AN ECONOMIC EVALUATION OF SHEET HYDROFORMING AND LOW VOLUME STAMPING AND THE EFFECTS OF MANUFACTURING SYSTEMS ANALYSIS

by

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Submitted to the Department of Materials Science and Engineering
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ABSTRACT

The automotive industry is experiencing several new pressures as it adapts to meet twenty-first century needs. One of those pressures is the need to produce cars at lower volume. The motivations include wanting to enter new, untested markets like China and niche markets. Producing at low volume at a lower investment reduces a company's risk and exposure while testing uncharted waters. Learning how to produce at low volume is quite complicated, though. A tempting and easy solution is to take a high-production plant and simply make it smaller. This method takes the proven methods of high volume and inflexibly applies it to low volume plants. The result is a cost-prohibitive product due to high initial investment.

Thus enters new processes that reduce a plant's initial investment and caters to the plant's low volume mission. Sheet hydroforming might have a role in low volume production as its higher cycle times are no longer prohibitive. Stamping has adapted to the new low-volume mantra by using less expensive, lower volume dies. While preliminary analysis holds that sheet hydroforming remains cost effective versus stamping at volumes less than thirty thousand (German Analysis 1999), a formal comparison using technical cost modeling between sheet hydroforming and low-volume stamping has not been accomplished to validate that. In reality, a simple switching point does not exist. This thesis examines four separate automotive parts, all with the ability to be produced by stamping or sheet hydroforming. The general trend showed that high volume stamping should not be considered below sixty thousand and sheet hydroforming should not be considered below twenty thousand. All four cases produced different results and crossing points. With no clear general crossover point, cost modeling is an effective way to determine manufacturing strategy on a case-by-case basis. Also, in a low volume, low investment scenario, oftentimes, lowest cost is not the driving issue, but rather the driving issue is lowest investment. Cost modeling shows that sheet hydroforming has less initial investment cost especially when multiple low volume stamping dies are needed.

Technical cost modeling currently does not incorporate a sophisticated approach to look at the relationships between machines in a manufacturing process. Previously, cost models assumed no machine interactions. Not understanding the impact of this assumption can lead to naïve decisions, but understanding when the assumption is

reasonable can help minimize its effect. Also, previous models assumed infinite buffers between machines to minimize machine interactions, but the models did not account for those buffers in its costs. As expected, removing those assumptions adds to part costs and shifts the crossover points between a processing choice. The driving motivation for this is to have intuition concerning manufacturing systems engineering and its impact on technical cost modeling. Results from this analysis and lessons learned are presented in an attempt to achieve that intuition.

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Table of Contents

List of Figures

List of Tables

List of Equations

Chapter 1 Introduction

Car companies are pushing themselves into new frontiers. Developing countries, while often economically unstable, offer tremendous opportunities for profit. This comes as the automobile industry struggles to achieve profitability and maintain market share. Automotive companies face additional risks entering untested markets. Cultural differences can affect whether a car's aesthetic appearance gains acceptance or whether the car fails. Economic backgrounds and geographic and demographic concerns will also affect what types of cars sell. These regional differences can be seen even in the United States. A country's instability can deter external investment. To minimize the risk of entry into these markets, low investment and low volume strategies are adopted. Low investment and low volume productions reduce a company's exposure in an untested market. Low volume production is not only for new regions; it also has potential to supply the emerging demand for niche vehicles and diverse products in developed countries. Then, with lessons learned and entry into a market established, high production methods can be adapted, or manufacturers may choose to remain at low volume.

Sheet hydroforming is commonly mentioned with low volume production in lieu of conventional, high volume stamping. Sheet hydroforming has diversified into several variations, and much research is being done to extend its competitiveness. This thesis will focus on hydromechanical deep drawing. Sheet hydroforming offers many advantages over conventional stamping. Tooling times and costs are dramatically reduced, material waste and part over-engineering can be reduced, and fewer operations are needed per part. Conventional stamping has adapted to meet the demands of the low volume market with low cost dies. Using different materials, different dies, reduced automation, and simplified parts, low volume stamping methods can drastically reduce investment costs. Thus, conventional stamping and sheet hydroforming have met to seemingly supply the same demand. Developing an understanding for when sheet hydroforming outperforms low volume stamping will aid automakers' strategic decision-making. This can be achieved through cost modeling comparisons. Other than the different dies, high and low volume stamping appear to be similar processes. Knowing why the processes' costs are different provides valuable insight and may provide a smoother transition from one to the other. Technical cost modeling is the method to quantify those differences and allows robust testing.

Examining the two different processes using technical cost modeling, a potential problem has surfaced. Technical cost modeling accounts for machine up and down time by requesting a daily downtime input. Imbedded in this input is the assumption that the machines do not interact with each other and that production rates are dependent only on the slowest machine. Contrary to the cost model methodology, when several steps of machining are needed to produce even simple parts, experience has shown that designing a production line requires some thought to achieve a desired level of production at a minimal cost. Machine inefficiencies are not isolated. If a machine goes down, the machine upstream may not be able to produce more parts and the machine downstream may not have any parts on which to operate. The result is machines standing idle, and production levels dipping. A natural reaction to place buffers between machines might be costly. Through manufacturing systems analysis, an optimal design can be achieved resulting in an efficient, cost effective system. A method to compare various forming process from a technical and material properties perspective is technical cost modeling. Until now, inefficiencies for a specific machine have been calculated in the modeling, but the interactions between machines have been ignored. Combining technical cost modeling and manufacturing systems analysis will allow quantitative calculations to show the economic impact of various strategies from beginning to end of parts fabrication.

Knowing what regimes machine interactions are important and what regimes do not need attention is valuable. Sheet hydroforming and low volume stamping are ideal case studies because the processes contain various machine operating speeds and multiple machines. From the case studies, generalized conclusions applicable to any process can be made. The case studies allow to see when and where the assumption holds and what an appropriate response is. In cases where simple down times are sufficiently accurate, the cost models will not need modification. Otherwise, analysis on the specific system will be needed and those results incorporated into the model.

Chapter 2 Technical Cost Modeling Background

Technical Cost Modeling has been developed as a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial and error innovation and process optimization (Busch 1990). It differs from other, more commonly used accounting methods by taking an inputted piece description and deriving a piece cost, cycle time, and an investment cost among other things. It has been shown to be a valuable tool in material selection, process selection, and plant design. Specifically, it is a good way to take a less subjective approach to exploring the economic benefits and limits of sheet hydroforming with respect to low volume stamping. It is a good attempt to quantify the differences between the methods and develop an understanding of the strategy at various production levels with little investment. The result is a robust design insulated against risk.

2-1 Development

Creating a process-based cost model is as much an art form as it is a technical process. Development involves three steps: identifying relevant cost elements, establishing contributing factors, and correlating the process operations to the cost of factor use (Kirchain 2001). The development phases is the reverse of the information flow in the cost model; it starts generally and grows more specific. The first step, identifying cost elements, narrows the scope of the model. It makes little sense to model every minute cost detail especially when the cost is not technology dependent. An example of this is marketing costs. Understanding the process involves making judgment calls about the importance of each cost and what to include in the model. The relevance of any particular cost element is a function of both the process under consideration and the question the model is to address. For example, while transportation may not be a direct consequence of a forming technology, it may be pertinent if one is comparing the cost of producing two parts of different weights (Fuchs 2002). A continuing example will be given to illustrate the steps. A relevant cost element for sheet hydroforming is the process equipment costs. Press types and costs vary between different processes and form a significant fraction of the part cost. The second stage of model development is to establish the contributing factors to the relevant cost elements. For sheet hydroforming, equipment costs consist of the blanking machine, hydroforming press, trimming machines, and flanging machines. These four different machines’ cost make up the process’s equipment cost. This stage of development also includes understanding what determines the choice the contributing factors. For sheet hydroforming, a press is chosen based on its bed size and press tonnage. A larger press implies higher equipment costs. The final stage of development involves correlating part description inputs like material choice and part size to the process operations. This is where the value of process-based cost modeling is realized. To continue our example, hydroforming a large piece will cost more than a smaller part, not just because of increased material cost but also because of the increased press size needed to form the part. From the previous step, we know what determines press selection, and the model inputs bridge the information gap. Thus, the three developing steps have guided a path to model development. The developing process is repetitive and always being tweaked for improvement, but the final product has a consistent information flow as seen in Figure 2.1.

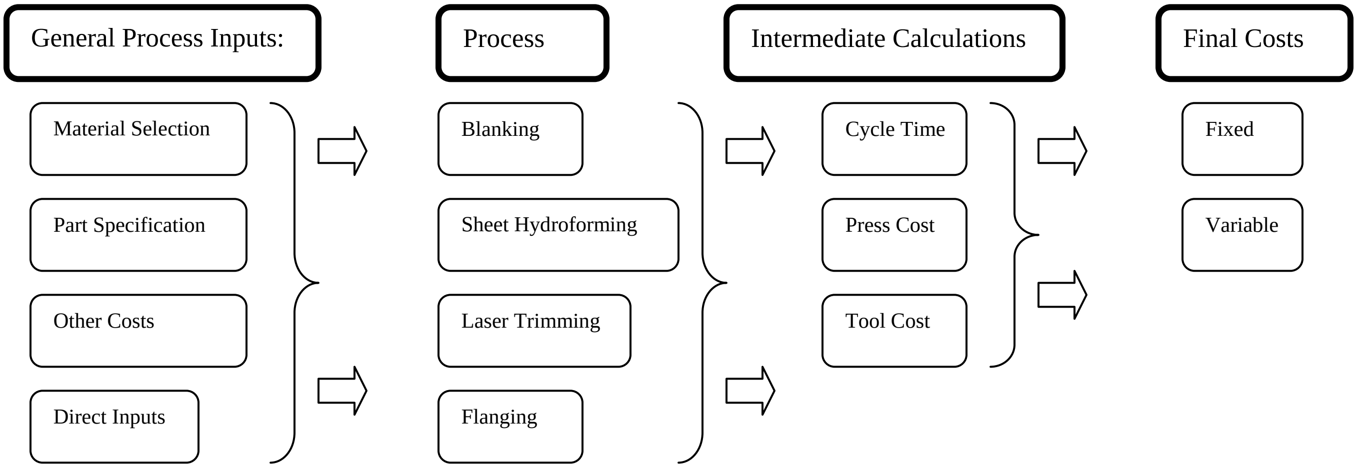


Figure 2.1: Information Flow Diagram for Sheet Hydroforming Model

2-2 Advantages and Disadvantages

Like all tools, technical cost modeling has generalized advantages and disadvantages. Advantages include ease of use and alteration, quantified results, and ability to perform sensitivity analysis. Cost models are easy to use. An inputs section clearly delineates what inputs are required, and an outputs section clearly displays the results. Beneath the process cost breakdown are the process calculations. Cost models follow a similar format regardless of what process it is modeling. While cost modeling is just a methodology, in practice, the models are built using Excel. Excel is widely used and understood. Because of its familiarity, Excel is user-friendly and causes little confusion as to how the models work. Again, with Excel, the models are easy to alter and transform. Technical cost modeling displays quantified results. It returns specific process characteristics and associated costs. Often, users of the cost models do not think in terms of process characteristics but in costs. Calculating and displaying the costs enables easier user interpretation. One of the strongest advantages of cost modeling is its ability to perform sensitivity analysis on any desired variable. By looking at a range of values, much information and insight can be gleamed about the process. This is especially valuable when comparing different processes.

Disadvantages also exist for cost modeling. The two biggest drawbacks are time and resources. Developing a cost model requires a large investment in time. Process understanding and investigation is needed before undertaking a cost model. Unlike accounting methods, cost models step through the process and account for costs. Time is required to research the process. In another sense, time makes cost models obsolete. To update them, new data must be supplied to support new analysis. Another hurdle is finding pertinent resources to support the cost model. The information needed for a cost model is often safely guarded and difficult to get or may not be thought of in the terms desired.

2-3 Model Types

Different types of cost models have been developed to fit different time, information, and purpose scenarios. The four variations of cost models are financial, full process, simplified process, and a slight modification to a body model format. A financial model is created for three different situations- 1: cost information is widely known and can be simply inputted, 2: cost or process information is difficult to attain and not widely known, so estimated costs are inputted, or 3: development time is limited. Unfortunately, for reasons two and three, the end result is a mediocre product that cannot estimate manufacturing costs accurately. While the outputs of all the models look similar, the inputs look different. Unfortunately, the quality of the model in estimating manufacturing cost depends largely on the quality of the inputs. An example of financial model inputs is investment cost, cycle times, number of workers, and tooling cost. Another variation is the full process model. This is developed when process and cost information can be collected and adequate time is allotted for design. A full process cost model does the best, most thorough job of cost estimation. It takes as many part description inputs and then does a rigorous job transferring that data into an outputted cost. The downside of this method is the long development times and the large amount of data needed.

Often, a simplified model based largely on the full process model is created. It reduces the quantity of inputs needed and is a user-friendlier product. Reducing description inputs is achieved by making process assumptions. The results are not as accurate and especially vary when the assumptions needed to create the model are violated. A good example of how a model is simplified is looking at blanks. For a full process model, length and width of the part and the blank are required as inputs. For a simplified process model, an assumption is made relating the part size to the blank size. This is a small assumption, and one that is not bad. Table 2.1 shows the number of inputs for various technical cost models developed by the Material Systems Laboratory. Some model variations have not been created.

	Financial	Full	Simple
Die Casting	*	43	7
Stamping	17	16	8
Sheet Hydroforming	15	15	*
Extrusion	4	6	*

Table 2.1: Model Inputs

2-4 Equipment Investment

One common difficulty in technical cost modeling is relating the part description to the tool cost. Identifying the pertinent data to estimate die cost is difficult at best. In low investment, low volume manufacturing, being sensitive to expensive overhead is imperative, and accurately predicting die cost becomes very important. One method to attack this is through regression analysis. The method takes a series of inputs and outputs, develops a relationship between the two and then uses that relationship to predict future outputs. In reality, calculating this figure is difficult, as previous data is needed to develop any regression analysis. In emerging technologies, that data is difficult to obtain. One final item to discuss about cost modeling is calculating payments on investment. When comparing processes in the low volume, low investment arena, we pay special attention to the amount of investment a process requires. We calculate yearly and piece cost from investment with the assumption that all of the money used to purchase the various fixed capital components was borrowed, and that it is being paid back over the respective accounting lifetime of the investment (Busch and Field, 1990). The accounting formula for payment per period where I is debt, R is interest rate per period, and N is number of periods:

$$I \cdot \frac{R \cdot (1+R)^N}{(1+R)^N - 1}$$

Equation 2.1: Yearly Investment Payment

This includes principal and interest. If any piece of equipment is dedicated, the part cost includes the entire equipment investment. If a piece of equipment is non-dedicated, the part cost includes the allocated equipment investment. The percentage of investment a part cost includes is the percentage time the investment uses for the part.

A final thing to discuss about cost modeling is regional factors. In an attempt to compare two processes as fairly as possible, differing regional factors are not included in a model. Oftentimes, a brownfield plant, used press equipment, or cheaper labor is available for parts fabrication, thus reducing piece cost. We assume all equipment to be greenfield and account for it accordingly. Again, a cost model answers a question, which in our case is not comparing different regions for production but rather two different forming processes. For more information on regional factors, see Erica Fuchs' unpublished thesis.

Overall, the automotive industry is competing to advance technologically. To advance in the area of low volume manufacturing, companies need to know what areas deserve focus. Technical cost modeling is a powerful tool that provides this focus.

Chapter 3 Process Background

The analysis of this thesis compares the sheet hydroforming process against low volume stamping. Before diving into the analysis, some background information on the two processes is in order. The entire sheet hydroforming process consists of four steps: blanking, sheet hydroforming, laser trimming, and flanging. Blanking and flanging processes are the same with sheet hydroforming as stamping and will not be discussed. Low volume stamping uses dies that are both cheaper and shorter-lived. This chapter will discuss sheet hydroforming, laser trimming, and low volume dies.

3-1 Sheet hydroforming

Many variations of sheet hydroforming exist, one being hydromechanical sheet forming. Figure 4.1 illustrates a hydromechanical press. This process consists of a punch drawing into a blanked sheet backed by pressurized liquid. The die cavity is typically filled with oil or water. Sheet hydroforming is the same as the normal deep drawing process, except for the fact that the die cavity is filled with liquid so that hydraulic pressure is applied during the forming process. The mere application of hydraulic pressure from the bottom creates a huge impact on the forming process (Nakagawa 1997). The liquid allows the material to flow better and increases its tensile resistance to break. These factors increase the drawing limit ratio. As a result, it allows forming to be carried out in one process while the normal deep drawing method requires two processes or cannot accomplish the process at all (Nakagawa et al 1997). The drawing ratio of a conventional stamping process is 2.2 where sheet hydroforming can achieve a drawing ratio of up to 3.2 in one step (Nakagawa et al 1997) or even up to 6 for a radial-pressure system in two steps

(Zhang et al 1998). A radial-pressure system, also called a hydro-rim process, pushes on the flange end as well as on the blank surface. The hydraulic pressure on the flange increases material flow, thus improving thinning consistency. Improved thinning control means that less material is needed per part, saving money and weight. Sheet hydroforming has better forming capabilities than conventional stamping, meaning increased flexibility and less forming strokes per part (see Figure 3.2).

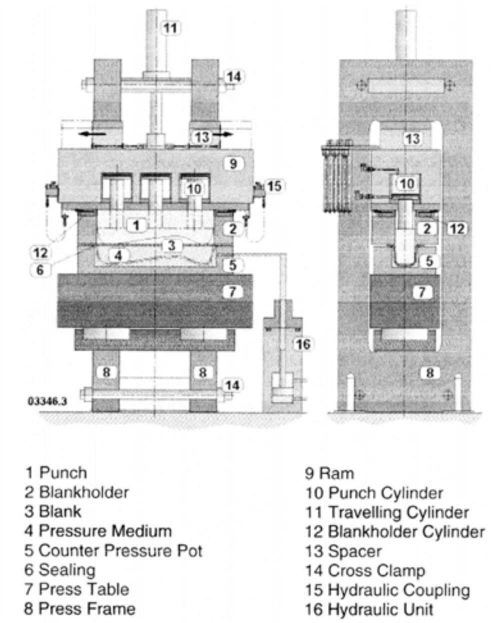


Figure 3.1: Hydromechanical Press (Derived from Aust)

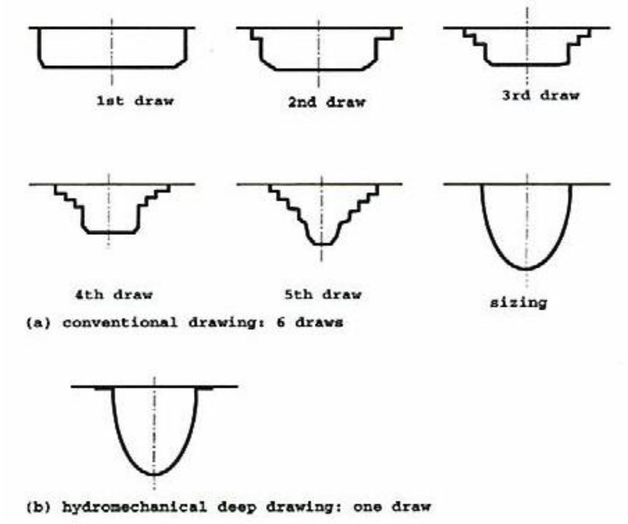


Figure 3.2: Conventional Drawing vs Sheet Hydroforming (Derived from Aust)

The sheet hydroforming has several forming stages. The process starts with the press ram in the top position, and the blank placed over the filled fluid cavity. The blank is then closed and clamped. Next, the fluid is pressurized, and the blank is elongated over its surface until it is completely pressed against the punch. The controlled plastic deformation produces a strain hardening effect on the blank. After the prestretching step, the punch is displaced downwards with a moderate opposing fluid pressure on the chamber. For calibration, the punch is locked towards the top against the ram, and calibration pressure is increased. Finally, the fluid pressure is released, the ram retracted, and the part removed (German 1999). Cycle times are based on press tonnage, part size, and part complexity and can vary from fifteen to forty-five seconds.

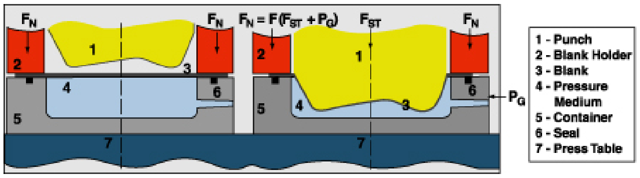


Figure 3.3: Sheet Hydroforming Illustration (Derived from R&D Update)

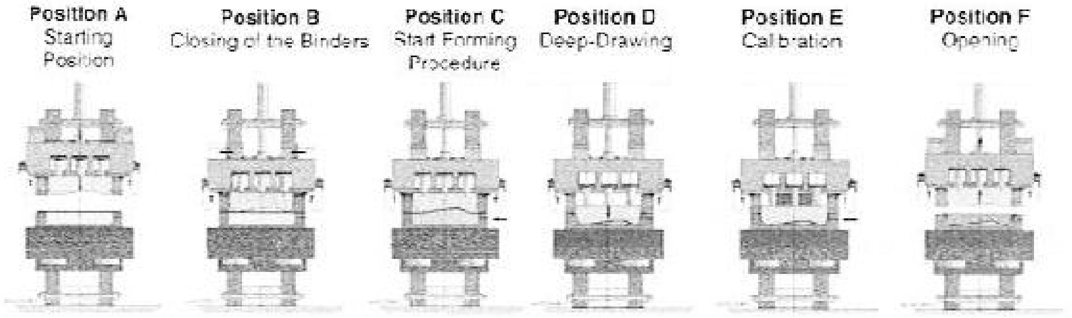


Figure 3.4: Sheet Hydroforming Steps (Derived from Zhang, et al 1998)

Many advantages of sheet hydroforming exist. Dimensional accuracy increases in sheet hydroforming because spring back after forming is eliminated. Accuracy problems are caused when the sheet metal does not contact the punch and die closely during the forming process. Also, localized thinning and thickness distribution are problems encountered in conventional sheet metal forming. Sheet hydroforming controls these problems better since the sheet metal is pushed against the punch by hydraulic pressure. Hydroforming allows 50% less material thinning than for conventional deep drawing (Zhang et al 1998). The omission of a female die provides a few advantages. Female dies cost more than male dies and require time-consuming labor for adjusting to the male die and adjusting the clearance between the male and female dies (Nakagawa et al 1997). Having only a male die means that the same forming tools can be used to form pieces with different thickness, including tailor-welded blanks (Keeler 2000). Less forming restrictions means a lower grade of material or even different material can be substituted for a part (Nakagawa et al 1998). A water punch is frictionless which eliminates a forming system variable and leaves an excellent finish on the sheet surface exposed to the liquid (R&D Update 2002). Also, having a short-life, male die allows shorter die production time and shorter time for trials and die optimization due to die machineability (Aust et al 2000). Much cost savings occur from this reduction in development time. The main drawback to sheet hydroforming is its longer cycle time which causes the process to be cost prohibitive at high volumes. Another drawback is lack of knowledge. The process has developed for decades, but little experience in the process exists for mainstream products.

Much research is being conducted to extend hydroforming's capabilities. Some avenues being researched include hydroforming of aluminum alloys at elevated temperatures using a warm hydroforming fluid, local heat treatment in the flanges just prior to forming, and usage of different alloys (Novotny et al 2001). Another avenue being explored is forming sheet metal pairs in an integrated hydroforming, trimming, and welding system (Kreis et al 2001).

3-2 Applications in industry

Hundreds of different parts are being produced with sheet hydroforming. Materials range from mild steel sheets to aluminum sheets, titanium alloys, and stainless steel sheets with thickness of .2 to 3.2mm. The sizes range from 30x30x30mm to 1200x1000x250mm (Zhang et al 1998).

Reflectors of lighting equipment are produced with sheet hydroforming. These complicated and large parts are usually made of aluminum sheet. They typically require six forming steps by a conventional stamping process but only one with sheet hydroforming. The production rate is 8 pieces per minute (Zhang et al 1998).

In the UltraLight Steel Auto Closure program, sheet hydroforming was looked at as a way to produce lighter parts with little cost penalty. Using a Duel Phase 600 steel, the validation door developed with a sheet hydroformed outer panel weighs 9.77 kg while meeting all performance and safety requirements. This is a .7kg weight reduction, 27% lighter than a best-in-class door and 46% lighter than the average door. Research concluded that further development could increase the weight reduction even more (Steel Vs Al). Sheet hydroforming was advantageous because of the advanced high-strength steel materials used and the small radii required by the door design (Advanced 2001).

3-3 Laser Trimming

A low volume tool for trimming is laser trimming. Laser trimming eliminates the need for a trimming die but comes with a higher initial investment. Laser trimming time, the process's limiting factor, is too slow for high volume productions but appropriate for low volume (Economic Analysis 1999). Laser trimming is currently used in tube hydroforming parts fabrication. Cutting speeds for laser trimming varies with the thickness of the material, the curvature of the path, and the material type (Boothroyd et al 1994). Lasers can trim both steel and aluminum. There are several types of lasers used in manufacturing operations: CO_2, Nd:YAG, glass, ruby, and Excimer. For metal cutting, CO_2 and Nd:YAG lasers are most common. Advantages include high speed, accuracy, and flexibility. Disadvantages include high investment cost, material restrictions, thickness limitations, and fumes. The steps of production include manufacturing a laser trimming fixture to hold the part to be trimmed and then programming the computer-guided laser to follow the trim lines (Rinke 1989). The primary advantage of laser trimming over conventional trimming is that a trim line change can be made with ease.

3-4 Low Volume Stamping

Low volume manufacturing is more important as businesses adapt to a growing trend to produce locally and in lower volumes. Producing effectively in low volumes can mean many things. Some ideas include standardizing tool parts, using high machineability material for dies, casting dies from models, layering laminate dies, splitting progressive dies, and designing more simple parts (Nakagawa 2000). Dies used for low volume production need to be produced quickly and at low costs. Several alternate tooling technologies exist, each of which require significantly lower initial investments and suffer from greatly reduced tool lives. The use of these technologies at intermediate to high volumes requires multiple tool sets thus eliminating their cost advantage (German Tooling 1999). One material of interest is kirksite. Kirksite has been used in prototype manufacturing for years. Kirksite has a lower tensile strength than does cast iron, allowing quicker machining but earlier deterioration. Kirksite dies can last from 100,000 to 150,000 strokes before needing replacement while standard cast iron dies can last up to five million strokes (German Tooling 1999). Kirksite is advantageous because its low melting point and low shrinkage coefficient allow it to be cast directly over a negative of the die (German Tooling 1999). Most of the economic difference between kirksite and cast iron dies is from the reduction in machining and assembly necessary for kirksite. Kirksite costs $1.48/kg, and cast iron costs $.07/kg. Kirksite can be recycled after use, reducing material waste and enabling its economic competitiveness. Low volume tooling provides large economic benefits. Building a low volume Opel T-Car in India, the total tool cost amounted to $27 million versus a typical amount of $60 to $75 million for high volume dies. Additional information can be found in Luis German’s PhD thesis.

Chapter 4 Developing the Cost Models

To compare sheet hydroforming and low volume stamping, technical cost models were constructed for each process. The sheet hydroforming cost model required addressing every aspect from the start. The low volume stamping model was built into a conventional stamping model previously constructed. A toggle switch alternates cost calculations from high volume production methods to low volume methods. The differences that it entails will be discussed shortly. For each step of a process, the models address fixed costs like main equipment costs, tooling costs, maintenance costs, overhead costs, building costs, and indirect labor as well as variable costs like labor, energy cost, and material cost.

Sheet hydroforming consists of four steps: blanking, sheet hydroforming, laser trimming, and flanging. The model addresses the fixed and variable costs for each step and then adds the costs together for the completed piece cost.

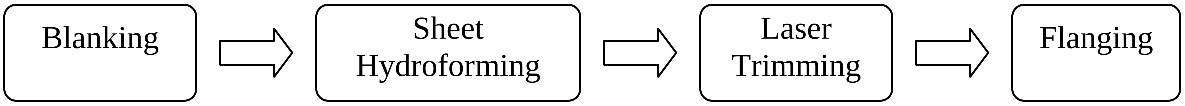


Figure 4.1: Sheet Hydroforming Fabrication Steps

4-1 Variable Costs

Generally, all the costs except equipment and tooling costs are calculated the same way among the processes. Material costs are calculated by knowing the blank size dimensions, the material type, density, and the cost per kg. Multiplying them all together and subtracting trim scrap results in the final material costs. Material input costs are only calculated for the first process, in this case, blanking. Each additional step generates more trim costs that are subtracted from the material costs. An input requiring a material selection enables the model to look up material characteristics like density and cost per kg. For this model, Table 4.1 shows the values used.

ID Number	Material Name	Density g/cc	Material Price $/kg	Scrap Price $/kg
1	Aluminum	2.70	$1.60	$1.10
2	Steel	7.90	$0.73	$0.11

Table 4.1: Material Properties Used in Sheet Hydroforming Model

Between high and low volume processes, trim scrap values remain the same as only a fraction more are created for low volume.

Energy cost is determined by machine selection. With an appropriate machine selected for a part, its accompanying energy consumption is used with machine time for a part and the cost of energy to calculate a part's energy costs. Labor costs are calculated by knowing a part's cycle time and how many workers per station are needed. Labor is non-dedicated which means that the piece cost only pays for its share. An input into the model accounts for daily work stoppages due to breaks, scheduled and unscheduled. Since sheet hydroforming is considered a low volume process, each process step requires two workers due to the lack of automation. The tooling lacks the ejector pins and robots seen in high production systems. The workers per station is an input into the model and can be changed easily. For the fixed costs, building, maintenance, and overhead are all calculated the same way. Maintenance and overhead are percentages of equipment, tooling, and building costs. As equipment, tooling, and building costs increase, maintenance and overhead costs will also increase so the assumption goes. The fixed overhead figure is 20%, and maintenance is set at 10%. The percentages are inputs into the master table and are reasonable industry values. Building costs are calculated by multiplying a general cost per m^2 (set at \$1500/m^2 in the sheet hydroforming model) by a process's space requirement. The space requirement is calculated through the press choice.

4-2 Fixed Costs

The other two contributing costs are machine costs and tooling costs. The blanking and sheet hydroforming machine costs use a lookup table to determine press selection, cost, and other pertinent characteristics. Both use part length, width, and tonnage needed for the part to select a press. Tables 4.2 and 4.3 show presses available and its characteristics.

Press Classes properties	**Class 1 1**	**Class 2 2**	**Class 3 3**	**Class 4 4**	**Class 5 5**	**Class 6 6**	
max. blank weight (kg)							
Capacity	50	100	200	400	600	1000	tons
Bed Width	1500	1800	2000	3000	4000	4500	mm
Bed Length	1200	1500	1800	2000	2500	2800	mm
Shut Height	600	600	600	600	600	600	mm
Power Rating	100	150	200	300	400	500	kW
Line Cost	$300,000	$325,000	$375,000	$1,000,000	$2,000,000	$3,000,000	without Install. and Aux.
Clean Running Rate (shear)	2500	2500	2000	2000	1500	1000	parts/h
Tool Cost (shear)	$40,000	$40,000	$40,000	$50,000	$75,000	$100,000	

Table 4.2: Blanking Press Information

Press Classes properties	**Class 1 1**	**Class 2 2**	**Class 3 3**	
Capacity	1200	3000	4000	tons
Bed Width	1200	1800	2800	mm
Bed Length	800	1200	1400	mm
Shut Height	300	300	300	mm
Power Rating	140	250	300	kW
Line Cost	$2,500,000	$4,000,000	$4,500,000	without Install. and Aux.
Min SPM	3	2	2	SPM
Max SPM	4	3	3	SPM

Table 4.3: Sheet Hydroforming Press Information

Tooling costs and machine costs can be calculated discretely or using regression analysis. Using regression analysis links important part characteristics to cost. A part's length and width are often used since a bigger piece will need a larger, more expensive die and therefore a larger, more expensive press. A part's complexity implies a more expensive die because it requires more development time, material, and labor. Regression analysis requires previous knowledge of part characteristics and tooling and machine costs. Then, independent, causal relationships are formulated.

Flanging machine costs use a regression equation. Piece weight determines press tonnage, and part dimensions determine bed width and length. A machine is used for each operation and robot fixtures are added for improved automation. Dr Roth determined the flanging machine cost equation.

$$\text{Flanging Machine Cost} = 2945.7 \cdot Tonnage^{.5} \cdot \left[\frac{bedwidth \cdot bedlength}{25.4^2}\right]^{.2588}$$

Equation 4.1: Flanging Machine Cost

Tooling costs are the most difficult prediction made in a cost model. Using regression analysis enables a user to have little process knowledge and still have the model return a reasonable answer. Experience has also shown that even experts familiar with the process often cannot estimate tool costs from part descriptions well. Cost equations remove the model's subjectivity and allows more consistent and accurate comparisons. Table 4.4 shows how the costs are calculated for the tool.

Tooling Costs	Equations
Sheet Hydroforming	$= 10^{5.237} Complexity^{.459} + .5 \cdot 10^{5.237} Complexity^{.459} \cdot (\#Tool - 1)$
Flanging	$= 10^{5.173} \#Operations^{1.124}$

Table 4.4: Tooling Cost Equations for Sheet Hydroforming Process

Laser trimming costs are accounted for through an input based on accepted industry standards. A value of $2.5 million covers the cost of the laser heads, machinery, and setup equipment.

4-3 Cycle Times

A brief explanation of cycle times concludes the explanation of the sheet hydroforming model. Blanking, sheet hydroforming, and flanging use press performance to determine cycle times. Laser trimming's cycle time depends on the part trimming length. Laser trimming is much quicker for steel than aluminum, meaning two equations are used. Baseline estimations are taken from an internal General Motors' document recommending Nd:YAG lasers. From that data, the equations in Table 4.5 were determined for trim speed using regression analysis. The input is thickness in millimeters.

Cycle Time:	Equations:
Laser Trimming	$= -10.816 \cdot \text{Ln}(\text{Al}) + 14.46$ $= -5.8774 \cdot \text{Ln}(\text{Steel}) + 11.844$

Table 4.5: Cycle Time for Laser Trimming

4-4 Low Volume Stamping

The low volume stamping description will discuss changes from the conventional stamping model. For an explanation on the stamping model, consult previous studies (German 1998). The changes include: workers/line, line rate, # tools needed, tooling cost, stamping time required, and maintenance.

For low volume tooling, much data and information from experts in the field was available. General Motors retained a die cost quote from Ogihara Corporation along with parts description for their India low volume project. The dies quoted and built are kirksite and have a die life of one hundred and fifty thousand. Analysis done on more than 80 parts determined the most accurate relationships between various piece inputs to final die costs. The die cost equation is:

$$= 10^{3.2518} \cdot (\text{Projected part area})^{.3537} \cdot \text{Complexity}^{.5423}$$

Equation 4.2: Low Volume Tool Cost

for transfer and tandem presses. At low volume, using fast and expensive progressive dies makes little sense. The projected part area accounts for cost better than separate entries for length and width. Also, complexity divided the parts into three levels of detail where a complexity of 1 implies a simple, shallow, flat, small design requiring few stamping hits, a complexity of 3 implies a deep, curvy, sharp design requiring several stamping hits, and a complexity of 2 falls in between. The stamping cost equation remained the same because the press does not change.

The number of tools required increased. High volume stamping dies last for the production of the part. Low volume dies last for 150 thousand hits and then need replacing. A cost reduction for additional dies of 50% is the researched cost savings for kirksite dies (German Tooling).

More maintenance is needed for the low volume dies, so costs are increased accordingly solely for the tooling. Kirksite dies require more maintenance to achieve its die life (German Tooling).

Line rate decreased by a half to account for the reduced automation. The percentage decrease has been verified with low volume experts at General Motors' Research and Development facility (Urbance). The press machine's output is reduced without ejector pins and other piece removal equipment causing a slower part cycle time. The press is the same for low and high volume fabrication, but a non-automated system cannot keep the pace of 2.5 seconds per part that a high volume shop maintains. Besides part placement into the press, manual labor is used to convey the parts from each station. Manual labor replaces robots and conveyor systems placing blanks and removing parts from the press. The lack of automation requires more stamping time.

Doubling the number of laborers per station increased labor costs. The stamping model interpolates labor needed based on progressive or tandem operations. Based on advice from General Motor’s low volume expert, the low volume option doubles the labor (Doshi).

Chapter 5 Sheet Hydroforming and Stamping Analysis

Finally, the results of the four case studies comparing stamping and sheet hydroforming are presented. First, the four parts being examined are briefly introduced. Then, the cost breakdowns of the four parts produced at the target volume of thirty thousand parts per year are examined. Thirdly, sensitivity analysis on production volume and cycle time is shown to see if economies of scale exist. From there, investment cost breakdown is presented. The objective of this analysis is to gain a further understanding of the economic factors between the two processes.

5-1 Part Descriptions

With input from automotive designers, four parts have been identified that can be hydroformed or stamped. These four parts, the dash panel, the rear compartment pan, the plenum, and the body side outer, are used as a case study. The part descriptions of each:

	Plenum	**Dash Panel**	**Rear Compartment Pan**	**Body Side Outer**
Part Weight (kg)	3.9	5.5	14.50	14.11
Maximum Part Length (mm)	180	560	1380	1180
Maximum Part Width (mm)	1360	1400	1450	2800
Blank Width (mm)	600	750	1600	1500
Blank Length (mm)	1450	1550	1700	3100
Blank Thickness (mm)	0.8	0.7	0.8	0.85
Trimming Length (mm)	3300	5000	6000	16000
Trimming Segments	2	3	5	3
Percent of Trim Length in Straight Sections	0.5	0.25	0.25	0.5
Trim Scrap	40%	40%	40%	40%
Material Specification	GM6093M 180 A U	GM6093M 180 A U	GM6093M 180 A U	GM6093M 180 A U
Press Technology	Tandem	Tandem	Tandem	Tandem
Complexity Level	3	3	3	3

Table 5.1: Part Descriptions

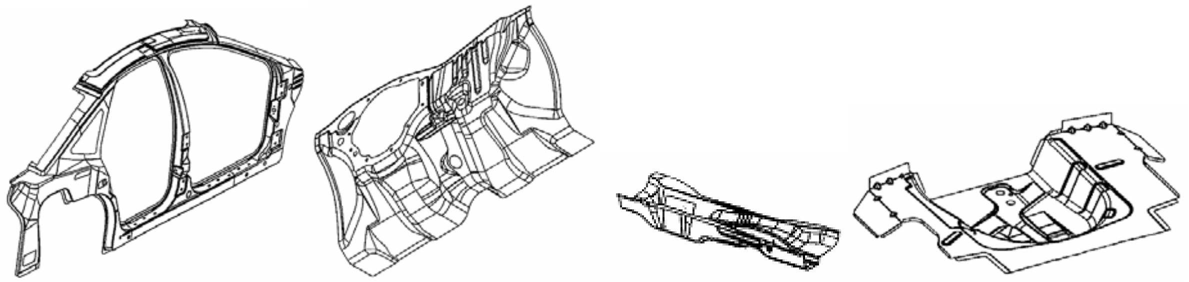
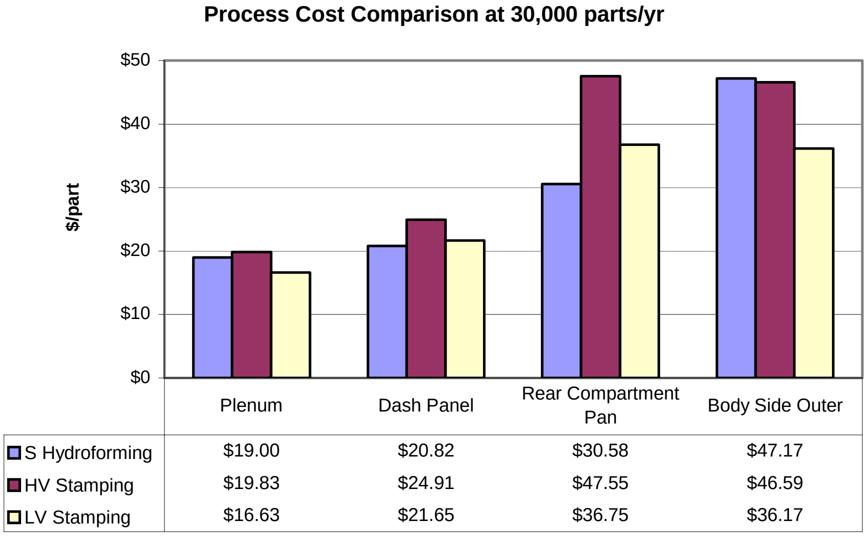


Figure 5.1: Body Side Outer, Dash Panel, Plenum, and Rear Compartment Pan (GM Internal)

5-2 Base Case Cost Comparison

Sheet hydroforming caters to low volume production and prototype production. Figure 5.2 shows the cost breakdown of the four parts by process. Sheet hydroforming is more economical for the dash panel and the rear compartment pan. Low volume stamping is the economical choice for the plenum and body side outer.



Process Cost Comparison at 30,000 parts/yr

	Plenum	Dash Panel	Rear Compartment Pan	Body Side Outer
🟦 S Hydroforming	$19.00	$20.82	$30.58	$47.17
🟥 HV Stamping	$19.83	$24.91	$47.55	$46.59
🟨 LV Stamping	$16.63	$21.65	$36.75	$36.17

Figure 5.2: Process Cost Comparison for Base Case

For the plenum and the body side outer, low volume methods have the cost advantage due to its lower equipment and tooling costs. Sheet hydroforming does have lower tooling costs, but since its cycle time is 30 seconds versus the low volume stamping cycle time of 4.5 seconds, hydroforming's equipment costs are much higher and so is the final part cost. This effect is partly offset by the lower cost of a hydroform press versus the multiple stamping presses needed. High volume stamping shows the lowest equipment costs due to its low cycle time but the highest tool costs.

Among the four parts, the two factors that show strong tendencies are the equipment cost and the tool cost. The other costs vary and are not as process dependent. On average, sheet hydroforming's average tool cost is $6.50 or 20% cheaper than the low volume stamping and 175% cheaper than the high volume stamping. High volume stamping's equipment costs are $1.68: 89% cheaper than low volume stamping and 175% cheaper than sheet hydroforming. Since high volume stamping has lower equipment costs and higher tooling costs than the other processes, high volume stamping can benefit the most from economy of scale. At thirty thousand parts, it has high dedicated costs and low non-dedicated costs. Comparatively, sheet hydroforming and low volume stamping have similar equipment costs. When low volume stamping's part cycle time is less for smaller parts, it's equipment costs are lower. Low volume stamping has much larger press investment and cannot amortorize the costs as well for slower productions. Sheet hydroforming's cycle time depends more on machine type than part size and thus has a more consistent equipment cost.

Looking at the costs for sheet hydroforming fabrication steps provides insight as to what contributes to cost. As material costs always contribute heavily to parts fabrication, it was included. Sheet hydroforming has more steps while stamping accounts for many of the operations during the stamping steps. Laser trimming cost increases with each part's trimming distance. With a trim press, trimming distance is not important and is done in conjunction with the stamping hit. Across the four parts, the sheet hydroforming step shows little variation. As stated earlier, the cycle time strongly dictates equipment costs and since the cycle time for the sheet hydroforming step is mostly affected by the press type, the cycle time varies little between the parts. The differences can be attributed to different tooling costs. Figure 5.3, which graphically compares the four parts' fabrication cost, shows that the laser trimming cost can vary widely between parts.

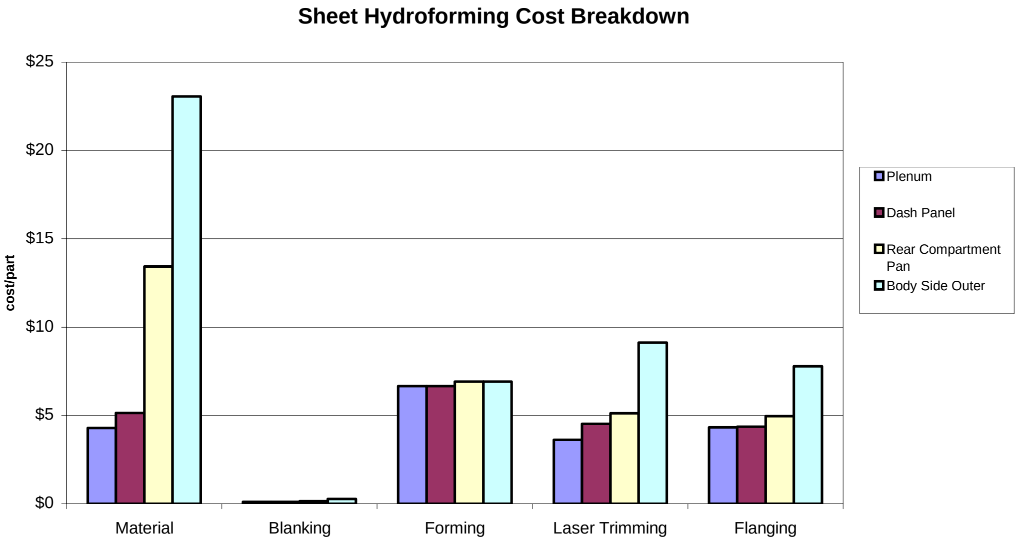


Figure 5.3: Sheet Hydroforming Cost Breakdown by Fabrication Step

The body side outer has the highest laser trimming cost. Figure 5.3 looks at the trim length's impact on the final part cost. Even with significantly reduced trim length, sheet hydroforming the body side outer is more expensive than low volume stamping. While laser trimming adds substantial cost, the process choice for a part with high trim length does not change. Flanging costs depend on the number of bending operations. Since all four parts are considered complex parts with similar number of bends, the comparative cost is minimal.

Figure 5.4: Base Case Trim Length Sensitivity Analysis

Overall, at thirty thousand parts per year, using sheet hydroforming produces a mixed result. Material costs, laser trimming costs, and flanging costs vary widely by part. This can be attributed to differing part characteristics like trim length and flanging operations needed.

5-3 Sensitivity of Part Cost

An important factor for low volume's competitiveness is die life. When a new die is required, even at reduced cost, the piece cost jumps dramatically. Figures 5.3 through 5.6 shows piece cost versus production volume. In reality, the cost jumps for low volume stamping would be less severe. Manufacturers could extend die life through extra maintenance to meet a close production volume.

The sensitivity analysis shows that process selection is not easy. Sheet hydroforming is economical for the dash panel and rear compartment pan at thirty thousand parts, but at volumes much less or more than that, conventional stamping is preferred. An advantage of choosing stamping is that, save for a small production range, one stamping press line will serve all your needs. This will provide manufacturing flexibility. Motivations behind a low investment, low volume project include testing uncharted waters. Once new markets have proven successful, companies will consider ramping up production. Not having to reinvest in press machines would simplify the process.

The production volume sensitivity analysis distinguishes process traits. High volume stamping can handle high production volumes on one tool. The part cost drops smoothly as production volume increases since the fixed costs do not fluctuate. Low volume stamping increases in part cost when additional tooling dies are needed. Since tooling costs are a significant cost contributor, the cost increases more than for sheet hydroforming. Sheet hydroforming has inexpensive dies, causing a smoother cost. Figures 5.5 to 5.8 show the part cost for sheet hydroforming, high volume stamping, and low volume stamping for various production volumes. Crossover points occur when a process becomes more economical than another. These graphs show inconsistently placed crossover points between parts. For the dash panel, a cost advantage can be gained by each of the three processes at varying production levels. For the body side outer, low volume stamping is effective until around seventy thousand parts at which high volume stamping is effective. Sheet hydroforming is not an economic consideration for the body side outer because of its long trim length. The laser trimming takes too long and slows the production rate even more. A conclusion is that using cost modeling for each part is necessary. Another is that high volume stamping should not be considered for volumes fewer than fifty thousand parts per year.

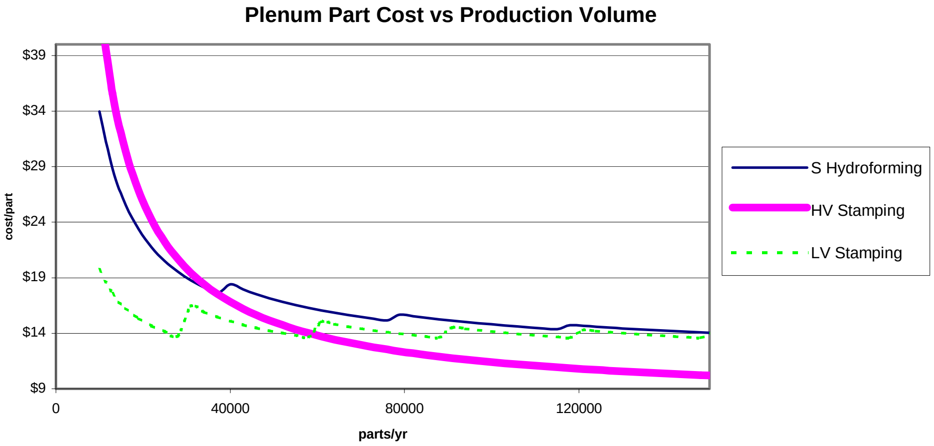


Figure 5.5: Plenum, Varying Production Volume

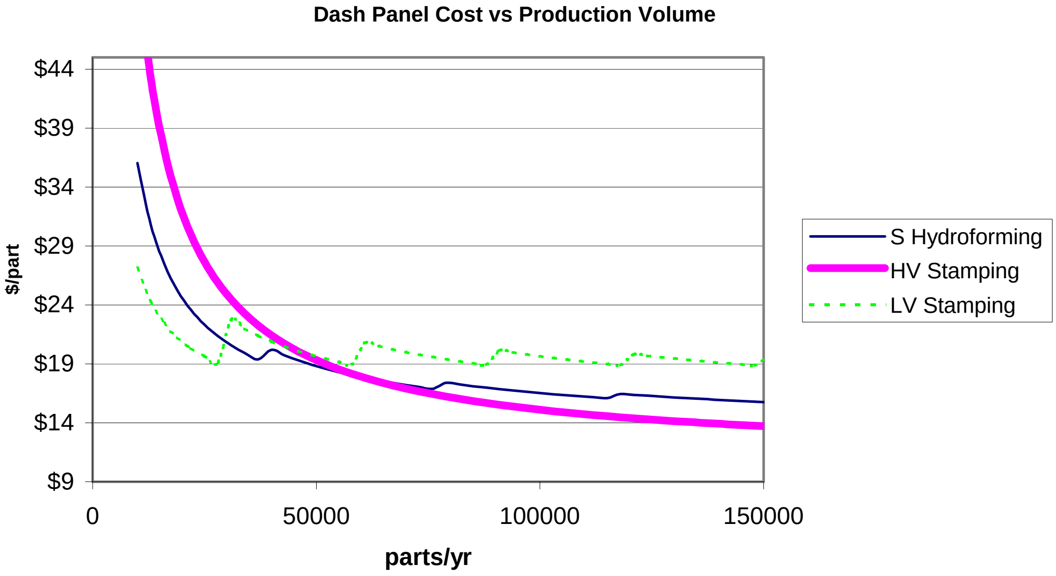


Figure 5.6: Dash Panel, Varying Production Volume

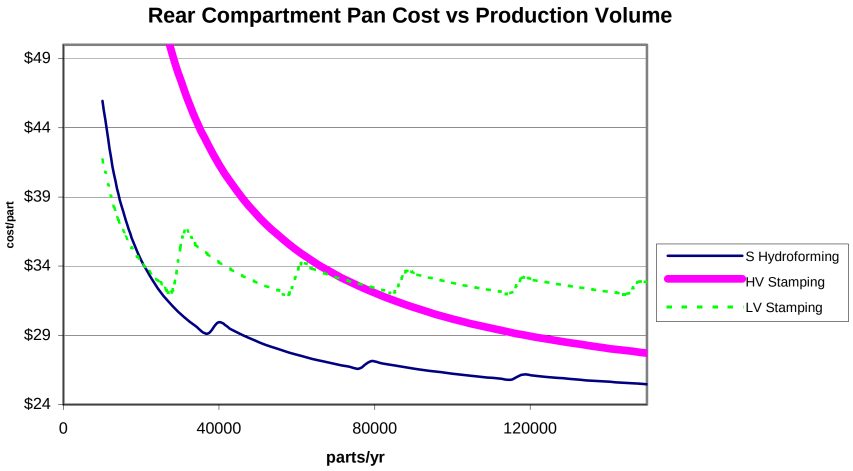


Figure 5.7: Rear Compartment Pan, Varying Production Volume

For the rear compartment pan, sheet hydroforming fabrication is dramatically less than stamping. Hydroforming has much lower die cost and equipment cost but similar operating costs. The result is an economic advantage from twenty thousand parts per year and more. In comparison, the other three parts do not have such a tooling cost difference between processes.

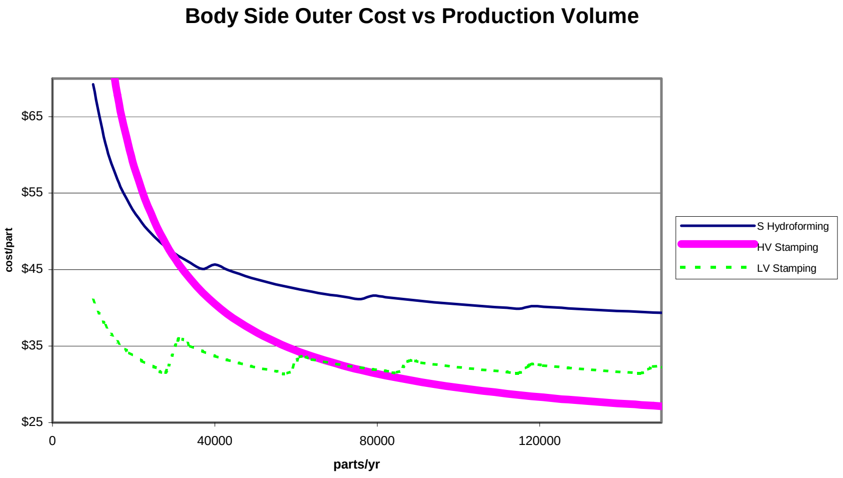


Figure 5.8: Body Side Outer, Varying Production Volume

The predictive capabilities of cost modeling in regards to cycle time should always be questioned with regards to its accuracy. Sensitivity analysis on cycle time brings to light the amount of robustness part cost has to cycle time. Figure 5.9 shows the part cost variation by increasing and decreasing main machine cycle times by 10% from its predicted amount. The average piece cost difference between the slow and fast cycle time is 12% for a 20% cycle time swing across all production volumes. Cycle time variation equally affects equipment costs, labor costs, and overhead costs- all non-dedicated equipment. Dedicated pieces like tooling are not sensitive to cycle time changes. Calculating cycle times is an inexact science, and given the method of determining cycle time, deviations from the predicted time is probable. With further data, further investigation and regression analysis should be conducted to try to connect part characteristics to cycle time. Figure 5.9 shows that a cycle time swing of 20%, or 6 seconds, changes the process selection. With a cycle time reduction, sheet hydroforming is economically advantageous from thirty thousand parts out to one hundred thousand parts. An increase in cycle time removes sheet hydroforming from consideration. Any time deviation in sheet hydroforming strongly affects the process selection.

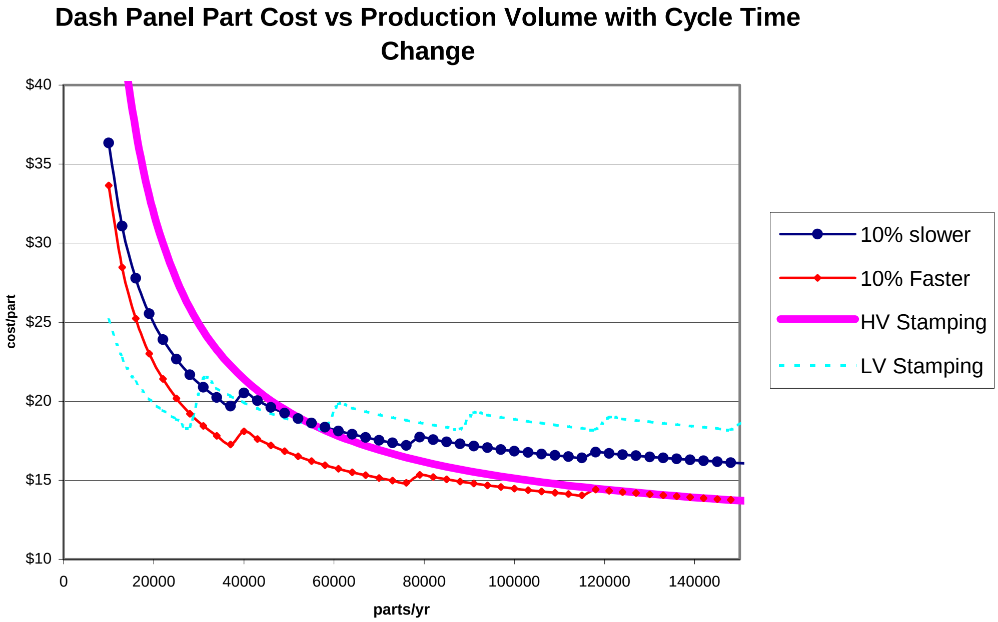


Figure 5.9: Dash Panel Sensitivity Analysis, Varying Cycle Time ± 10%

5-4 Sensitivity of Investment

Another area of concern to manufacturers is investment. In certain circumstances, companies are much more sensitive to initial investment costs than lowest piece cost. For accounting purposes, if a machine is considered non-dedicated, the allocated press cost is the cost of the press multiplied by the percentage use time. Tooling is part specific and is considered dedicated. The total tooling cost is attributed towards investment. The production volume of interest is thirty thousand. At that production volume, the dash panel investment for the three processes can be seen in Figure 5.10. As the sensitivity analysis looks similar for the dash panel, plenum, and body side outer, only the dash panel is shown. The investment cost includes tooling and machine cost. Sensitivity analysis shows a clear choice at high volumes and indicates that high volume stamping should be avoided at volumes below sixty thousand.

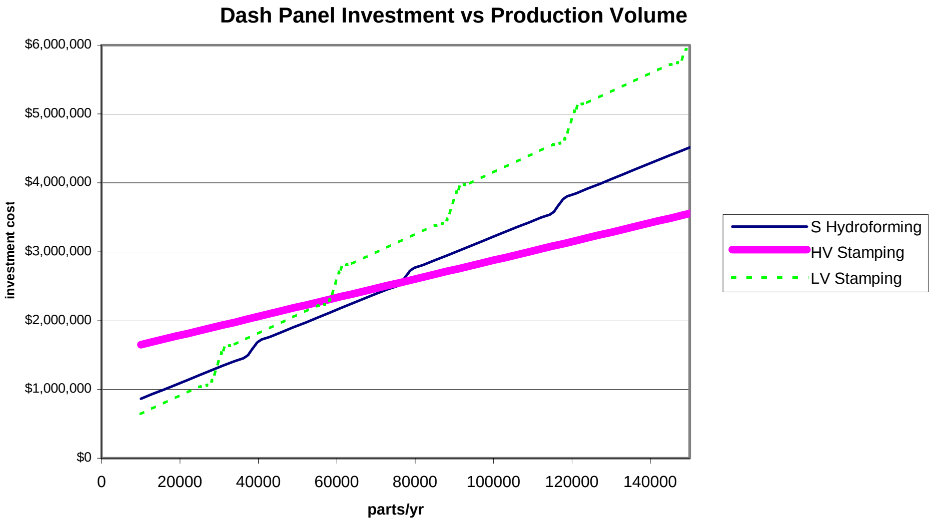


Figure 5.10: Dash Panel Investment Cost

The dash panel shows little investment advantage for sheet hydroforming because of stamping's low cycle time. Sheet hydroforming has a slight economic advantage over low and high volume stamping from thirty thousand parts per year to eighty thousand parts per year. The reasons are the same as for part costs: the low and high volume stamping die costs are considerably higher than sheet hydroforming's, but stamping can produce more rapidly. At high production volumes, high volume stamping is an economical choice because tooling costs per part are less and the production rate keeps the allocated equipment costs low. At low volumes, low equipment costs drive low volume stamping's cost down. Investing in low volume stamping is not advantageous over sheet hydroforming once the process requires multiple dies.

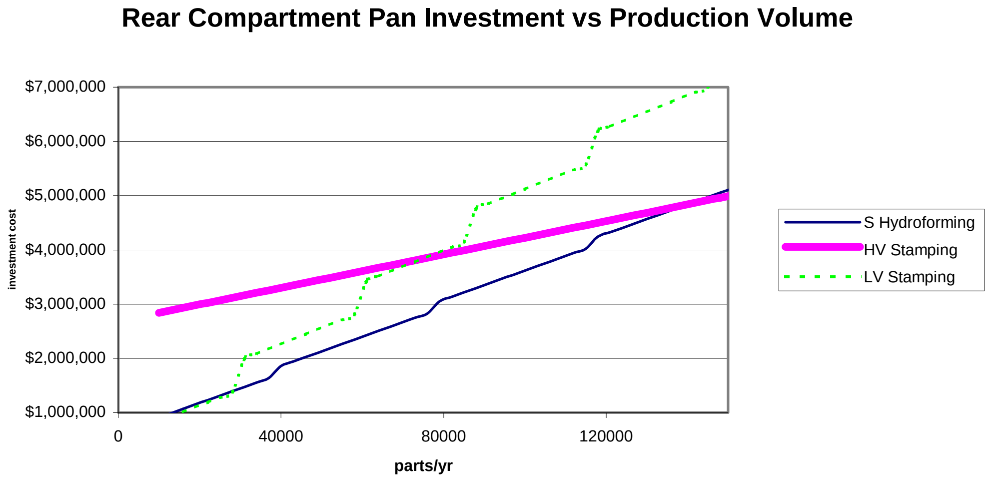


Figure 5.11: Rear Compartment Pan Investment Cost

Figure 5.11 shows the rear compartment pan investment cost against varying production volume. In this case, the sheet hydroforming tools, at $640,000, are considerably cheaper than high or low volume's tool cost which cost $2,700,000 and $1,070,000 respectively. The die costs are for thirty thousand parts per year. The low tool cost enables sheet hydroforming to be a competitive process from thirty thousand parts per year to one hundred forty thousand parts per year.

The tooling investment costs were similar for the four case studies and so only Figure 5.12 is presented. Press investment cost increases linearly with production volume while tool costs step with die life. This is in accord with allocating non-dedicated equipment and dedicated tooling. Low volume stamping dies are more expensive than sheet hydroforming and have the shorter life of one hundred fifty thousand strokes. Because of this, low volume stampings have a sharper increase than the other two processes. Looking at low investment processes is beneficial in making a process decision, but other factors need to be included. The aim of achieving low investment can be misguided if not taken in context with operating costs.

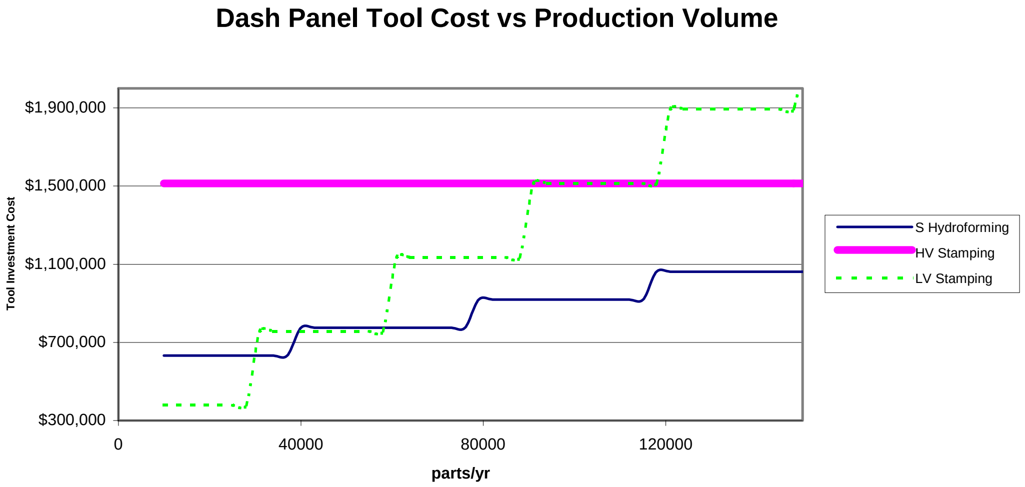


Figure 5.12: Dash Panel Tooling Investment Cost

Through the four case studies, several general conclusions can be reached. First, for volumes under sixty thousand, high volume stamping is not economically advantageous. Its tool costs are too high to be competitive. Second, for volumes under twenty thousand, hydromechanical deep-drawing is not economically advantageous over low volume stamping. Sheet hydroforming and low volume stamping have similar tool costs at low volumes, but sheet hydroforming has higher equipment costs due to slower production times. Low volume stamping is a better economic process choice over sheet hydroforming until multiple stamping dies are needed for higher volumes. And, third, laser trimming loses cost effectiveness with high trim lengths although not significantly affecting process selection.

Chapter 6 Manufacturing Systems Analysis Background

Manufacturing Systems Analysis looks at the interactions of machines. In a production line with various machines, those machines depend on the other machines up and downstream. When a machine fails, it no longer processes parts, and, after time, downstream machines no longer have parts to work on. As these machines sit idly being starved by the upstream machine, the throughput of the production line drops. Conversely, a failed machine downstream can block upstream machines. If a machine goes down, the upstream machines continue producing parts until no place exists to put those parts. Then, they are blocked from production and become idle until the machine is repaired. Again, the production rate drops. A way to compensate for unreliable machines is through storage buffers, but this comes with a price. Having work in progress requires space and ties up working capital. An optimal solution to balancing buffer sizes and determining expected throughput is solved through manufacturing systems analysis.

This chapter provides the background to understand where the transfer line models come from in the following chapters. The first topic is a description of a continuous two-machine transfer line followed by the solution to find its production volume and average buffer level. Then, a description of a continuous processing model follows and then, finally a multiple-part-type tandem systems.

6-1 Two Machine Continuous Transfer Line

A simple continuous transfer line, depicted in Figure 6.1, is a continuous time, mixed state Markov process.

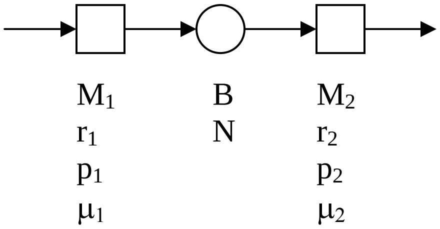


Figure 6.1: Three Parameter Continuous Model

Where

p_i = the probability that machine *i* will fail in the next time unit given that it is currently up and not blocked or starved by another machine, geometrically distributed

r_i = the probability that machine *i* will be repaired in the next time unit given that it is currently down, geometrically distributed

N = the capacity of the buffer

μ_i = the average rate of production by stage *i* when it is operational, not starved or blocked, exponentially distributed (Burman 1995).

The solution of a continuous transfer line begins with the form of

$f(x,\alpha_1,\alpha_2) = Ce^{\lambda x}Y_1^{\alpha_1}Y_2^{\alpha_2}$, where α represents the machine state. C, λ, Y_1, and Y_2 will be determined. The transfer line has achieved steady state if the equations

$$\sum_{i=1}^{2} p_i Y_i - r_i = 0$$

$$-\mu_1\lambda = (p_1Y_1 - r_1)\frac{1+Y_1}{Y_1}$$

$$\mu_2\lambda = (p_2Y_2 - r_2)\frac{1+Y_2}{Y_2}$$

Equation 6.1: Steady State Equations

are satisfied. To clarify, $p\partial t$ describes a machine's failure rate, so that p is failures per unit time. In a similar fashion, $r\partial t$ describes a machine's repair rate. The processing rate is μ. By factoring and substituting, the equations reduce to a quadratic equation:

$$-(\mu_2-\mu_1)\,p_1Y_1^2+\left[(\mu_2-\mu_1)(r_1+r_2)-(\mu_2p_1+\mu_1p_2)\right]Y_1+\mu_2(r_1+r_2)=0$$

Now, the special case where $\mu_1 = \mu_2$ will be examined. The quadratic equation reduces to a linear equation where

$$Y_2=Y_1=\frac{r_1+r_2}{p_1+p_2}$$
$$\lambda=\frac{1}{\mu}(r_1p_2-r_2p_1)\left(\frac{1}{p_1+p_2}+\frac{1}{r_1+r_2}\right)$$

Equation 6.2: Linear Equation for $\mu_1 = \mu_2$

The boundary conditions yield

$$\mathbf{p}(0,0,1)=C\frac{\mu}{r_1p_2}(r_1+r_2)$$
$$\mathbf{p}(0,1,1)=C\frac{\mu}{p_2}\frac{r_1+r_2}{p_1+p_2}$$
$$\mathbf{p}(N,1,0)=C\frac{\mu}{r_2p_1}e^{N\lambda}(r_1+r_2)$$
$$\mathbf{p}(N,1,1)=C\frac{\mu}{p_1}e^{N\lambda}\frac{r_1+r_2}{p_1+p_2}$$

Equation 6.3: State Probabilities

where C is found by the following normalization:

$$\sum_{\alpha_1=0}^{1}\sum_{\alpha_2=0}^{1}\left[\int_0^N f(x,\alpha_1,\alpha_2)dx+\mathbf{p}(0,\alpha_1,\alpha_2)+\mathbf{p}(N,\alpha_1,\alpha_2)\right]=1$$

Equation 6.4: Normalization

Then, the production rate and average inventory for $\lambda \neq 0$ is

$$P = \mu_1 e_1 (1 - p_b)$$
$$\bar{x} = C\left(\frac{1+Y}{\lambda}\right)^2 \left[e^{\lambda N}(\lambda N - 1) + 1\right] + N\left(\mathbf{p}(N,1,0) + \mathbf{p}(N,1,1)\right)$$

where p_b is the probability of the machine being blocked. It is found from the equation

$$p_b = \mathbf{p}(N,1,0) + \left(1 - \frac{\mu_2}{\mu_1}\right)\mathbf{p}(N,1,1)$$

Equation 6.5: Blocked Probability

All the previous equations and a more thorough treatment of the subject for all possible cases can be found in Dr Gershwin's Manufacturing Systems Engineering.

6-2 Multiple Machine Transfer Lines

In situations where an asynchronous, unreliable transfer line has multiple machines, a method for solving for production rate and average inventories is through decomposition. Decomposition breaks down a line into multiple two-machine continuous lines by denoting an upstream machine and a downstream machine. All two machine lines are evaluated for production rate, and the repair rate, failure rate, and processing speed of these upstream and downstream machines are adjusted to represent the aggregate behavior.

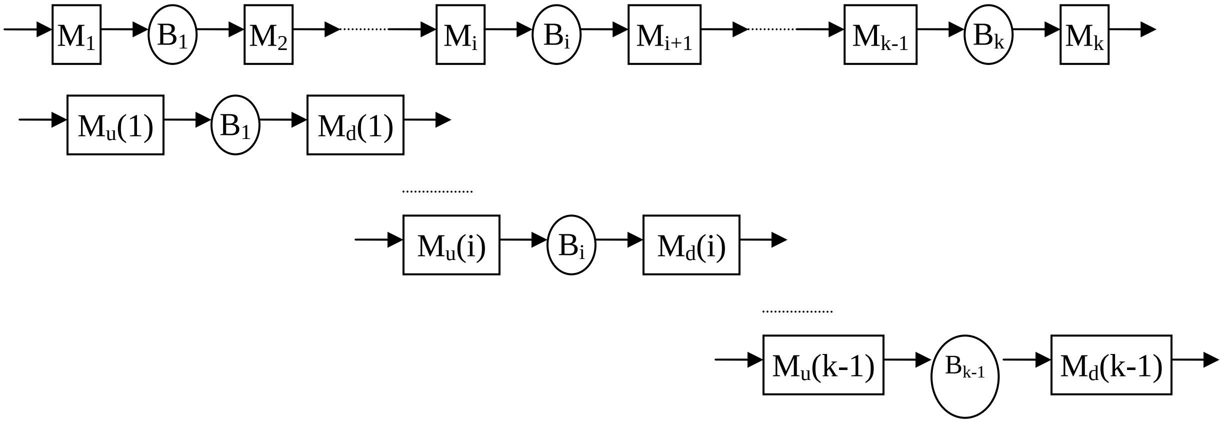


Figure 6.2: Decomposition Method for Solving Long Transfer Lines

Different algorithms have been developed using decomposition. Decomposition of long, continuous transfer lines is accomplished in this thesis by following Mitchell Burman's Accelerated Dallery-David-Xie algorithm developed in his MIT thesis. A complete explanation and treatment of the derivation can be found in New Results in Flow Line Analysis by Mitchell Burman. His algorithm improves the Dallery-David-Xie decomposition by improving the calculating speed by up to ten times and improving the reliability of convergence to 100%. To summarize his algorithm:

First, initialize the parameters of each two-stage line with a guess:

$$\begin{aligned}
&p_u(i) = p_i \\
&r_u(i) = r_i \\
&\mu_u(i) = \mu_i \\
&p_d(i) = p_{i+1} \\
&r_d(i) = r_{i+1} \\
&\mu_d(i) = \mu_{i+1} \qquad \text{for } i = 1,\ldots,k-1
\end{aligned}$$

Equation 6.6: Initialization

Second, perform steps 1 and 2 until $\left\|P(i) - P(i-1)\right\| < \delta$ for $i = 1,\ldots,k-1$ for some specified δ.

Step 1: Let *i* range over values from 2 to k-1. Evaluate the two machine continuous model L(*i*-1) with the most recent values of r_d(i-1), p_d(i-1), μ_d(i-1), r_u(i-1), p_u(i-1), and μ_u(i-1). Then substitute these parameters and the resulting P(i-1) into the following equations in the given order.

$$
\begin{aligned}
K_1 &= p_i\left(\frac{\mathbf{p}_{i-1}(0,1,1)}{P(i-1)}\left(\frac{\mu_u(i-1)}{\mu_d(i-1)}-1\right)\right)+\left(\frac{\mathbf{p}_{i-1}(0,0,1)}{P(i-1)}\right)r_u(i-1)\\
K_2 &= \left(r_u(i-1)-r_i\right)\left(\frac{\mathbf{p}_{i-1}(0,0,1)}{P(i-1)}\right)\\
K_3 &= \frac{1}{\dfrac{1}{P(i-1)}+\dfrac{1}{e_i\mu_i}-\dfrac{1}{e_d(i-1)\mu_d(i-1)}}\\
p_u(i) &= \frac{p_iK_2K_3+r_ip_i+r_iK_1K_3}{r_i+K_2K_3-K_1K_3}\\
r_u(i) &= \frac{p_iK_2K_3+r_ip_i+r_iK_1K_3}{p_i+K_1K_3-K_2K_3}\\
\mu_u(i) &= \frac{K_3\left(r_i+p_i\right)}{r_i+K_2K_3-K_1K_3}
\end{aligned}
$$

Equation 6.7: Step 1 for ADDX

Step 2: Let *i* range over values from k-2 to 1. Evaluate the two machine continuous model L(*i*+1) with the most recent values of r_d(i+1), p_d(i+1), μ_d(i+1), r_u(i+1), p_u(i+1), and μ_u(i+1). Then substitute these parameters and the resulting P(i+1) into the following equations in the given order.

$$
\begin{aligned}
K_4 &= p_{i+1}\left(\frac{\mathbf{p}_{i+1}(N,1,1)}{P(i+1)}\left(\frac{\mu_d(i+1)}{\mu_u(i+1)}-1\right)\right)+\left(\frac{\mathbf{p}_{i+1}(N,1,0)}{P(i+1)}\right)r_d(i+1)\\
K_5 &= \left(r_d(i+1)-r_{i+1}\right)\left(\frac{\mathbf{p}_{i+1}(N,1,0)}{P(i+1)}\right)\\
K_6 &= \frac{1}{\dfrac{1}{P(i+1)}+\dfrac{1}{e_{i+1}\mu_{i+1}}-\dfrac{1}{e_u(i+1)\mu_u(i+1)}}\\
p_d(i) &= \frac{p_{i+1}K_5K_6+r_{i+1}p_{i+1}+r_{i+1}K_4K_6}{r_{i+1}+K_5K_6-K_4K_6}\\
r_d(i) &= \frac{p_{i+1}K_5K_6+r_{i+1}p_{i+1}+r_{i+1}K_4K_6}{p_{i+1}+K_4K_6-K_5K_6}\\
\mu_d(i) &= \frac{K_6\left(r_{i+1}+p_{i+1}\right)}{r_{i+1}+K_5K_6-K_4K_6}
\end{aligned}
$$

Equation 6.8: Step 2 for ADDX

6-3 Multiple-part-type Tandem Systems

A multiple-part-type tandem system describes the scenario where a machine or multiple machines make different parts. An extension of this is the scenario where a non-dedicated machine outproduces another machine. Making the simplifying assumption of steady state operations allows the model to be broken into multiple tandem systems (Gershwin 1994). Figure 6.3 illustrates this situation. Another simplifying assumption being made is that the multiple tandem systems do not interact. The tandem lines do not incorporate any interactions between the lines whereas a broader look at an entire factory's production would address this. Addressing tandem line interactions requires taking the technical cost model from a part-based model into a production model with decisions beyond the scope of the model. Some of those decisions include assessing demand of parts, scheduling parts, and queuing parts fabrication. This decomposition into multiple machines is a good way to model non-dedicated machinery because it allows machine speeds to be altered.

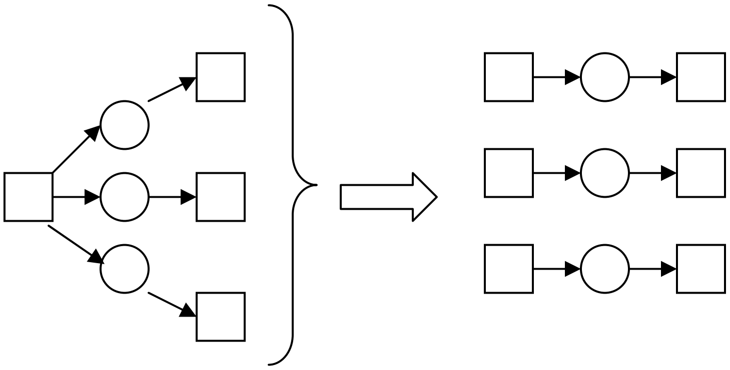


Figure 6.3: Multiple-part-type Tandem Systems

Chapter 7 Theoretical Look at Manufacturing Systems Analysis

Looking at manufacturing systems analysis from a theoretical perspective will provide a better feel for how a machine system interacts. In technical cost models, down time has generally been accounted for with a set of simple inputs, from which annual available uptime and downtime can be computed directly. To date, this approach has not accounted for the frequency or duration of downtime. Answering whether and where this is important is the purpose of this chapter.

7-1 Machine Characteristics

Throughout the chapter, a base case is used. The repair rates, failure rates, and processing rates are taken from stamping and blanking data (Table 7.1). From the repair and failure rates, the efficiency for blanking is 66%, and the efficiency for stamping is 55%. The machines presented in Section 7.2 have the process characteristics given in Table 7.1 unless otherwise noted.

Machine	MTTR (min)	MTTF (min)	Speed (parts/min)
Blanking	39	74	13.52
Stamping	10	12	5.65

Table 7.1: General Inputs For MSA

7-2 Two Machine System Interactions

Figure 7.1 shows an increasing throughput for different repair rates and quickly shows why machine interactions deserve study. The line on this figure represents the throughput of a pair of machines, both of which can operate at the same rate and which are up and able to produce the same number of hours per year. Nonetheless, even with these important quantities the same, the frequency and duration of individual downtimes can change net throughput by as much as 11%.

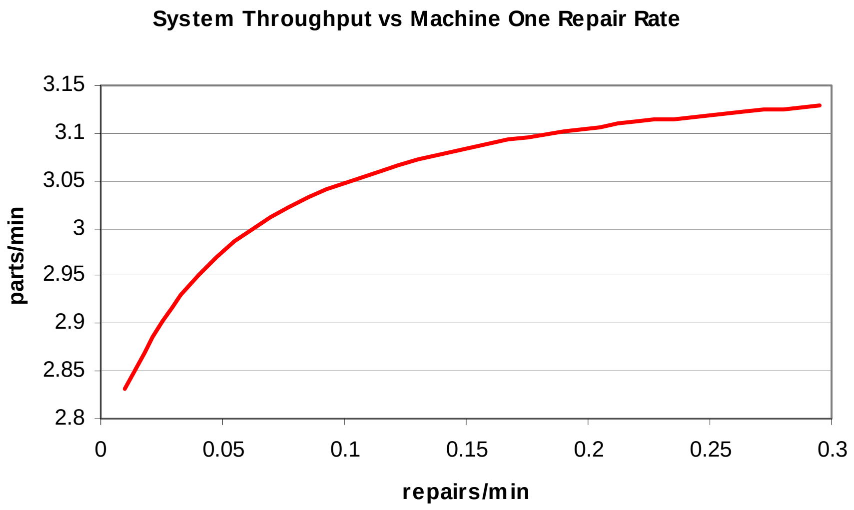


Figure 7.1: Throughput vs Repair Rate while Holding Efficiency Constant

Figure 7.2 also shows how the throughput of a two machine line is affected by the first machine's repair rate with varying buffer sizes. The different lines represent different buffer sizes between the two machines. The line on Figure 7.2 labeled "Max P" is the production rate for an isolated machine system. This is a theoretical production rate that occurs when the downtimes of machines do not effect each other. This can occur in an infinite buffer system which isolates each machine from others. To date, this is what technical cost models use as the systems throughput.

In Figure 7.2, the efficiency and processing rates of each machine is kept constant. In other words, machine one, even with different repair rates, still operates the same amount of time. The different throughputs are all products of machines working the same amount of time. Since machine efficiency is kept constant, as repair rate increases, failure rate also increases at a rate of $\frac{r-er}{e}$, where r is repair rate and e is efficiency. To maintain constant efficiency, as repair rate increases, the machine experiences more frequent but shorter downtimes. Figure 7.2 shows that machine systems are more effective with more frequent but shorter downtimes, resulting in more throughput.

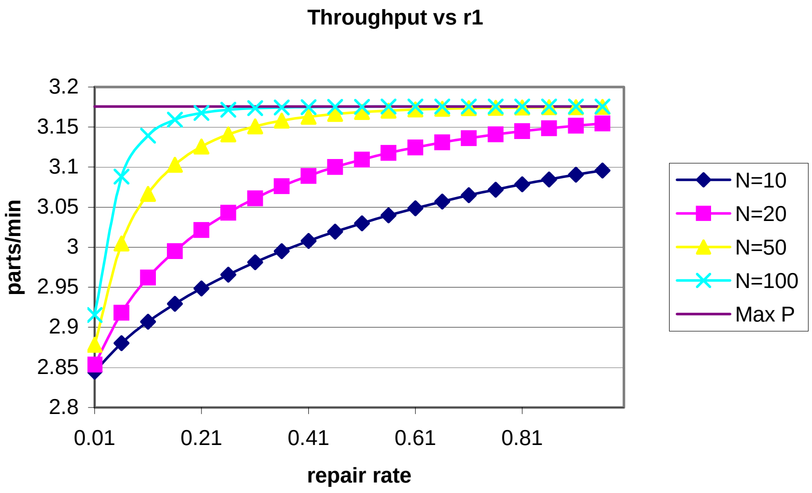


Figure 7.2: Throughput vs Repair Rate

Having some general guidance for determining whether a system varies considerably from its max output without having to run a complete model is valuable. Unfortunately, manufacturing systems engineering is complex. Each variable plays an important role in affecting machine interactions. Figure 7.2 shows how buffer size greatly impacts deviation from the max output. So do the repair and failure rates for each machine. Once a production graph is produced, the effect of altering a single variable can be predicted rather easily, but without analysis, looking at process variables leads to little intuition. Using the same values as the previous graph save for a narrower range of repair rates, Figure 7.3 is generated. Using higher buffer sizes, a similar graph appearance results. A way to insulate from varying from the max theoretical output is to design a system with a large buffer. The larger the buffer, the more insulated each machine is from the other, and the system production approaches that of the slower isolated machine's production rate.

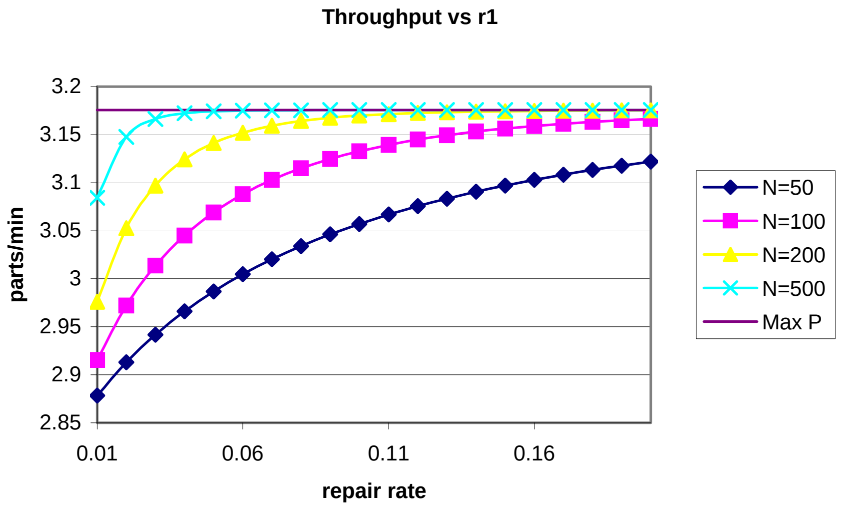


Figure 7.3: Throughput vs Slow Repair Rate

After some experimenting, a good rule of thumb to determine whether a machine system varies from its theoretical output is based on the ratio of one machine's isolated throughput per time to the other machine's isolated throughput per time. The closer this ratio is to one, the greater the error. Figure 7.4 plots the throughput of the system versus the ratio of machines' throughput. To increase $\frac{e_1\mu_1}{e_2\mu_2}$, μ_1 is increased, and the other variables are held constant. The theoretical throughput, marked as Max P, assumes an infinite buffer. It represents a two machine production rate where the throughput is the minimum throughput of either machine. Before $\frac{e_1\mu_1}{e_2\mu_2} = 1$ on the x-axis, the slope represents the increasing machine 1 processing rate. After $\frac{e_1\mu_1}{e_2\mu_2} = 1$, the theoretical throughput levels off, implying that the second machine limits the system.

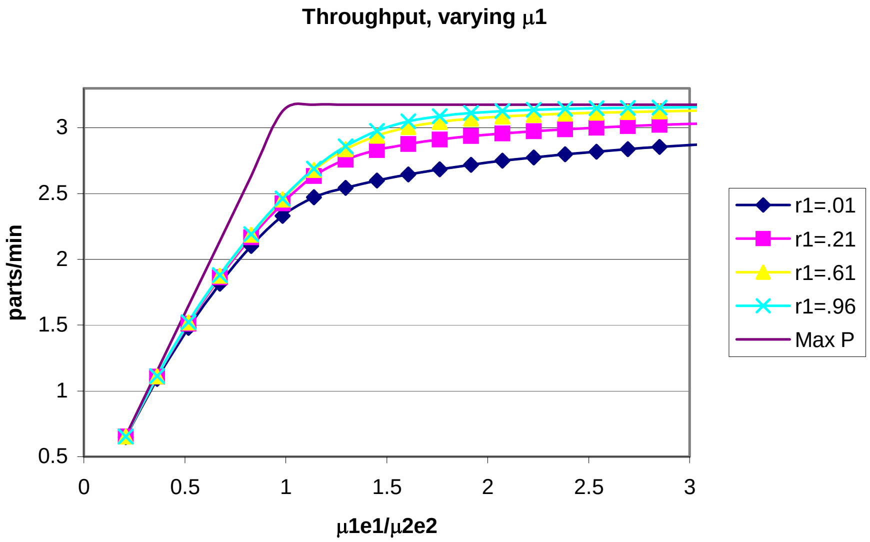


Figure 7.4: Throughput with varying μ1

The max throughput occurs where the least deviation from the theoretical throughput occurs- when the first machine far outproduces the second. With a much faster first machine, lag time and downtime are quickly made up to keep the slower machine constantly operational. As the slope levels out though, little is gained by increasing the faster machine's speed even more. A common desire is to make machines faster. Figure 7.4 shows that, especially for a ratio over 1.5, a better way to raise throughput is by improving repair rate. Figure 7.5 interprets the results better by showing the difference between the infinite buffer case against systems with 20 as a buffer size. The greatest difference occurs at $\frac{e_1\mu_1}{e_2\mu_2} = 1$.

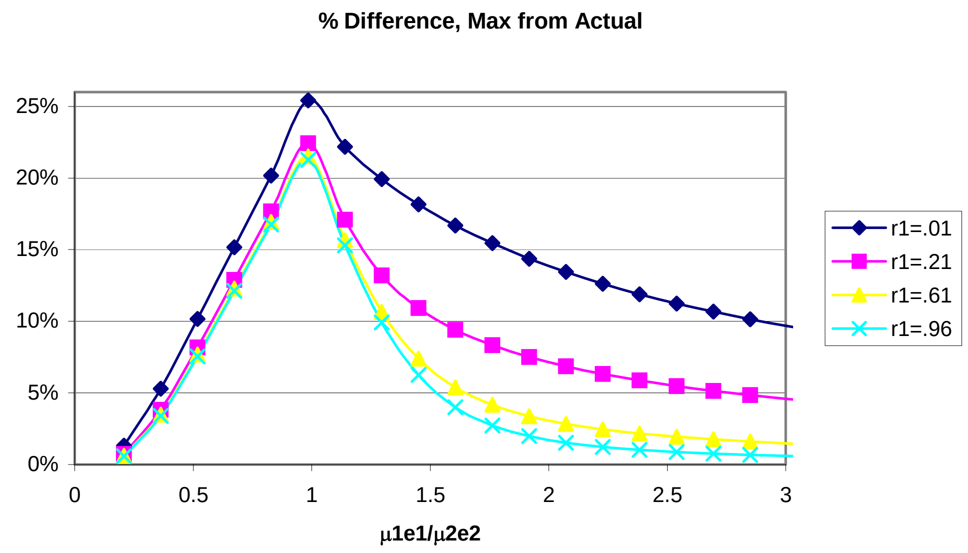


Figure 7.5: % Difference

At different buffer levels, the percentage difference changes. Graphing throughput versus $\frac{e_1\mu_1}{e_2\mu_2}$ with multiple buffer sizes, Figure 7.6 shows the effect of buffers. Adjusting the buffer size, the deviation in results adjusts inversely. A smaller buffer size yields a higher difference from an infinite buffer system's results, and it also reduces the repair rate's effect on the system. Conversely, a larger buffer system has a lower difference from a smaller buffer system's results and has a much smaller region over which the difference occurs. With a large buffer system, repair rate improvements have more effect. Figure 7.6 demonstrates that a good way to lessen the deviation that occurs at $\frac{e_1\mu_1}{e_2\mu_2} = 1$ is to increase buffer size. When one machine outproduces another, increasing buffer size does little to improve throughput.

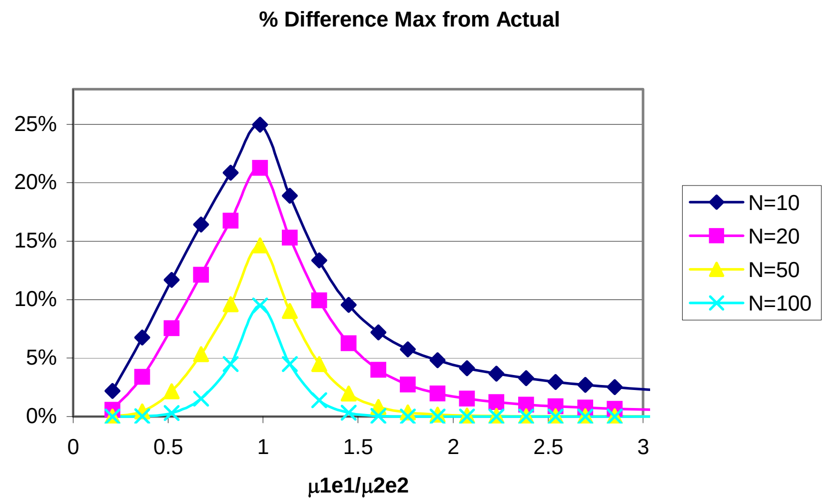


Figure 7.6: % Difference

Another avenue for sensitivity analysis is adjusting repair rate of the two machines in relation to each other. Figure 7.7 shows the percentage difference in throughput from an infinite buffer system and machine systems with varying repair rates. As a variation of previous figures, machine one has an increased efficiency of 95%, and machine two has an increased efficiency of 85%. The figure shows that faster repair rates only improve throughput once a machine greatly outproduces the other.

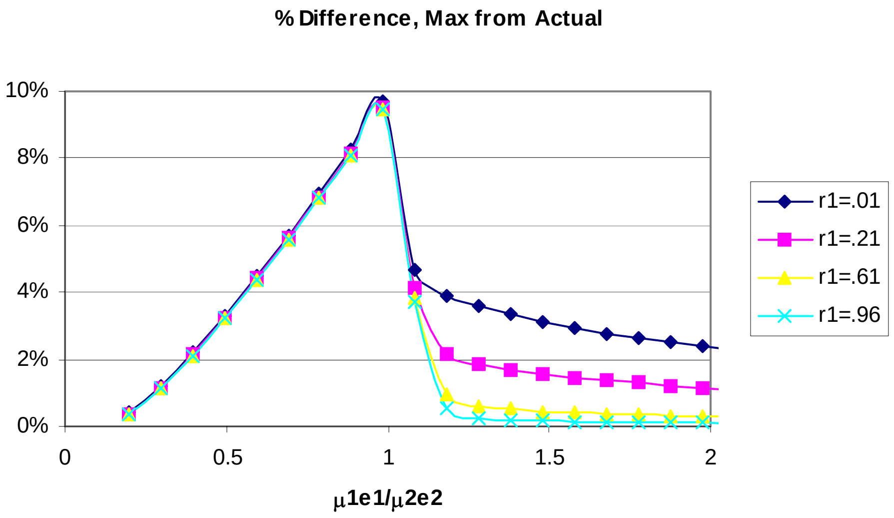


Figure 7.7: % Difference

Figure 7.8 shows how the average buffer inventory between two machines changes when the operating speeds between the two machines change. The figure reinforces the developed ideas about machine interactions. When the first machine can consistently outproduce the second one, the average inventory nears its buffer capacity. Looking at Figure 7.6 shows the throughput of the system with the same variables. Having a high average inventory is not good, but the large buffer size corresponds with an increase in throughput. For a steady state system at $\frac{e_1\mu_1}{e_2\mu_2} = 1$, the average inventory is half the buffer size. As the average inventory levels out as machine one outproduces machine two, the return on increased buffers and increased repair rates decreases. Establishing buffer size is case specific and depends on variables like inventory cost, machine cost, and throughput profit. In scenarios where inventory is cheap but machines are expensive like in stamping, having large buffers turns out to be most profitable. In each case, though, an optimal buffer size can be determined.

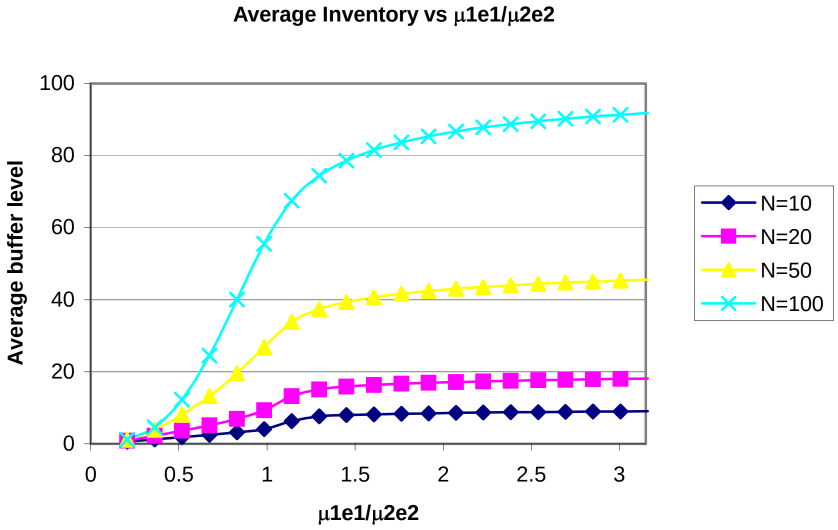


Figure 7.8: Average inventory vs machine speed ratio

7-3 Multiple Machine System Interactions

Up to this point, the concern has solely been with the interactions between two machines. A look at multiple machine systems builds on the lessons learned from that investigation. For simplicity, the following analysis looks at homogeneous production lines where all machine characteristics are identical. The performance characteristics used for each machine in Section 7-3 is similar to the blanking machine in Table 7.1 except a slower machine speed of 5 parts per min is used. Much higher repair rates are needed to approach the maximum throughput. Similar to the two machine system, the throughput varies with repair rate as the ten machine line in Figure 7.9 shows.

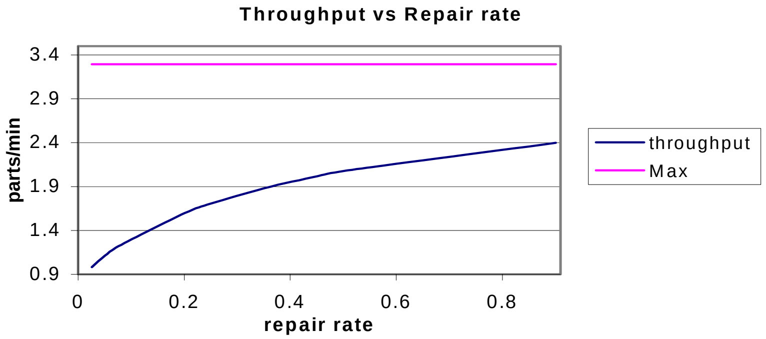


Figure 7.9: Multiple Machine Throughput vs Repair Rate, N=10

Another interesting aspect of multiple machine lines is how the line length affects buffer inventory. As a machine line grows longer, the average inventory per buffer increases, especially at the front of the production line (see Figure 7.10). As each machine fails and is repaired, that downtime affects more machines. The further upstream the machine is in a production line, the more often downstream blockages and starvations cause its inventory to increase. The logic then follows and Figure 7.11 then supports that more machines in a system will cause the system throughput to lessen. The disparity between the theoretical output and the output with machine interactions increases.

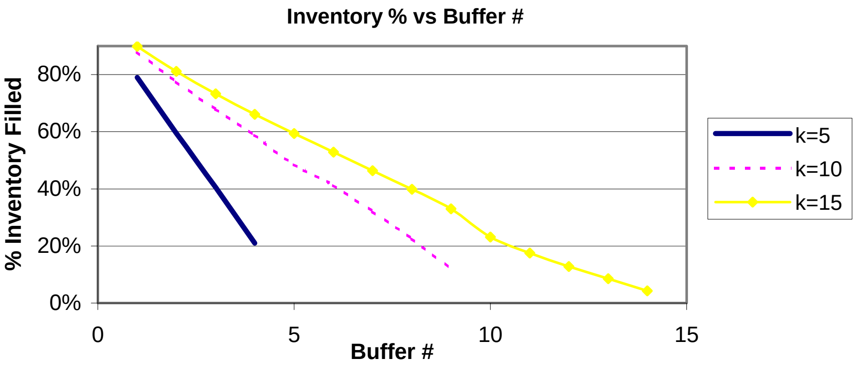


Figure 7.10: Inventory % vs Buffer #, N=10

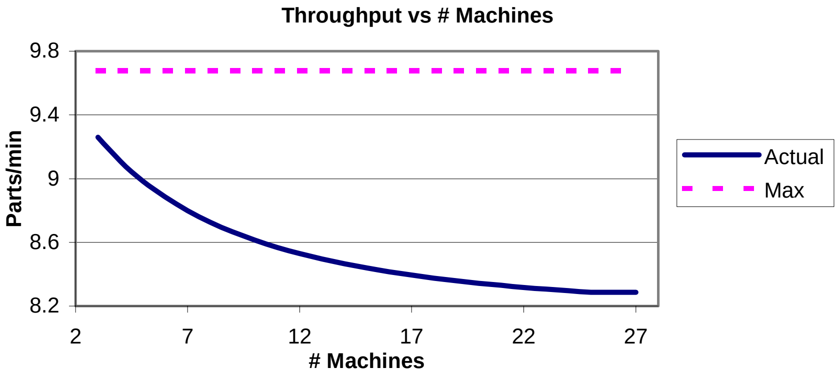


Figure 7.11: Throughput vs # Machines in Production Line, N=10

To conclude the thoughts from this chapter: a simple downtime input for a technical cost model is inadequate especially when dealing with similarly paced machines, processes that require many machines, and in processes where machines have relatively low repair rates with concern to their production and failure rates.

Chapter 8   Incorporating MSA into Cost Models

8-1 Altering Production Rates

Incorporating the continuous transfer line models into technical cost modeling required a few modifications: changed machine speed to account for complications from machine interactions, introduced a toggle to turn on or off the effects of machine interactions, added the expense of a buffer, and altered the transfer line's machine processing speeds. In factory production, few machines will be dedicated. One particular case when machines will be dedicated is when two machines operate at the same speed. They cannot support multiple machines. More often, though, faster machines will support multiple slow machines. Discussed in the previous chapter, a steady state transfer line models this occurrence by dividing into multiple tandem lines. To model this, the non-dedicated equipment's speed was changed to the supported equipment's operating rate. A quick example using the stamping process will better illustrate the concept. Blanking will support several stamping machines. A flanging machine can finish parts from multiple stamping machines. Blanking can operate at 3000 parts/hr while a stamping machine can achieve 600 parts/hr or higher. The transfer line adjusts the processing speeds and calculates a throughput with a processing rate of 600 parts/hr for both the blanking and stamping machine. The idea is that if blanking is fully utilized, it can support five stamping machines and will, over the long term, be able to produce 600 parts/hr for each stamping machine.

8-2 Accounting

A problem arose when trying to account for the reduced throughput due to machine interactions. Cost modeling calculates the amount of time each machine uses and bills it accordingly. When the throughput does not match the machine speeds, the implication is that the machines are used for a longer time than anticipated. This drives up costs. Devising a strategy to fairly attribute any throughput shortcomings is difficult. After the transfer line model computes the process's throughput, a simple calculation produces the percentage deviation from the infinite buffer scenario. That percentage is multiplied by the ratio of the adjusted processing speed over the machine's actual processing speed. Then, that number, plus one, divides into the actual processing speed to produce a new, accounting processing speed. This new processing speed is used for accounting purposes only- to calculate how long that machine worked on a particular part.

$$\mu_{accounting} = \frac{\mu_{actual}}{\left(1 + \frac{\mu_{adjusted}}{\mu_{actual}} \cdot \%\right)}$$

Equation 8.1: μ accounting

This adjustment to bill the machine makes sense on a few levels. First, there is proportionality. A machine that operates much faster than a slower machine should not bear the brunt of an interacting system, but it should still carry its share. Conversely, only billing the slowest machine for something that is the responsibility of the whole transfer line does not properly distribute the added cost. Multiplying by the ratio accomplishes this proportionality. Also, previous analysis has shown that the biggest deviation from an isolated scenario occurs for similar machine speeds. Multiplying the percentage deviation by the speed ratio accounts for this tendency. This devised method is an approximation and should be accepted only with some skepticism.

Potential complexities that arise out of dividing a non-dedicated machine's production include die changes, divided tandem lines interacting with each other, and prioritizing parts. These complexities are assumed to affect the process minimally.

8-3 Buffers

Cost models with manufacturing systems analysis include the cost of storage buffers. Costs come from part inventory, floor space, and money invested in the part. All are possible and used in different scenarios. In sheet metal parts fabrication, buffers are accounted for through part space. Parts do not lose value in the buffer and little capital is invested in an inventory. The transfer line model returns an average inventory for each buffer. Assuming a part can be stacked fifty parts high, the inventory is divided by fifty, multiplied by part size and by building cost per square meter.

Toggles were added to turn on and off the effects of machine interactions. This provides a way to compare costs of transfer lines in a cost model against a cost model that does not have those costs. Located all in the cost model's general inputs sheet, each machine's MTTF, MTTR, and buffer sizes are inputted. Table 9.1 shows the MSA inputs section in the technical cost model. The buffer sizes used are the optimal buffer sizes as explained in Chapter 9.

Machine	MTTR (min)	MTTF (min)	Buffer Size
Blanking	39	74	650
Stamping	10	12	
Machine	MTTR (min)	MTTF (min)	Buffer Size
Blanking	39	74	110
Sheet Hydroforming	51	102	110
Laser Trimming	22	81	110
Flanging	22	81	
Machine Interactions?	0	(0=no,1=yes)	
Buffer Accounting include space?	1	(0=no, 1=yes)	

Table 8.1: General MSA Inputs For TCM

Chapter 9 Manufacturing Systems Analysis Applied to Case Studies

This chapter combines the various tools and analysis presented into one. Using the two machine continuous model and the multi machine model, dash panel cost is reexamined. The effect of Manufacturing Systems Analysis is the same regardless of part.

Before the analysis, an optimal buffer size is calculated. A benefit Manufacturing Systems Analysis has to manufacturing planning is the gained ability to understand appropriate buffer sizes. Buffers insulate a fabrication line from machine failures, but it can be costly. Knowing how to balance buffer size with the added cost depends on machine cost, part cost, buffer cost, and part demand. Figure 9.1 shows that an optimal buffer size exists and can be determined. Figure 9.1 determines an optimal buffer size of 110 for the multiple machine, sheet hydroforming process.

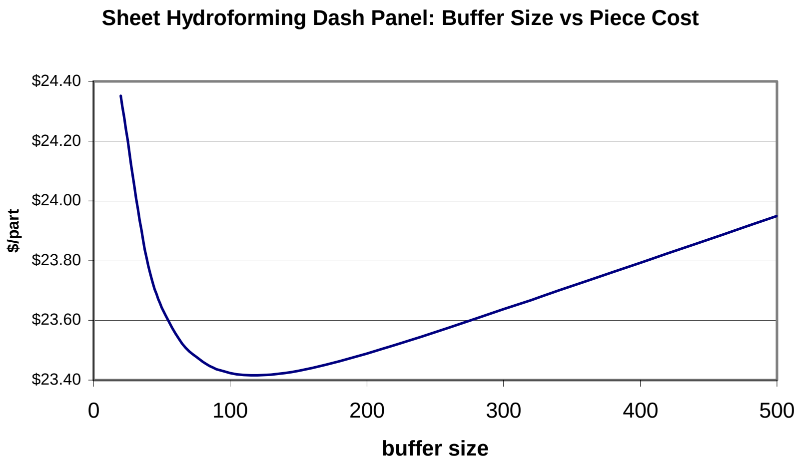


Figure 9.1: Sheet Hydroforming Dash Panel Cost vs Buffer Size

Figure 9.2 shows an optimal buffer size of 650 parts for a dash panel production volume of thirty thousand per year using low volume stamping. Any greater than that means that storage costs increase more than productivity improves. Any less means that increasing storage will provide greater returns by improving throughput. The following analysis incorporates these optimal buffer sizes.

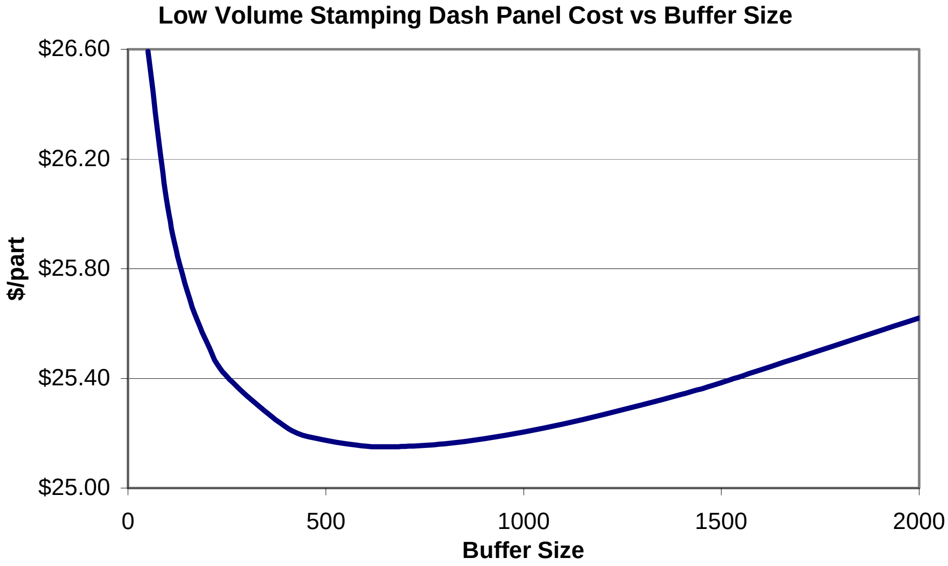
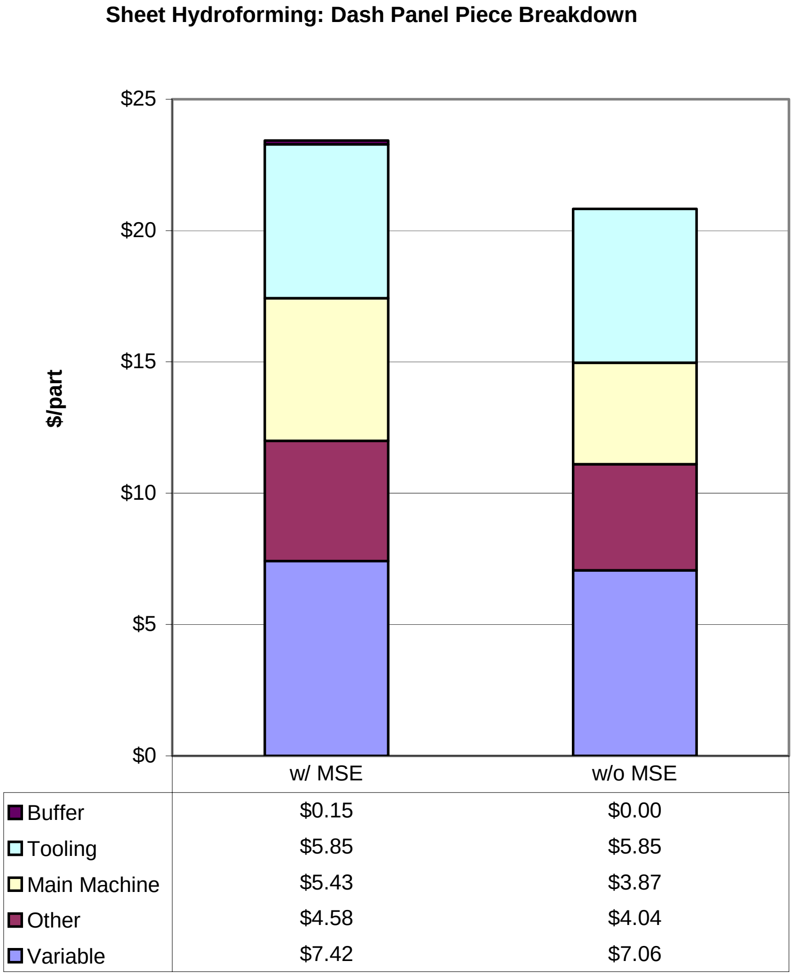


Figure 9.2: Low Volume Stamping Dash Panel Cost Vs Buffer Size

Figure 9.3 compares the cost breakdown of sheet hydroforming thirty thousand dash panels per year with and without machine interactions. The added cost can be attributed to the increase in time needed to produce the same number of parts. Including machine interactions essentially leads to added, unaccounted downtime. The cost breakdown of the dash panel without the machine interactions still has the same amount of planned downtime to make the comparison fair. The added production time influences machine, overhead, labor, energy, maintenance, and building cost. Two things it does not influence is material cost and tooling cost both of which are time independent. In Figure 9.3, other costs include maintenance, building, indirect labor, and fixed overhead costs. Variable costs include material, energy and labor.



	w/ MSE	w/o MSE
Buffer	$0.15	$0.00
Tooling	$5.85	$5.85
Main Machine	$5.43	$3.87
Other	$4.58	$4.04
Variable	$7.42	$7.06

Figure 9.3: Piece Cost Breakdown Comparison for Dash Panel

Figure 9.4 extends the analysis by looking at the part cost difference with production volume for low volume stamping. The sharp breaks show how cost jumps when additional tool dies are needed. As production volume increases, the cost difference diminishes due to more parts absorbing the costs.

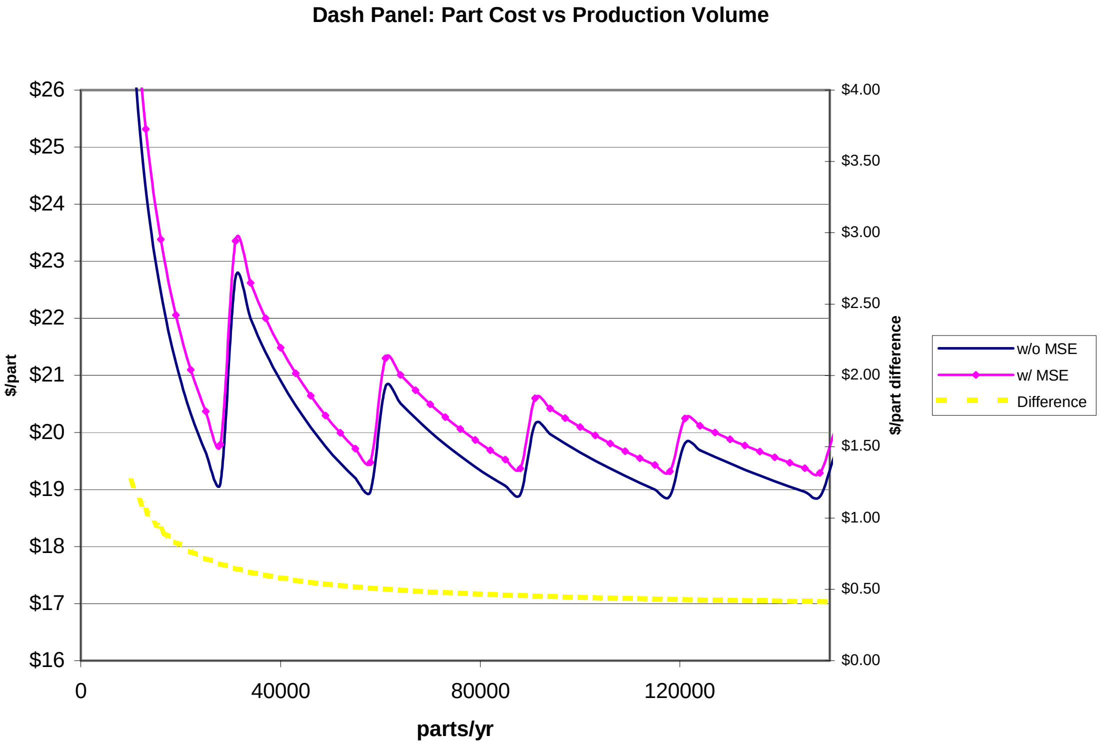


Figure 9.4: Low Volume Stamping Dash Panel cost with and without MSA

By including machine interactions in the cost model, part cost rises, but the interesting question is if that part cost would mean a change in process choice. A process requiring more steps is more affected by machine interactions than a process with fewer steps. Figure 9.5 shows similar results as Figure 5.4 except that this includes machine interactions. Sheet hydroforming has increased in price more than low volume stamping and has little to no advantage over a conventional stamping process. This greater increase of sheet hydroforming over low volume stamping (see Figure 9.6) can be attributed to having more manufacturing steps and thus greater inefficiency. Machine interactions can have a role in process choice especially when the comparing processes have dissimilar steps.

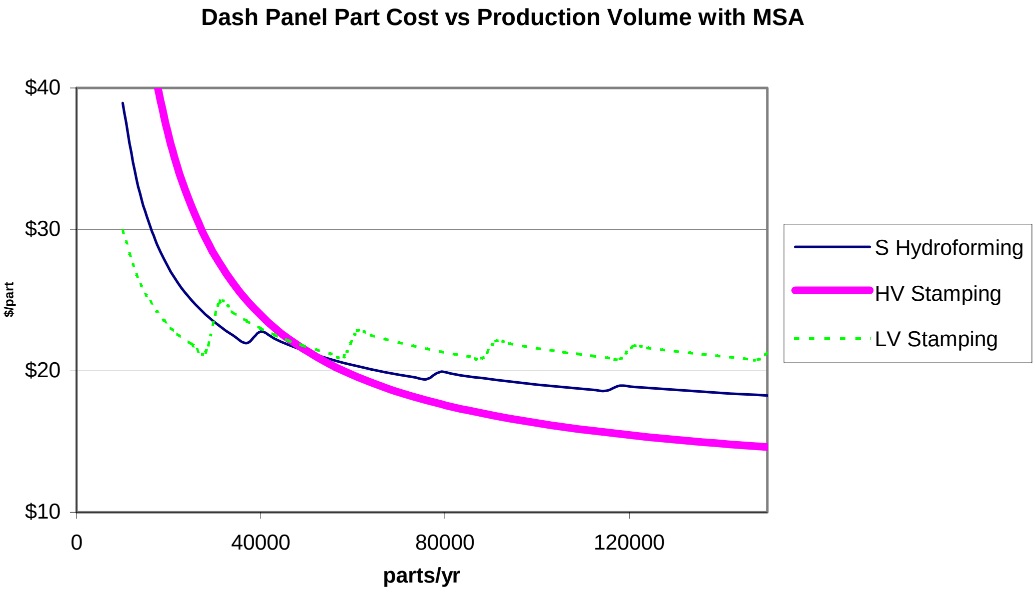


Figure 9.5: Dash Panel with MSA

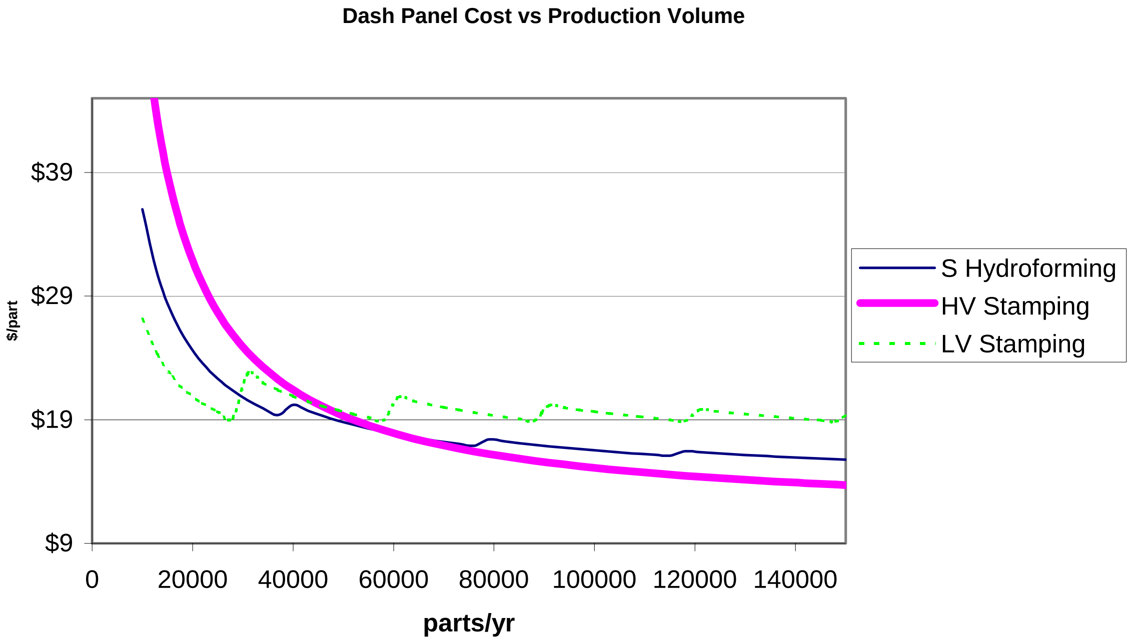


Figure 5.4: Dash Panel, Varying Production Volume

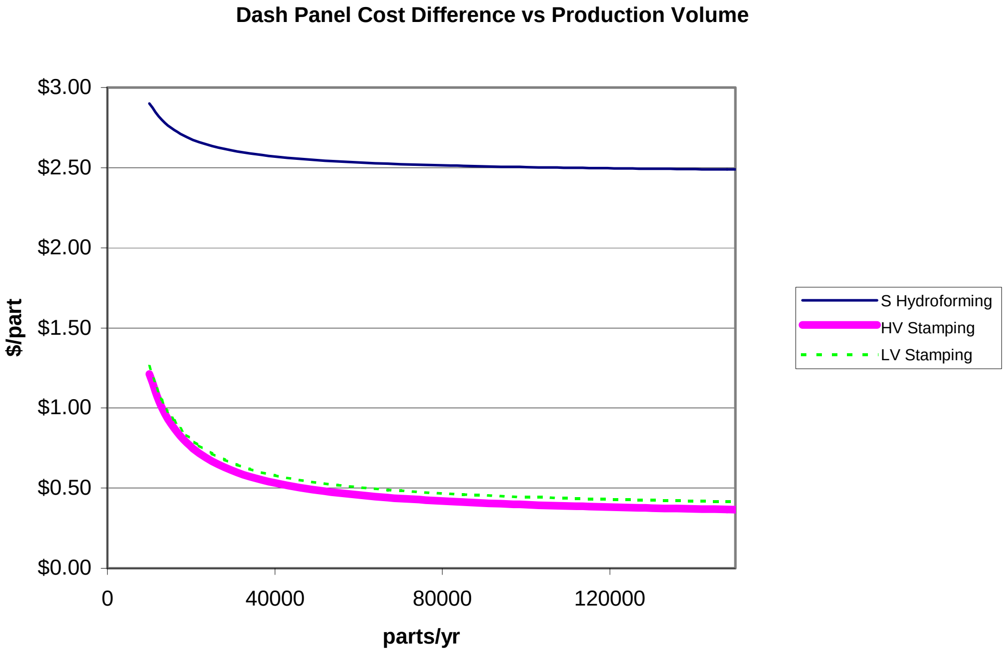


Figure 9.6: Dash Panel Cost Difference from Including Machine Interactions

Again, Figure 9.7 with Figure 5.8 show the same story with investment costs. Previously, sheet hydroforming held an investing advantage over low volume stamping from thirty one thousand on. Now, sheet hydroforming has a higher investment for all production volumes. The longer fabrication line means less throughput. This translates to higher machine investment.

To conclude, analysis has shown that multiple machine processes are more affected by machine interactions than processes with fewer steps. The comparison of sheet hydroforming and stamping reflects this, as sheet hydroforming is less economically competitive against stamping when including machine interactions. Crossover points between various processes can change and part costs increase significantly. The solution to this problem is to consistently include machine interactions by incorporating Manufacturing Systems Analysis into technical cost models.

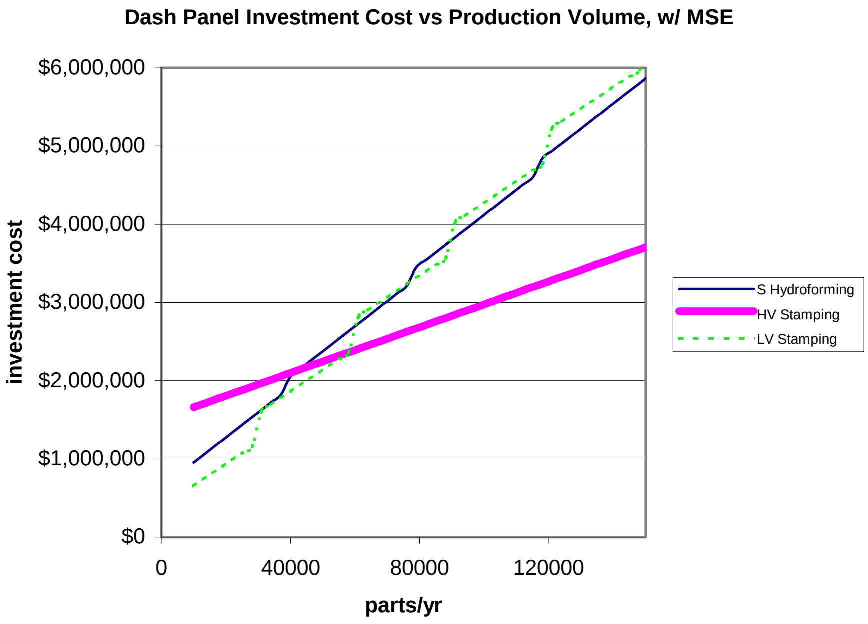


Figure 9.7: Dash Panel Investment Cost with MSA

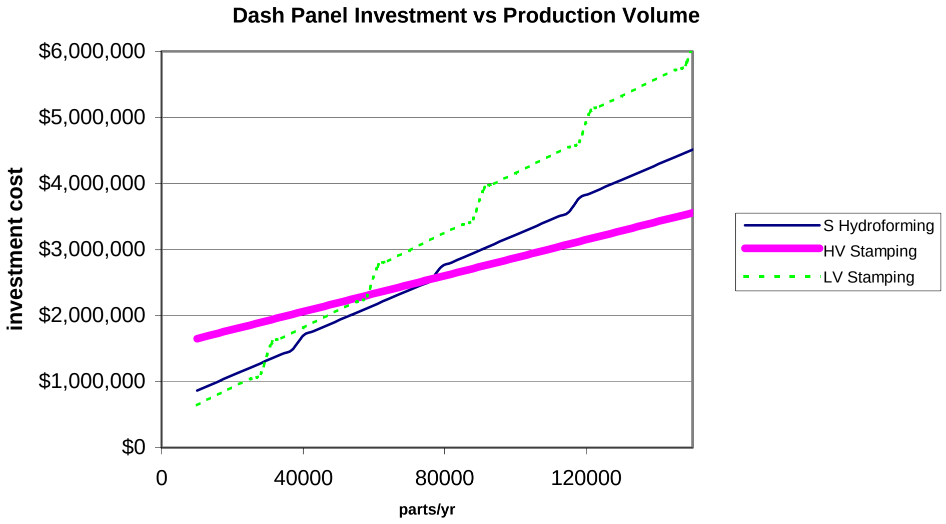


Figure 5.8 Dash Panel Investment Cost

Chapter 10 Lessons Learned

A few conclusions can be drawn from this study, and a few loose ends are still left to be explored.

Process selection shows a difficult choice between stamping and sheet hydroforming without production volumes giving a part-specific rule of thumb. For volumes under sixty thousand, high volume stamping is not economically advantageous due to high tool costs. For volumes under twenty thousand, hydromechanical deep-drawing is not economically advantageous over low volume stamping. Tooling costs are similar, but equipment costs are higher due to slower production times. Finally, laser trimming loses cost effectiveness with high trim lengths. Low volume stamping transitions easily to high volume stamping and should be a consideration in process selection. For sheet hydroforming to be more competitive, even at lower volume, a lower cycle time is needed. When this happens, it is expected that laser trimming will also increase in speed. The analysis has shown that machine interactions are a needed inclusion in technical cost modeling and can make a significant difference in process selection. Determining where production varies from an isolated machine production is difficult to determine without using a model. Some insight was gained to determine where the system varies: the closer $\frac{\mu_1 e_1}{\mu_2 e_2}$ is to 1, the more variation a system will experience from an isolated machine system. This is does not take into account buffer sizes, repair rates, or failure rates. All of those characteristics greatly influence a transfer line's performance. The answer to this problem is simply to include a transfer line model in every technical cost model for more realistic results.

Another interesting point not discussed in previous looks at technical cost modeling is the effect of increasing machines to a process. Several examples throughout this thesis demonstrated increasing machines in a system increases downtime and effects the whole production line. This can make a significant difference in process selection. Using this for complex, multi-step processes might yield some interesting results.

One advantage sheet hydroforming still maintains over stamping is formability.

Additional research might be able to make a more sophisticated approach to this problem when more information becomes available.

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