after approximately 100,000 strokes. It is expected that cracks formed on the nickel concrete interface will propagate rapidly and damage the mechanical integrity of the die.

These alternative die technologies are in most cases in a developmental stage. Precise information on cost, life and reliability are difficult to obtain and may not yet be known. To evaluate the potential of these tooling technologies, a die manufacturing model is used. This model uses an analysis of the cost drivers for manufacturing traditional cast iron stamping dies [Rampulla, 1997] as a baseline for estimating and comparing the cost of alternative dies. Other important parameters such as the expected die life are estimated based on interviews conducted with die manufacturing experts.
It is important to note that die manufacturing is only one part of launching a new vehicle (see figure 30). Lead times for a new vehicle takes around five years, out of which the production of new die sets takes roughly 12 to 18 months [Drees, 1989]. The alternative die technologies under consideration in this thesis would result in the reduction of lead times. That, in turn could have significant financial and competitiveness implications that are beyond the scope of this dissertation.

**Vehicle Development**

- Market Research
- Concept Sketches
- Clay and Scale Models
- Scanned Data
  - Die Process Design
    - Alpha Dies
    - Prototype Dies
  - Alpha Build
  - Prototype Build
  - Pilot Build
  - Start of Production

**Prototype Dies**

**Production Dies**

- Die Design and Formability Analysis
  - Die Construction
  - Primary Tryout
  - Secondary Tryout

Figure 30: *Die development as a component of product development*

The die cost driver analysis begins with the identification of manufacturing operations involved in making production dies. Typically the die production process can be split into seven different stages. These are:

- **Technology Analysis**: This is the initial stage in which the part to be stamped is studied in order to define the needed process steps.
• *Project Integration*: At this stage every manufacturing detail is added to the analysis done the previous stage.

• *Modeling*: A die model (usually in polyurethane) is built to be used in the casting stage.

• *Casting & Materials*: The model is taken to the foundry and the die is cast.

• *Machining & Assembly*: Machining of the die is done and all the die set parts are assembled.

• *Tryouts*: This accounts for both primary and secondary tryouts. The first ones are conducted at the die manufacturing plant. The second ones are conducted at the stamping line.

• *Quality Control*: Part geometrical accuracy is checked and the quality of the die is assured.

For each of these die making stages, either labor, equipment or material account for most of the cost. Table 4 a & b present cost analysis results for making a roof forming die. Each column presents the costs for a particular die manufacturing stage. The eighth column tracks other costs such as some overhead expenditures, transportation, documentation, and other minor general activities. The first six rows show information related to making a single (or the first of the series) die. This table includes the number of hours needed to complete each of the die manufacturing stages, the cost derived from labor, equipment and material, the total cost for each manufacturing stage, and the percentage represented by that cost. These tables also show the estimated savings for making subsequent identical die sets. These savings are presented as a percentage of the first die set manufacturing cost. The last row shows the resulting cost for each manufacturing stage of these subsequent die sets and their total cost.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Technology Analysis</th>
<th>Project Integration</th>
<th>Modeling</th>
<th>Casting &amp; Materials</th>
<th>Machining &amp; Assembly</th>
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Table 4a: Die manufacturing cost estimates (first and second roof forming dies)
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<td>$6,111</td>
<td>$6,503</td>
<td>$5,219</td>
<td>$8,886</td>
<td>$4,017</td>
<td>$7,881</td>
<td>$30,739</td>
</tr>
<tr>
<td>Cost contribution (%)</td>
<td>7%</td>
<td>11%</td>
<td>13%</td>
<td>14%</td>
<td>11%</td>
<td>19%</td>
<td>8%</td>
<td>17%</td>
<td>100%</td>
</tr>
<tr>
<td>2nd set savings (%)</td>
<td>100%</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd set cost ($)</td>
<td>$6,111</td>
<td>$6,503</td>
<td>$3,653</td>
<td>$5,332</td>
<td>$4,017</td>
<td>$5,123</td>
<td></td>
<td></td>
<td>$30,739</td>
</tr>
<tr>
<td>Working hours needed (#)</td>
<td>100</td>
<td>160</td>
<td>200</td>
<td>30</td>
<td>25</td>
<td>150</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor cost ($)</td>
<td>$3,333</td>
<td>$5,333</td>
<td>$5,556</td>
<td>$667</td>
<td>$764</td>
<td>$4,167</td>
<td>$1,667</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment cost ($)</td>
<td>$1,464</td>
<td>$541</td>
<td>$4,720</td>
<td>$1,138</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NICKEL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$43,218</td>
</tr>
<tr>
<td>Material cost ($)</td>
<td>$1,667</td>
<td>$5,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>$3,333</td>
<td>$5,333</td>
<td>$7,222</td>
<td>$7,131</td>
<td>$1,305</td>
<td>$8,886</td>
<td>$2,804</td>
<td>$7,203</td>
<td>$43,218</td>
</tr>
<tr>
<td>Cost contribution (%)</td>
<td>8%</td>
<td>12%</td>
<td>17%</td>
<td>17%</td>
<td>3%</td>
<td>21%</td>
<td>6%</td>
<td>17%</td>
<td>100%</td>
</tr>
<tr>
<td>2nd set savings (%)</td>
<td>100%</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd set cost ($)</td>
<td>$1,806</td>
<td>$7,131</td>
<td>$913</td>
<td>$6,220</td>
<td>$2,804</td>
<td>$3,775</td>
<td></td>
<td></td>
<td>$22,650</td>
</tr>
</tbody>
</table>

Table 4b: Die manufacturing cost estimates (first and second roof forming dies)
The most important difference between the cast iron dies and the other technologies is the significant reduction in the machining and assembly stage. As where 700 hours are required for this step in the cast iron case, less than 100 hours are needed for the others. In the cast iron case, this translates into over $50,000 representing 46% of the total die cost. The reason this stage is so expensive is the need for specialized labor and expensive milling machines (both five and three axis milling machines are often required) [Thonhoff & Hernandez-Camacho, 1989]. Table 5 summarizes the most important baseline numbers for comparing these different die technologies.

<table>
<thead>
<tr>
<th>TOOLING TECHNOLOGY</th>
<th>TECHNOLOGY RELIABILITY</th>
<th>FIRST ROOF FORMING DIE COST</th>
<th>EXPECTED TOOLING LIFE (# of strokes)</th>
<th>SECOND COST SAVINGS (% of the first die)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAST IRON</td>
<td>Proven</td>
<td>$110,000</td>
<td>&gt;5,000,000</td>
<td>32%</td>
</tr>
<tr>
<td>KIRKSITE</td>
<td>Prototypes</td>
<td>$55,000</td>
<td>100,000</td>
<td>38%</td>
</tr>
<tr>
<td>EPOXY</td>
<td>Uncertain life</td>
<td>$47,000</td>
<td>10,000</td>
<td>35%</td>
</tr>
<tr>
<td>NICKEL SHELL</td>
<td>Unproven</td>
<td>$43,000</td>
<td>100,000</td>
<td>48%</td>
</tr>
</tbody>
</table>

Table 5: Die technologies assumptions

The relative cost calculated for the forming step of a roof are extended to each of the other stamping steps required to produce the part. Model simulations are done for two different scenarios; one with a four year product life and the other with a eight year product life. These two scenarios illustrate the effect of product life on the breakeven points for each die making technology. As the product life increases, the cast iron die utilization increases and therefore the part manufacturing cost for this technology decreases, making the alternative low volume tooling technologies less attractive. Figures 31a and 31b illustrate the breakeven points. The epoxy die technology is not shown in these figures since their use results in breakeven points outside the ranges of these figures. Two values for the life of a kirksite die are used to illustrate the sensitivity of the breakeven point to the tool life and because of the uncertainty in the value of the tool life for kirksite.
Figure 31a: Die technology comparison. 4 year product life scenario

Figure 31b: Die technology comparison. 8 year product life scenario
Breakeven analysis for the utilization of these alternative technologies is very sensitive to the assumptions used in the models. Some of these assumptions, like the product life, are market dependent and there is no way to know an exact value. Others, like tool life, carry large uncertainties due to the developmental stage of the technologies. Figure 32 compares the utilization of the cast iron tooling with that of the alternative technologies under three different scenarios; optimistic, baseline, and pessimistic. The baseline scenario uses the expected values for product life, tool life, 1\textsuperscript{st} tool cost percent, and 2\textsuperscript{nd}+ tool cost savings. The 1\textsuperscript{st} tooling cost indicate the cost of a die set produced with one of the alternative technologies as a percent of the cost of the equivalent conventional cast iron die set. The 2\textsuperscript{nd}+ tool cost savings indicate how much less it cost to produce a die sets after a first one has been already made. The optimistic scenario assumes a shorter product life (which is more favorable to low volume tooling) and improvements in the other 3 areas. The pessimistic scenario assumes a large product life as well as a short tool life and a high tool cost. These scenarios allow the determination of realistic ranges of productions volumes for a given technology.

<table>
<thead>
<tr>
<th>Tooling Tech.</th>
<th>Scenario</th>
<th>Product Life (years)</th>
<th>Tooling Life (strokes)</th>
<th>1st Tooling Cost (% of standard tech.)</th>
<th>2...n Tooling Savings (% of 1st tooling cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kirksite</td>
<td>Optimistic</td>
<td>4</td>
<td>250,000</td>
<td>45%</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>6</td>
<td>100,000</td>
<td>50%</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>Pessimistic</td>
<td>8</td>
<td>50,000</td>
<td>55%</td>
<td>34%</td>
</tr>
<tr>
<td>Ni shell</td>
<td>Optimistic</td>
<td>4</td>
<td>150,000</td>
<td>35%</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>6</td>
<td>100,000</td>
<td>39%</td>
<td>39%</td>
</tr>
<tr>
<td></td>
<td>Pessimistic</td>
<td>8</td>
<td>20,000</td>
<td>43%</td>
<td>50%</td>
</tr>
<tr>
<td>Epoxy</td>
<td>Optimistic</td>
<td>4</td>
<td>25,000</td>
<td>33%</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>6</td>
<td>1,000</td>
<td>43%</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>Pessimistic</td>
<td>8</td>
<td>0</td>
<td>53%</td>
<td>53%</td>
</tr>
</tbody>
</table>

Figure 32: Potential for the utilization of low volume die technologies
Figure 32 shows that the epoxy technology is competitive only at very low volumes, those typical of series productions, rather than even low volume manufacturing. Both the kerksite and the nickel shell-concrete reinforced technologies have similar potential, with breakeven points ranging from a few thousand parts per year to production volumes of more than 100,000 part per year.

In general all die technologies involve a trade-off between tool cost and tool life. It is also true that these alternative tooling options have a higher tool cost to tool life ratio. Otherwise, as explained early in this section, these alternative technologies would become the technology of choice at all production volumes, making it cheaper to use multiple alternative technology tool sets than a single cast iron tool. Since tooling is such a large component of the overall part cost for low volume stamping, an analysis of the total tooling investment over the lifetime production volume gives a good approximation of the full cost analysis (inherent in this approach is the assumption that the alternative technologies affect only the tool cost and life, not the other process variables). A generic comparison of this kind is presented in figure 33.

This figure illustrates how the competitive position of an alternative technology can be estimated quickly. Two tool technologies are compared in that chart. Technology A represents a situation with high unit tool cost and a long tool life, such as traditional cast iron dies for stamping. Technology B represents a low cost, low tool life alternative. Each tool technology takes a shape of a step function, and each step represents the need for using one more tool to achieve the desired life time production volume. For each added tool the production volume capacity is extended by the tool life. Each step function is bound by two lines. The lower bound represents how much a technology would cost if it were possible to pay for fractions of tools. This is an ideal situation only reached when a tool is fully utilized (at the intersection of the step function and the lower bound line). The upper bound represents the other extreme in which an additional tool set is required only to produce the last part.
Figure 33: Tooling break even comparison

However there are still cases in which technology B is preferred. At production volumes for which the lower bound tooling investment for technology B is preferred. At these volumes the investment in die set A is too high. One or more die sets using technology B can produce these volumes at a lower cost. At production volumes for which even the lower bound tool investment for technology B is greater than the upper bound (worst case) cost for technology A, technology A is always the preferred case. At intermediate volumes there is no unambiguous choice, but rather the preferred technology depends on the actual production volume and the resulting tool utilization.

8.3.3. The Use of an Alternative Processing Technology

This chapter has shown that tooling is the dominant factor affecting the economics of low volume stamping, and that alternative cheaper tooling technologies could improve the
situation. This section will explore an alternative solution; the possibility of reducing dedicated tooling investment by changing the stamping processing technology. Different processes have different cycle and setup times, and thus, different economies of scale that require a careful analysis.

For more than 40 years there has been research conducted on hydroforming a metal sheet instead of stamping. For almost 30 years there has been some type of production application [Nakagawa, et. al., 1997]. Recently this technology has matured to the point where auto makers are starting to seriously consider it as a standard production technology [Roth R., et. al., 1998]. Previous experiences with this technology have resulted in the successful production of a number of different parts such as lighting reflectors, door panels, fuel tank panels, roofs, fenders, wheel house panels and hoods. Toyota is already producing several large panels with this technology for its Sera and Supra models [Amino Corporation, 1994].

Sheet metal hydroforming offers some substantial advantages over conventional metal stamping technology:

- Hydroforming allows the use of thinner blanks to save material, due to the cold hardening of the blank prior to forming. For large panels the saving can be on the order of 10%. In some cases, reinforcing elements can be eliminated as well, with the subsequent savings in subassembly operations. This also leads to control of localized thinning and thus a consistent thickness distribution throughout the part.

- There could be a reduction of forming stages in deep drawing since hydroforming can produce a part with a drawing ratio 30% larger than can be achieved by the conventional stamping method. Thus, for parts that require more than one forming step, hydroforming may eliminate operations.
Optimal surface quality can be obtained since the blank exterior is formed only by the fluid, thus reducing friction. Better control over body wrinkling can be obtained with this process as well. These can potentially allow the forming of pre-painted blanks.

Hydroforming of sheet metal is known under various names including, pressure lubricating deep drawing, hydromech, acquadraw, fluid former, and active hydroforming. For this thesis active hydroforming is used.

The active hydroforming process is capable of replacing all of the forming steps of the stamping sequence with a single step. However, additional steps are still needed for the trimming, piercing, and flanging operations. The hydroforming step results in metal forming through the use of only one half of a typical die, the other is replaced by a pool of fluid. When the press is closed and the fluid is pressurized, the metal is forced to take the shape of the die. In reality, the process is a bit more complicated involving the seven steps shown in figure 35. The proposed manufacturing system will employ laser cutting for the trimming and piercing step (although these can also be done using conventional press systems). The flanging will be done in a conventional press system. Figure 34 illustrates the changes to a regular stamping line when an average panel is produced in the proposed active hydroforming system.
Figure 34: Changing from a conventional stamping line to an active hydroforming system

Figure 35: Steps on a active hydroforming operation
The three figures represent the main steps of the hydroforming process, while the two charts on the lower right show the behavior of the fluid pressure on the press chamber, and the position of the punch over time [SMG Engineering, 1997]. The process starts with the press ram in the highest position and the blank placed over the fluid cavity. At this point the fluid is not pressurized and the system is at rest. Steps 1 and 2 represent the closing of the press as the blank is being clamped. The chart shows no fluid pressure on the chamber. The punch, although lower, is not in contact with the blank yet. Step 3 is the pre-stretching of the blank. The fluid is pressurized and blank is elongated over its surface until it is completely pressed against the punch. The controlled plastic deformation produces a stain hardening effect on the blank. After finishing the first elongation step, the punch is displaced downwards (step 4) with a moderate opposing fluid pressure on the chamber. In step 5 the chamber is pressurized to the required level and the forming of the roof is completed. In step 6 the fluid pressure is released and in step 7 the ram is lifted to allow the removal of the part.

In all, the cycle time for this process is long (approximately 30 sec) and thus it will prove not to be economically efficient at high volumes. However, it offers an advantage at low volumes, namely, the reduction of dedicated investment in tooling. This is mainly achieved by eliminating the female die, thus, only the punch and the blank holder have to be produced. Furthermore, numerous forming steps can potentially be eliminated, further reducing the tooling investment. Also, time consuming and expensive adjustments of the dies done during tryout are significantly reduced. It is estimated that a cast iron die used for hydroforming costs only about 30% of the die investment needed for the forming steps when using a conventional system. Of course this saving is highly part dependent. Further, a non-traditional, more economical and rapidly manufactured punch, can be used with this forming process. In active hydroforming, because static hydraulic pressure is applied, friction on the die and blank holder is reduced. The die experiences less wear and therefore less durable tool materials could be used.
Laser cutting follows the active hydroforming step. Laser cutting involves the use of a highly focused electromagnetic beam to cut or pierce a sheet of metal. Laser cutting offers the advantage of eliminating die requirements, however the initial capital investment is higher than that for the equivalent steps in a conventional stamping line. The real limiting factor for using this technology at high volumes is the cutting speed [Weick, 1985]. Figure 36 presents cutting speeds for several steel thicknesses and three different power levels for the laser beam. For example, a 1 mm thick mild steel sheet can be cut by a 1,250 watt laser at about 10 m/min, and therefore a part such as a roof with a 4 meter perimeter can be trimmed in about 24 seconds. While this is too long for a conventional stamping line, it matches the cycle time required for the hydroforming step, making it a good fit with the low volume active hydroforming system.

![Figure 36: Laser cutting speeds for mild steel sheets](image-url)
The final step is flanging. Unfortunately there is no reliable alternative that can better suit low volume manufacturing.

The cost of producing a roof panel using the active hydroforming system is modeled and compared to the cost already shown using a conventional press system. It was assumed that the hydroforming step requires a 3,000 ton, double action press, costing $1,400,000. The cycle time for this step is approximately 30 seconds. Trimming was done using a 1,250 watt laser costing $1,500,000, operating at a speed of 6 m/min. Flanging was done using a conventional system despite the poor tooling utilization at low volumes.

Flanging became a major contributor to the overall cost at low volumes. At 60,000 parts per year, the roof produced by active hydroforming is estimated to cost $25.93. Figure 37 shows the distribution of this cost among the various process steps. As expected the hydroforming step is the single biggest cost driver due to the large investment and long cycle time. The flanging cost is high since a method better suited to low volume production could not be found.

![Cost Breakdown Chart](chart.png)

*Figure 37: Cost breakdown by process step at 60,000 parts per year*
Figure 38 shows the cost of producing the roof using the conventional stamping line with cast iron dies, and using the active hydroforming system, AHF. For the active hydroforming system three die options are studied, the standard cast iron die set, the kirksite dies set and the nickel shell-concrete reinforced technology.

![Cost comparison graph](image)

*Note: Full automated line, 4 years product life

**Figure 38**: Conventional stamping versus active hydroforming comparison

The breakeven production volume between the conventional stamping and the active hydroforming technology is in the range of 60,000 to 65,000 parts per year. Neither the kirksite nor the nickel shell die technology significantly affects the range of economic competitiveness of active hydorforming system. As the production volume drops below 60,000 parts per year, the tooling content becomes more important and the nickel shell technology shows a slight advantage over the other competing technologies.
Figure 39: Tooling cost comparison between hydroforming and conventional stamping

Figure 39 shows a cost comparison of the standard technology and active hydroforming at three production volumes. In each case the tooling cost is broken out to show its relative importance. At the breakeven production volume, the tooling cost component for the hydroforming process is insignificant compared with the other costs. Therefore, using cheaper die technologies will not significantly improve the cost competitiveness of hydroforming at these volumes. At lower volumes tooling becomes more important and thus there are additional savings to be made through the use of alternative tool technologies.

8.4. Case Conclusions

Low to medium volume stamping operations have become common throughout the world. It is an important industry issue to find ways to produce low volume stampings more efficiently. The conventional high stamping operations rely heavily on achieving minimum
scales economies, which occur at about 200,000 parts per year. These scale economies are mainly dictated by the efficient use of the standard, expensive cast iron dies. Cast iron die sets can cost well over a million dollars depending on the part and can last up to 5 million strokes. Three alternative tooling technologies; kirksite dies, epoxy dies, and the nickel shell-concrete reinforced technology offer the option of trading tool cost and life. Even at higher tooling cost to tooling life ratios (seemingly less economically effective), these technologies offer savings at low volumes since only a limited tooling life is required. These technologies are still in the developmental stage and thus many of the important manufacturing parameters are still unclear. Kirksite and nickel shell dies both show promise, although the kirksite technology is currently in a more advanced developmental stage. These technologies could become a preferred alternative to cast iron dies in production volumes of less than 100,000 parts per year. Epoxy dies, on the other hand, appear to be a useful only for extremely low volumes, in most cases associated with series production.

The role of automation on press line operations is explored as well. The use of automation can almost double the line running rates and decrease the direct labor content to an even greater degree. For low volume stamping operations, automakers rely heavily on the use of labor (particularly true in developing economies) to avoid low equipment (capital) utilization. However, the cost penalty at low volumes comes from tooling not equipment utilization. Despite common beliefs, highly automated stamping lines performed better in both low and high labor cost environment (provided enough different products are made to allow high line utilization). Only at extremely low production volumes (20,000 units or less) does automation lose its competitive edge over labor intensive operations.

Finally, die investment can be indirectly reduced by changing the stamping process technology. Active hydroforming was proposed in this chapter as the most promising low volume alternative to conventional stamping. This technology has a slower cycle time, which in turn limits its applicability to low production volumes. But at low volumes, hydroforming offers the advantage of requiring much lower dedicated tooling investment.
The hydroforming step uses only a punch and does not need a female die. Expensive and time consuming die set adjustments and tryout are also significantly reduced. That in turn reduces die cost by almost two thirds. The laser cutting step replaces and trimming and piercing operations, and although it uses expensive equipment, it does not need any die investment at all. Finally, the active hydroforming system still utilizes a conventional flanging step at the end of the line. For this particular operation no extra savings are achieved.

Active hydroforming offers other advantages over stamping such as a reduction in the part weight (for equal performance), and a reduction in production lead times, among others. All in all, this is a very attractive alternative technology that promises significant manufacturing cost savings for production volumes less that 60,000 parts per year.
9. SUMMARY

9.1. Summary

Driven by the globalization process, low volume manufacturing has become increasingly important. Automakers and their suppliers have to learn to produce at these volumes in different locations throughout the globe. The use of high volume manufacturing and process technologies to produce low volumes has proven to be economically inefficient. To be cost competitive at low volumes requires identifying and using the most appropriate process technology for these volumes. The process technology choice is usually neglected in the Operations Research or Management literature. Most of the past work has focused on work flow optimization, inventory reduction and logistics improvements.

This thesis presented a methodology for examining low volume manufacturing cases. It identified some typical areas of concern for low volume producers which result in high costs, and presented general strategies for reducing these cost penalties.

Four cases were studied in this thesis. The applied methodology consisted of a detailed mapping of a manufacturing scenario in order to get a complete picture of the economics of a process across a spectrum of external variables. This economic perspective and technical information about process technologies are combined in models that facilitate the comparison of the economic behavior of alternative manufacturing processes under different scenarios. This method facilitates the understanding of the relationship between part manufacturing cost and variables such as production volume, labor cost, and equipment utilization. This, in turn permits the analysis of the economic implications of different manufacturing strategies and business conditions.

Different low volume operations may require different strategies to improve their competitiveness. The cases studied in this thesis represent some of the most common issues affecting low volume manufacturing and concentrate on three areas; the selection of optimal
low volume alternative manufacturing technologies, tooling related issues such as the optimal investment levels and the choice of tooling technologies, and the choice of low volume automation levels.

9.1.1. Alternative Process Technologies

The use of alternative process technologies can provide a means for addressing many of the problems associated with low volume manufacturing. This thesis has already outlined several of these difficulties including those arising from long set-up times and poor equipment and tooling utilization.

Generally speaking, processes which have long setup times are ill suited for low volume manufacturing. Low volume (as well as small lot size) production tends to involve far more set-up operations than if the same process were used for high volume manufacturing. Consequently, the penalty incurred from having long set-up times is greater. An alternative process technology that has a reduced set-up time (even if it requires a longer cycle time) can be beneficial for low volume production. The use of the forge-extrusion process by the Argentine engine valve manufacturers is one such example. The forge-extrusion process sacrifices production speed (cycle time) in favor of reducing the setup times. While this process remains uncompetitive at high volumes where relatively few set-up operations are needed, it provides a less expensive process route at lower overall production volumes and lot sizes due to the time saved when setting up the line to begin the production of new parts.

Processes that use expensive investments in equipment and tooling to achieve fast cycle times also run the risk of being very expensive at low production volumes. If the line or tools are not fully utilized, a slower, but less capital intensive process may be more cost effective. The Thai steering wheel production is an example of this. The use of die casting to produce the wheel structure requires large investments, particularly in tooling. At the low volumes being produced by the Thai manufacturers, these tools have very poor utilization and thus their effect on the per piece manufacturing cost is great. The switch to the slower, but less
capital intensive, assembly process eliminates the need for expensive dedicated tooling and results in significant cost savings at low volumes.

9.1.2. Tooling Related Issues

For processes which require significant expenditures for tools it is important to achieve good tool utilization in order to avoid high per piece costs. In general this means the manufacturer must only invest in the optimal number of tools. However, for low volume operations, the optimum is often a single tool which is still poorly utilized. In this case there are several potential strategies. The manufacturer can look to a new process technology and perhaps sacrifice in terms of process speed in order to reduce or even eliminate the investment in tools, or the manufacturer may be able use tools which are less expensive, but have a shorter tool life.

The need for choosing the optimal number of tools is highlighted in the example of the injection molding step used for making steering wheels. High volume producers need several tool sets to achieve their production volumes. By simultaneously employing multiple stations they achieve higher throughputs and attempt to spread the equipment cost over a large number of pieces. This is particularly advantageous since the station and tooling cost is much smaller than the expensive equipment (such as tanks, pumps, and heaters) needed. At low volumes Thai producers also employ several injection molding stations to spread the equipment cost, but for them it proves to be an error. At low volumes it is impossible to achieve high tool utilization even for a single tool set. Additional injection molding tools further reduce the tooling utilization and offset any savings achieved by equipment sharing.

The wheel structure making portion of the steering wheel manufacturing process is an example of the use of an alternate process technology. As has already been discussed, the substitution of a series of assembly intensive steps for the tooling intensive die casting step results in the elimination of the investment in tools and a cost savings at low volumes.
Alternate stamping dies provide an example of the use of less expensive, but shorter life tooling. Conventional stamping operations rely heavily on achieving minimum scale economies mainly dictated by the efficient use of the standard expensive cast iron dies. Three alternative tooling technologies; kirksite dies, epoxy dies, and nickel shell-concrete reinforced technology each require far lower levels of investment, but have a much shorter useful lives. Consequently, technologies save cost at low volumes where long tool life is not important. Even though, these technologies are still in the developmental stage and thus many important manufacturing parameters are still unclear, kirksite and nickel shell dies could become a preferred tooling alternative to cast iron dies in production volumes of less than 100,000 parts per year, while epoxy dies appear to be a useful only for extremely low volumes associated with series production.

9.1.3. Automation Level Optimization

Some processes do not penalize the manufacturing of low volumes or small lot sizes. They simply require different levels of automation to produce the desired production volume. In these cases, the role of automation becomes a matter of choosing to produce fewer parts at slower rates manually, or to produce more parts at a faster rate by investing in automation equipment. Further, the use of automation directly affects the capital-labor balance, resulting in labor content reduction. The critical factor is whether the capacity increase would be fully utilized. Firms should select the process automation best suited to the market demand they face and their labor cost environment. Using a relatively expensive automated line (capable of producing high volumes) when only low volumes are required carries a cost penalty due to the low equipment utilization. Low automation, labor intensive operations thus better fit low volume operations. This is particularly true if that operation is done in a low labor cost environment.

The production of cooper-tin radiators can be achieved by only one manufacturing process, but allows the use of a large range of automation options. Each of the process steps
required short set-up times and low tooling investment, meaning that there is no cost penalty for producing low volumes or small lot sizes. Investment in automation increases the capacity of the plant and allows for the reduction of the labor content. US producers operate with highly automated lines, that allows them to reach high throughputs and to reduce labor content, a large expense in the US. This strategy is successful only because they produce volumes large enough to ensure full equipment utilization. The same approach is inappropriate for the Thai radiator manufacturing companies where there are insufficient volumes to achieve full utilization at high automation levels, and the savings in labor cost are minimal due to their low wages.

Processes for which automation only costs a small fraction of the total investment, the use of automation almost always is justified. Relatively small capital investments lead to higher throughputs, and therefore only small increases in production volume or small savings in labor cost can offset the additional investment in automation. In these cases, the use of automation can be an economical option even at low volumes. For stamping operations modest investments in automation almost double the line running rates and greatly reduce the direct labor content, making this the most effective strategy even at low volumes.
10- CONCLUSIONS

Through the application of technical cost modeling to the analysis of low volume operations, this thesis has shown the economic inefficiencies associated with using high volume manufacturing and process technologies to produce at low volumes. From the cases studied we found that:

- Processes requiring long setup times relative to their cycle times are ill suited for low volume operations. Process technologies with reduced setup times could provide a better low volume manufacturing alternative, even if they require longer cycle times.

- Capital intensive processes carry high cost penalties at low volumes due to the overall low utilization of the investment. Less capital intensive alternative processes should be used when available.

- The use of expensive dedicated tooling processes results in high costs at low volume operations. Either a change in the manufacturing process or the use of alternative tooling materials and technologies could improve the low volume economics. Even when low volume alternative tooling have lower tool life to tool cost ratios, these technologies are economically effective provided that these tools are only needed for low volumes.

- Balancing tooling versus equipment investment is critical for low volume manufacturing and can be tricky particularly when tooling is far less expensive than equipment. Simultaneously employing multiple tools to achieve higher throughputs, and thus spreading equipment costs over a large number of parts, looses its effectiveness at low volumes if the tools are not fully utilized.

- For processes that do not penalize low volume manufacturing, it is critical to implement the optime! automation level. Automation is justified almost always when its cost is a small fraction of the total investment. Otherwise, it should be adjusted to reach full investment utilization at the particular overall production volume. Automation affects the capital-labor balance, thus in general, low automation, labor intensive operations favor low volumes.
11- FUTURE WORK

The drive towards globalization by the automobile and other industries is likely to keep expanding, and with this, the need for producing more effectively at low volumes. This thesis has shown that technical cost modeling is an effective methodology for comparing processes over a large range of production volumes. Moreover, it shows some of the most common factors leading to cost penalties at low volumes and presents some solutions to these situations. However, this study focused on a limited set of processes. Future work should be continued to expand this analysis to other manufacturing processes and scenarios. A larger sample of processes, industries and scenarios will provide a stronger foundation upon which to build some general manufacturing strategies for low volume suppliers.

One approach is to categorize processes to try to learn if there are general strategies which apply to all processes of a similar nature. For example, it would be useful to have a general strategy which applies to all or most assembly intensive processes such as those used in the radiator manufacturing. Exploration of additional cases with common factors could lead to a more generalized set of strategies. The task then is to establish commonalities among various processes in terms of their low volume economics. This thesis demonstrated a few of these, such as assembly and tooling intensive processes, and those products for which multiple process routes are available. Future work should focus on developing a more comprehensive categorization of processes and examine the details of each to draw general conclusions. This understanding should in turn be incorporated into the decision making process, to allow manufacturers to better select and optimize the most economical low volume process. Future consideration must then be given to other manufacturing and managerial issues such as logistics cost, human resources availability and infrastructure resources. These factors could offset the manufacturing cost advantages of a given option. The incorporation of the cost modeling methodology into a decision analysis framework could allow manufacturers to choose among the alternatives.
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