CHARACTERIZING COST AND PERFORMANCE OF FLEXIBILITY STRATEGIES IN AUTOBODY MANUFACTURING

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Abstract

Consumer demand is hard to predict in any industry, let alone the automotive industry. Vehicle manufacturers try to produce according to what their customers want, but if these wants change, the company is faced with lots of unsold cars and a huge changeover cost. In order to help fight the problems of demand variability, automotive manufacturers have begun the move towards plant flexibility. This includes designing vehicles comprised of similar subassemblies and the development of flexible tooling. The hope is that multiple vehicles can be produced on the same line so if demand starts to fluctuate, they can change the production levels of their styles with minimal lead time.

There are a number of different approaches to flexible tooling. One approach using programmable robotic repositionable tools (PRRT) is particularly promising because it can handle a large number of styles and requires low style specific reinvestment costs. This thesis examines the PRRT technology as well as other forms of flexible tooling to understand the conditions under which these approaches make the most economic sense. For this project an algorithm was developed to choose assembly tools based on subassembly characteristics, production levels, style counts, and flexibility approaches. The algorithm was connected to an already existing vehicle assembly model and two forms of economic analysis were performed. The first looked at the costs of using PRRT versus other forms of tooling for various product mixes. The second analyzed the potential cost savings when considering product changeover.

The results indicated that the initial outlays for PRRTs cannot be justified even for a large number of styles unless multi-generational product changeover is also considered. However, PRRTs provide a cost effective flexible tooling option for plants producing multiple styles when considering product changeovers.

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I dedicate this thesis to my grandmother who passed away from a long battle with sickness an hour before I wrote this. She was one of the most loving people I have ever had the chance to meet. Nanny, I love you and will always cherish the memories we have had together. Say hi to Poppa and Amu for me.

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1. Introduction
1.1. Motivation:

Uncertainties in demand are often a large source of inefficiency in manufacturing production planning. This is especially true in the automotive industry; consumers, in the United States in particular, have become incredibly demanding as well as fickle in the past few years. A study by Holweg[10] found that 74% of consumers in the US would prefer a custom built car but the majority would wait a maximum of three weeks for their finished product.

The manufacturing process for cars is a long one; the time between initial design and prototype testing to commercialization can stretch into years. This is why the industry standard for production planning is based on market forecasts instead of actual customer demand. However, mismatching vehicle production to consumer demand has large associated penalties: the cost of storing unsold cars at dealerships and money lost when having to offer discounts on overproduced makes and models. This cost has been estimated to be $600-$1500 per vehicle[24].

In order to avoid this misalignment of production numbers and customer demand, many auto makers have started "build to order" initiatives. Volvo was one of the first companies to adopt this strategy in the 1990s[23]. Renault, Volkswagen, and Ford all have programs whose final goal is to make "built-to-order" autos in approximately two weeks while BMW has an especially ambitious initiative to reduce the time between customer orders and delivery to ten days[10]. To achieve these goals, many companies began focusing more heavily on lean manufacturing, with the most famous being Toyota. Lean manufacturing aims to establish the shortest possible cycle times for production and changeover by eliminating waste and incidental labor[6]. Companies began to employ lean manufacturing for larger reasons such as overall cost savings and manufacturing efficiency, but an added benefit is that it potentially puts them in a better position to deal with build to order. However, many auto makers are still a long way from reaching the goals of having strictly built to order production.

One recent study[10] investigated the implications in changing from a "make-to-forecast" to a "built-to-order" system. The results showed that though this type of change is logically optimal, customers get exactly what they want while negating overproduction. However, planning managers cited assembly plant flexibility as a major barrier to this type of change. Clearly, flexibility during manufacturing is a key to reducing production inefficiency.

In the case of auto manufacturing, there are two definitions of flexibility: volume-mix and changeover. Volume-mix flexibility involves changing the production volumes of vehicles already planned in a plant to meet customer demand. This change generally takes 30-60 days of lead time before the plant is back to full production. Full changeover flexibility occurs when a new product is introduced that is not currently in the plant's allocation. This happens approximately every six years and takes 12-36 months before the plant is fully operational. The major difference between the two being volume-mix is short-term flexibility while changeover is long-term. Because present-day demand is so hard to predict, car companies are forced to pay more attention to the volume-mix of the products coming off the line rather than focusing on a single model to generate revenue. This project is focused more on volume-mix flexibility because of its short-term capabilities.

Besides cost savings, another reason for flexibility is the ease at which quality control can be maintained[5]. As consumers become more demanding, the expectations of quality are constantly rising. Flexibility schemes are comprised of several "enablers" which must mesh together properly in order for the flex scenario to function. First, there needs to be a common build process beginning in body shop all the way through final assembly. This allows for robots with specific tasks to perform its function at a single workstation regardless of vehicle style[5]. Secondly, there need to be common gauging lines and locator points between the different models. This way a robot can easily and correctly find where it needs to apply a weld specific to the vehicle model[5]. Third, each model produced at a particular plant needs to be similar in size. Because the conveyor system has to be able to handle the weight and size of each model produced at the plant, the size variant can not be too large. Finally, the flexibility of a particular plant is constrained by the number of components its suppliers can produce for a given model. Therefore, the suppliers need sufficient notice in order to meet the demand of the plant[5]. Ideally, if the flex enablers are properly instituted in an automaker's plants, new quality improvement programs can be initiated to each location with minimal customization. For example, if a certain plant encounters a problem they can contact the other locations with the assumption that they have encountered this issue because they are running the same build processes and production systems. A solution can be quickly devised before too much time is lost. Conversely, "a dedicated plant with a unique vehicle build process would be more isolated in its efforts to combat production and quality difficulties[5]."

Some preliminary steps have been taken by auto manufacturers to become more flexible. One example includes transitioning from a strictly layer build of the overhead system to a more modular build[8]. For clarification purposes, the overhead system includes the headliner (trim of the underside of the roof) and the componentry located within its coverage area. Componentry includes fasteners, coat hooks, lighting, controls, garage door openers, etc. A fully modular build of the overhead system means that all componentry are pre-attached to the headliner prior to vehicle assembly installation. Layer build, on the other hand, implies that the headliner, fasteners and componentry are all installed separately. Ideally, auto manufacturers would like to move completely to modularity, but as of now production is comprised of a mix of both modular and layer built subassemblies, depending on the particular subassembly[8].

Efficiencies in the manufacturing process show that vehicles will be assembled with fewer operations on the main assembly line thereby allowing for easier implementation of flexible tooling. The smaller components are pre-assembled into logical “building blocks” and are delivered to the point of assembly for installation[8]. Preferably, the overhead systems would be pre-assembled at an offsite location, removing the structural costs for the vehicle manufacturer. However, in the case of the overhead system, modularity inhibits the ability to upgrade the base headliner to an uplevel system by substituting deluxe componentry as in a layer built line. Plus, major consideration must be placed on the packaging of the overhead system because of the delicate componentry already installed to the headliner. Elaborate packaging can get expensive but the bulky system is most vulnerable to damage during transport.

Other work in increasing flexibility includes development of automatic fixture planning systems[7]. The planner is a “feature based system which uses geometric methods to create fixture assembly scenarios involving modular fixtures and/or vises to hold prismatic parts. It uses a built-in solid modeler and a screw theory based restraint analysis system[7].”

Although this project discusses flexibility within the auto manufacturing industry, it is prevalent in all sorts of industries. This flexibility has had desirable results, but does come with hardships that need to be worked out. One study in the composite forming industry found that flexible tooling will result in a cost reduction of 24%[18] as well as maintaining low volatile emissions in accordance with the EPA[15, 16]. However the flexibility limits the complexity of the desired composite shape and creates a large potential for thickness variation. In the textile industry, a flexible mandrel has been developed which can change the cross-section and taper of a braided preform[17]. Triaxial braids are relatively stable structures that when being produced, need to be formed to the desired shape during the braiding process. To achieve this, the preform is overbraided on mandrels that either form part of the finished composite or are removed before the molding process[17]. Mandrels are expensive but multiple sizes are necessary as the composite tapers to smaller cross-sections. The flexible mandrel can size down mechanically, removing the need for multiple mandrels. Other work has shown that flexible tooling used in hemispherical shells production for pressure vessels results in various sizes and wall-thicknesses as well as a range of strengths[9].

1.2. Problem Statement

Vehicles today may look different on the outside, but on the inside, many of them have the same subassemblies. Due to the similarity, car companies hope to produce more than one model simultaneously on the same line. Tools designed to accommodate multiple vehicle subassemblies exist; however they are in the beginning stages at smaller plants and are not yet ready for commercial or industrial use. Larger scale production plants have been designed with vehicle specific machines, resulting in a huge expense when a changeover is needed. Therefore, flexibility of production is an integral part of the manufacturing scheme.

In order to combat the ever-changing desires of the consumer, at least one vehicle manufacturer as developed a programmable robotic repositionable tool (PRRT) which can automatically adapt to the various sizes and shapes of subassemblies as they arrive at the station. The main concern of PRRT is its large expense as compared to single style dedicated tools. It has been estimated that implementation of PRRT costs $100 million with an addition $30-$50 million for reprogramming when a new product is introduced into the plant[20]. For a plant filled with dedicated tools, it costs approximately $150 million to introduce a new vehicle. Therefore the hope is that once PRRT is implemented, the only costs will be associated with reprogramming, which is much lower than full changeover. Because this tool is so flexible, a style change will create minimal lead time which may generate enough revenue to make the tool cost effective.

In order to analyze the benefit of PRRT, several cases of different sharing strategies will be created, in order to see how the different flexible tools influence the cost per vehicle. Because the value of money is ever changing, additional analysis is necessary to better understand the costs of using PRRTs for changeover, as well as the limitations of using them in general.

The overall purpose of this paper is to analyze this particular flexible tooling and understand the specific subsystems and product mix scenarios that using PRRTs makes economic sense. In order to accomplish this goal there is the need to develop a better method for investigating the cost of using PRRTs versus other tooling solutions for a variety of scenarios. This method, combined with an already functional assembly model, will help determine the cost effectiveness of PRRTs as compared to other forms of flexible tooling.

1.3. Paper Overview

Chapter 2 is comprised of a description of the programmable robotic repositionable tool. This includes reasoning as to why PRRT is better than traditional fixtures in some circumstances.

Chapter 3 is comprised of two sections on the use of production level cost modeling in this project. The first section will outline the basics of cost modeling as well as give a description on modeling the automotive assembly. Section two includes an explanation of the structure of the tool choice algorithm, the method of how it selects the proper tool, and a description of its validation.

Chapter 4 describes the economic implications derived from the model, including reasoning for model use along with specific uses and economic conditions under which flexible tooling is cost effective.

Chapter 5 explores the possible market penetration given the economic analysis in section IV. This includes institution of flexible tooling in the autobody industry as well other manufacturing industries.

Chapter 6 concludes the thesis and provides ideas for future work on the model and on flexible tooling in general.

2. Flexible Tooling Technology

2.1. Programmable Robotic Repositionable Tool

Auto manufacturer have begun trial implementation of the programmable robotic repositionable flexible tooling in there smaller production plants. PRRT "is a servo-driven, programmable tooling system that can adjust to the contours and size of various automotive models and body components moving down a production line[22]" (see Figure 2.1). It reduces the need for model- specific tooling normally used for automotive

Figure 2.1: Station comprised of several PRRT units surrounded by RSW robots. The PRRTs are the smaller piston type arms[21].

applications such as robotic welding. One desirable characteristic PRRT has over traditional tooling is that if the primary positioner fails, a second positioner can be installed and its servo-controller will automatically download the calibration. The tool coordinator can then take this information and "make the necessary actuation command adjustments to compensate for the build variances between the first and second positioners."

From Figure 2.1, one can see that the station contains several PRRT units. Each unit is comprised of two pistons; one that moves vertically and a second that travels horizontally. The large robotic arms surrounding the PRRT units are resistance spot welding robots. Clamps on the end of the positioners hold the subassembly in place. Before the subassembly arrives, the clamps open completely and the pistons move to allow for easy placement. Once the subassembly arrives, the pistons position the clamps according to their programmed locations (based on particular subassembly), and close on the part, holding it in place. The robotic welders proceed to place the desired number of welds while the PRRT units remain rigid. After the robots complete the run, the clamps release and the pistons retract, allowing the newly welded part to travel to the next station and wait for a new subassembly.

2.2. Positive Characteristics of PRRT

The largest hope for PRRT implementation is that it will allow for quick changeover. Bombardier Aerospace has installed an Axis Reconfigurable Tooling System (comparable to PRRT) in its Belfast plant and they have been able to change complete part programs in a matter of hours, rather than weeks, and add components to tools at no extra cost[3].

Another positive characteristic of PRRTs is that are much smaller than traditional fixtures. According to company press releases, the installation of PRRT in the pilot plant will greatly reduce the occupied floor space. The elimination of style specific several welding cells in each unit can result in a reduction to 50,000 sq.-ft. (4,645-sq.-m) compared to 150,000 sq.-ft. (13,935 sq.-m) because the PRRT can handle multiple styles[2, 20]. Also contributing to the decrease was the addition of a new docking and delivery system which can transport subassemblies throughout the facility by way of conveyors, minimizing the need for pathways for forklift trucks[2].

2.3. Present Approaches to Flexible Tooling

Besides PRRT, several options exist to make single style fixtures more flexible. Some fixtures can be manipulated with holders that move into place when the particular style arrives at the station. In cases where the fixture cannot be manipulated to handle multiple styles, multiple single style holding fixtures are placed on a single "carrier." Carriers range from turntables which spin to put the correct fixture in place, or shuttles which slide the fixtures back and forth, depending on which style is arriving to the station. Each of these tooling systems have some flexibility associated with them, but programmable robotic repositionable tooling can handle a much larger amount of style sizes and shapes, and can also change faster than the others when particular subassemblies come through.

2.4. Strive for Multi-Vehicle Production Lines

Manufacturers hope to produce more than one vehicle on a single line to help decrease the lead times in product-mix changeover. Several challenges arise from the goal of assembling multiple vehicles on a single line. The most prevalent of these challenges include a combination of the production volume and labor rates of the particular plants because they determine what type of equipment will be necessary. This is known as the automation scenario. First, the production volume affects the choice of equipment and tools because it is impossible to cost effectively achieve the high throughput rates manually. Second, the labor cost affects the choice since it will influence the cost comparison between automated and manual production systems.

Therefore, the need for flexible tooling is not necessarily equal across all types of plants. Another challenge is that manufacturers have so far been able to run production of two vehicles on the same line, but would like to expand that capability ultimately to five.

3. Technical Cost Model

3.1. General Description

Technical cost modeling (TCM) was created to analyze the economics of alternative manufacturing processes while avoiding the need for trial and error experimentation[11] (Busch 1988). It has since evolved into an instrument that has the ability to analyze results after both the design specifications and process operating systems of a manufacturing plan have been manipulated[11, 1]. It can derive a cost assessment from the technical capabilities and constraints of the processes used in a product manufacture. Or it can become an investigative tool used in the analysis of relative cost effects that result from changing the design and/or manufacturing conditions early in the product or process development stages. TCM is focused on the primary manufacturing cost drivers: fixed investments (equipment, tooling, floorspace, maintenance, fixed overhead) and variable costs (materials, labor, energy. It is important to note that a TCM is not a complete business case, nor is it intended for determining purchasing costs. For the basis of this paper, the TCM becomes a process base cost model of the automotive assembly process.

Process based cost models (PCBM) are actually created in reverse, beginning with the cost and working backward to the technical parameters that can be manipulated. This involves three steps[1]: (i) identifying relevant cost elements, (ii) establishing contributing factors, and (iii) correlating process operations to cost of factor use. These technical parameters are considered the model inputs. “The modeling of cost involves correlating the effect of these physical parameters on the cost-determinant attributes of a process and then relating these attributes to a specific cost[13].” Generally, inputs for the PCBM can be broken up into four main categories: part and material related, process related, operational, and financial[13].

In the case of modeling autobody assembly the calculations are completed through the use of computerized databases linked together[14]. This allows for a low cost and high speed form of analysis because the user can easily modify the model to account for particular technological and economic situations[12]. A schematic representation of the original assembly model can be seen in Figure 3.1. Inputs are denoted by the boxes on the left side of the model and are

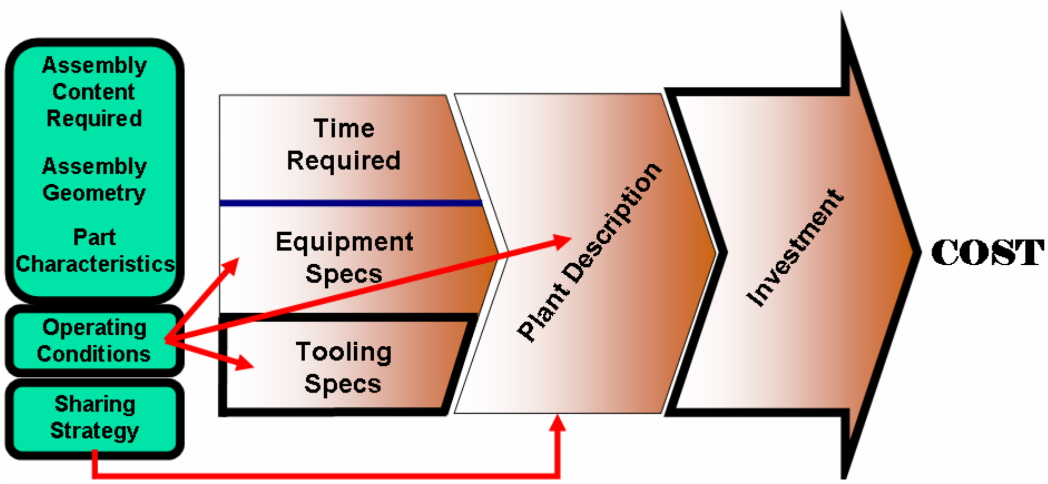

Figure 3.1: Schematic representation of process based cost model. Sections highlighted in bold black are specific to project.

separated into sections. Section 1 includes information about the assembly content required including method of assembly and amount (e.g. 20 resistance spot welds), assembly geometry (part size), and part characteristics (e.g. part count and material properties). Section 2, operating conditions, is data based on how the factory plans to run such as labor costs and hours of production. The final input is the sharing strategy of the lines, whether multiple vehicles can be produced at the same station or need to split into separate stations. All of these inputs feed into calculations on time required per station, equipment specifications (RSW robot, adhesive gun, etc.), tooling specifications (RSW fixture, adhesive fixture, etc.) and the determination of a theoretical plant description. This includes selection of equipment and tooling and how much of each need to be at each station. In autobody assembly, a tool is the same thing as a fixture; it holds the subassembly in place so the joining method has a stable surface to work on. From this newly formulated information, the amount of investment needed can be calculated ultimately determining the cost of the final vehicle body.

3.2. Overview of Tool Choice Algorithm

The newest addition to the model, and the focus of analysis in this project (see Figure 3.1), is an algorithm that can select tools needed in the assembly based on criteria sets and lowest cost. A generalized schematic representation of the algorithm can be seen in Figure 3.2. The tool

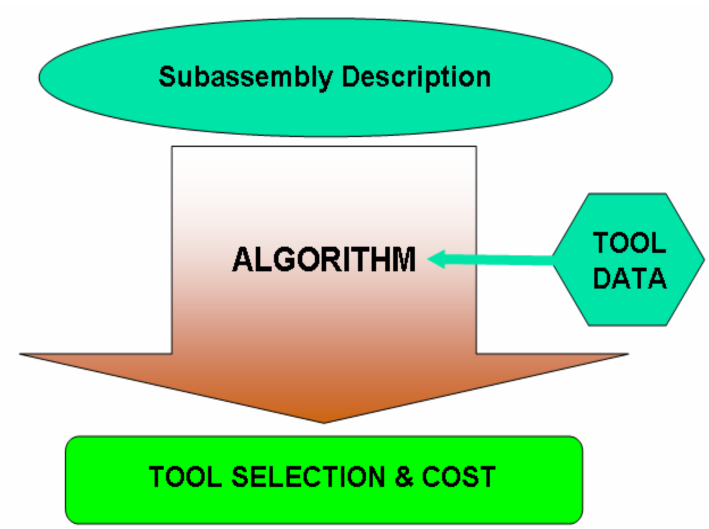

Figure 3.2: Schematic of generalized tool selection algorithm.

selection algorithm is comprised of three sections: (i) selection of a tool that is specific to a single style (termed *single style tool* (SST)), (ii) selection of a tool that is either flexible on its own or can be manipulated to become flexible to handle multiple styles, and (iii) selection of a carrier that can transport multiple SST into place, again for handling multiple styles. Specific inputs for the algorithm include the subassembly description which is comprised of subassembly size, part number, automation scenario (A.S.), and the method of assembly needed for that particular subassembly (see Figure 3.3). The *automation scenario* is an indication of labor costs and production volume at a particular plant and changes depending on where in the world the plant is located. Imbedded within the algorithm is autobody manufacturing tool data that create the criteria for tool selection. This includes maximum and minimum size requirements per tool

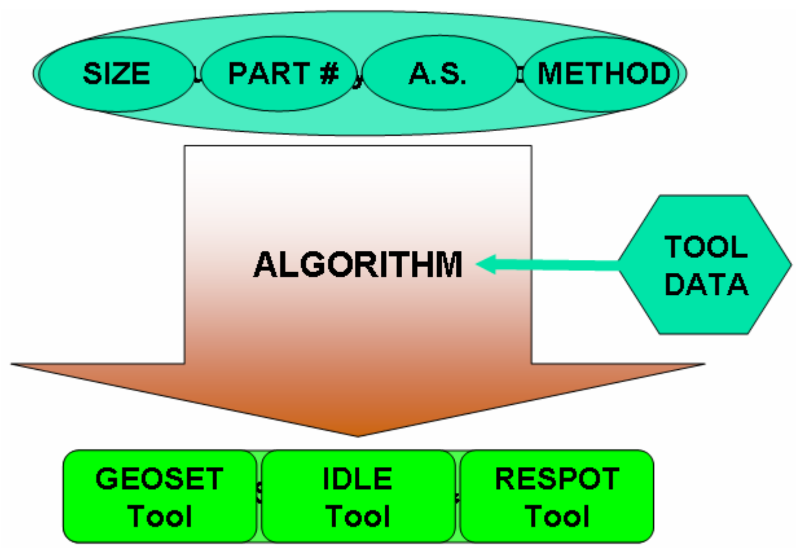

Figure 3.3: Detailed schematic of the tool selection algorithm.

and methods with which the tool is acceptable, among others. After calculations are complete, the model will select three tools of the lowest cost: *geoset, idle,* and *respot*. Because subassemblies can be composed of several parts all of various geometries, they would be unable to remain in the correct position as they travel through the production line if left on their own. A *geoset tool* holds the subassembly while the process method (e.g. RSW) makes the minimum number of joins to keep the structure stable. An *idle tool* is necessary because all of the stations complete their cycles at different times, so there are locations where the subassembly has to sit and wait for the next step. Finally, the *respot tool* holds the subassembly while the process method finishes all of the mandatory joins that began in the geoset step. Again, this version of the algorithm assumes the tool is subassembly specific.

Before discussing the multi-style portion of the algorithm, it is necessary to define the possible multi-style tools that can be selected; *tumbler-dump-slide (TDS)*, *PRRT*, *shuttle*, and *turntable*. *TDS* refers to a single style tool (e.g. a tool selected in Figure 10), modified to handle multiple styles. *PRRT* is discussed in further detail in Chapter 2. Both the *shuttle* and *turntable* are carriers that can hold multiple single style tools and either spin them in place (turntable), or slide them into place (shuttle). The algorithm needs to be additionally modified two separate ways first in order to select either the TDS or PRRT and then separately to select either the turntable or shuttle.

The inputs for TDS and PRRT selection are the same as in the single style tool algorithm, with the addition of the number of body styles being produced and if the tool will be reconfigurable. If a reconfigurable tool is desired, PRRT will be chosen and if non-reconfigurable is desired, the model will choose TDS. Data embedded within the algorithm is still the same as in the single style tool selection. Instead of having three outputs, only the geoset and respot selections are necessary because it is assumed that PRRT and TDS are too expensive to act as an idle tool.

There are actually two algorithmic calculations with the turntable/shuttle selection. The first step is to determine the size of the turntable or shuttle (small, medium, or large) based on the size and number of single style tools necessary for production. Cost is then calculated from the sum of the fixture costs plus the cost of the carrier.

3.3. Detailed Description of Tool Choice Algorithm

3.3.1. Data Table Creation

3.3.1.1. Fixture Data Table

The first step in creating the tool choice algorithm was to compile a table of all types of autobody assembly fixtures and their characteristics. Characteristics included cost of each fixture according to how many vehicles are being produced at once (up to five), the minimum and maximum number of parts each fixture can handle, which automation scenario is relevant for the fixture, the maximum and minimum sub-assembly size each fixture can hold, whether or not each fixture can act as a geoset, idle, or respot tool, whether or not the tool is reconfigurable, and the size of the tool. A second fixture table was created and filled with the corresponding methods, keeping in mind that some of the fixtures can manage more than one process. For example, a six gun auto-weld fixture will be used for hard-auto resistance spot welding, but will not be used for adhesive application. Conversely, an eight-clamp respot fixture could be used for both robotic resistance spot welding and adhesive application, so it is listed twice. Combining the two fixture tables generated a giant table of all the possible fixture and method combinations. It is from this table that the algorithm will run its fixture selection.

3.3.1.2. Group and Group Method Table

3.3.1.2.1. Group Table

The next step is to create a table for the data of all the vehicle subassemblies. This table is broken up into two sections: *groups* and *group methods*. The group table was composed of each subassembly with their corresponding part count and size. Subassembly size was calculated by estimating the largest x by y dimension of the largest part in the sub. Because some subassemblies are shared through multiple vehicles, while others are style specific, a sharing strategy had to be devised and act as an input into the model. If vehicles share the same subassembly, both subassemblies can be held with the same fixture. Using combinatoric calculations, it was found that 52 possible combinations of sharing exist when five vehicles are being produced. Each combination was given a number (1-52) to act as a code for input. For example, if Vehicles A and B share the same bodyside subassembly, but Vehicles C, D, and E all have their own specific bodysides, the input would be code #38: Vehicle A , Vehicle B | Vehicle C | Vehicle D | Vehicle E, where the vertical line denotes separate tools and the comma means shared on the same tool. From the results of the combinatorics it was also found that with five vehicles, there can only be a maximum of two tools shared, no matter the combination. For modeling purposes, the first shared tool of a subassembly was called *alpha* and if there was a second, it was given the name *beta*. In the case of code #38, there are four tools needed for that subassembly: 1 alpha tool and 3 single style tools. The secondary output of this code shows whether or not a tool will ultimately be a shared tool or a single style tool: Tool 1= alpha, Tool 2= single, Tool 3= single, Tool 4= single, Tool 5= none. Tool 5 is unnecessary because Tool 1 can handle two vehicle styles. These outputs will be used in the final tool selection detailed later in this portion of the thesis.

3.3.1.2.2. First User Override Option

At this point in the model, there is an option to override the selection for multi-style tools. In some cases, the lowest cost tool might not be the best option due to manufacturing logistics so the user can force the model to choose a particular tool. Plus there is the case that a subassembly is so similar between the multiple vehicles, the same SST can be used without modification.

Override commands are as follows: *MULTI* chooses the lowest cost multi-style tool, *SINGLE* chooses SST that can handle multiple styles, *TDS* chooses lowest cost TDS tool, *PRRT* chooses lowest cost PRRT, and finally, *TURNTABLE* and *SHUTTLE* force the algorithm to choose the carriers of the same name respectively.

3.3.1.2.3. Group Method Table

Using all of the information in the *group* section of the subassembly table, the *group method* section can be created based on the methods that each subassembly undergoes and the corresponding join intensity. For example, over the course of production, the bodyside subassembly is hit with 48 hard auto welds, 50 robotic welds, and 12 pedestal welds, all of which could potentially use different fixtures. Also at this point, the user must differentiate between geoset methods and respot methods to be used when the algorithm is connected to the overall model (explained in section 3.6.). Therefore, all of the bodyside subassembly information from the *group* section is repeated three times: one for each method (hard auto, robotic, pedestal). The algorithm uses the fixture data to choose tools for each group method in the *group method*.

3.3.1.2.4. Second User Override Option

In some instances of vehicle production, there can be two different sharing strategies within a single subassembly. For example, in the case the bodyside outer subassembly the geoset fixtures could be all style specific and a common material handler carries the sub from station to station, while the respot assembly of all the styles occurs on the same PRRT. Therefore, there is one more sharing code entry followed by an override option available to the user at the group method level. Sharing codes and overrides in this section are exactly the same as those discussed in sections 3.3.1.2.1. and 3.3.1.2.2. If the inputs are left blank, the algorithm runs of the first set of sharing codes and overrides.

3.3.1.3. Carrier Table

A data table was created comprised of all the information necessary for shuttle and turntable (carriers) selection. This included carrier type, size of the carrier, maximum and minimum fixture sizes each carrier could handle and the costs of the carrier depending on the number of styles being produced. It was given the name *carrier* table. The algorithm will select the appropriate carrier from this table as described later in the chapter.

3.4. Tool Selection Calculations

3.4.1. Single Style Tool Selection

The first step in the actual selection process is to choose a geoset, idle and respot tool for each group method of each style. An example of a group method would be robotic RSW on the bodyside outer. Because this model involved production of five vehicle styles, this selection section gets repeated five times. Each section uses style specific inputs but chooses using common tool criteria guidelines. In the case of the geoset tool selection for a single style, the model chooses all relevant tools according to the subassembly characteristics: part count, subassembly size, method, automation scenario, and geoset applicability. Next, the model looks for the cheapest of all possible tools and gives an output of both the identification number of tool and its corresponding name. This is repeated for idle and respot tool selection for all five styles.

3.4.2. Multi-Style Tool Selection

3.4.2.1. Necessary Preliminary Calculations

The next step in the algorithm is to choose flexible tools all of which can handle more than vehicle style. In order to accomplish this, several calculations were deemed necessary before the final multi-style tool selection can occur. First, the algorithm counts the number of styles in the first set of shared subassemblies (*alpha*) within each group method. Next, the algorithm finds the maximum geoset and respot tool base sizes within the alpha count as well as the maximum subassembly part count and maximum subassembly size. Again, this happens for each group method. After the algorithm finishes the count, it sums separately the total costs of single style tools needed later for shuttle and turntable calculations. All of these calculations are repeated for shared subassembly beta, if necessary.

3.4.2.2. PRRT and TDS selection

Once these preliminary calculations are complete, the algorithm moves on to PRRT and TDS selection. For this section, the algorithm uses the same criteria as in the SST selection, but instead the original subassembly input data, it uses the maximum part count and sub size that was determined in section 3.4.2.1. However, it does use the original method input and it looks for the additional criteria of reconfigurability. PRRT is reconfigurable while TDS is not. These calculations are completed for both PRRT and TDS geoset and respot tools of both alpha and beta tool sets.

3.4.2.3. Shuttle and Turntable Selection

For the turntable selection, the algorithm uses the maximum shared subassembly size and shared style count as calculated in section 3.4.2.1. Calculations in this section include comparing the maximum shared size with the minimum and maximum criteria from the *carrier* table and choosing the equivalent cost of the carrier according to the shared style count. Once the particular carrier has been chosen, the cost of the carrier is added to sum of the single style tool costs as previously calculated in section 3.4.2.1. This was repeated for both geoset and respot of both *alpha* and *beta* shared styles within the shuttle selection section as well as the turntable sections.

3.4.2.4. Multiple Style Single Style Tool Selection

In some cases, a part can be so similar from style to style, no modification is necessary and the same single style tool can be used for multiple styles. At this point, the algorithm finds the maximum of all the single style tool costs for a particular group method for both geoset and respot of both alpha and beta tool sets.

3.4.2.5. Override Tool Selection

As discussed in sections 3.3.1.2.2. and 3.3.1.2.4 there are overrides available to force the algorithm to select particular tool types if desired for both *alpha* and *beta* shared tool sets. At this point, the algorithm is able to sort the possible options according to the override input. It first looks at the second override option to see if there is a sharing code present. If there is, then it looks to the override entry. If there is no sharing code present, it looks to the first sharing code section and checks to see which override is entered. Using the front door subassembly as an example, if there is no sharing code entered at the second option, sharing code in the first section includes and *alpha* tool and *TURNTABLE* is entered as the override, the algorithm moves to the turntable selection (section 3.4.2.3.) and finds the output costs for the front door alpha geoset, alpha idle and alpha respot for each method. The reason for this resorting is to give the algorithm a more organized data for final tool selection.

3.5. Final Tool Selection

The final tool choice output is in tabular form with five major groupings (one for each possible tool style) and three minor groupings for each major (geoset, idle, and respot tool cost). Each group method gets an output for all of the tools, even if some tools are irrelevant. Just as in 2.2.5, the algorithm first checks to see if there is a sharing strategy present at the group method level. If none exists, it moves to the first sharing option and reads the output of the strategy. Using sharing code #38 as an example (Tool 1= alpha, Tool 2= single, Tool 3= single, Tool 4= single, Tool 5= none), the algorithm searches for each tool type. If the tool is an "alpha" tool, it gives the alpha cost outputs from section 3.4.2.5. for geoset, idle, and respot tools. If the tool is a "single" style of tool, it gives the SST cost outputs for the corresponding style number that was described in 2.1 for all three types of tools. Because Tool 2 is a single style tool, the cost outputs would be that of SST 2. If a tool is unnecessary, as is the case of Tool 5 in sharing code #38, there would be no cost outputs. Finally, the corresponding tool names are provided to help the user better understand which tools were selected.

3.6. Connecting Algorithm to Overall Assembly PCBM

While the algorithm gives the tool cost outputs, it does not give a fixture per station count which is needed to calculate the overall autobody cost outputs. In order to accomplish this, the algorithm must be connected to the larger assembly model. Algorithm inputs are mirrored in the inputs for the cost model, including subassembly groups, group methods, type (geoset or respot), and join intensity. Using imbedded data of fixture sizes and station necessities, the model is able to determine the necessary number of fixtures per station for that particular method. The model then looks to the algorithm for the tool costs, pulling the geoset cost if the method is a geoset, or pulling the respot cost if the method is a respot. The idle station costs are pulled from the algorithm as well, and the total tooling costs can be calculated.

3.7. Validation

Before the tool selection algorithm can be merged with the PCBM, it needs to be validated with actual data. The first step in this process was to create the correct fixture criteria against which the algorithm will run against. To accomplish this, the process sheets of an actual assembly program were analyzed to see which fixtures are used in the production of each subassembly. All of the subassemblies were compiled for each fixture, including part count, subassembly height, width and length, and the area using the maximum x by y dimensions. Please see Table 3.1 and Table 3.2 for examples of these compilation tables. Graphs of area vs. part count were created for each fixture to see if conclusions could be drawn on criteria. See Figures 3.4 and 3.5 for examples of graphs of the data in Tables 3.1 and 3.2. The data shows some clustering with some outliers. Ignoring the outliers, boundaries were drawn around the clusters, denoting

Table 3.1: Subassemblies that can be Handled by the 2 Gun Autoweld Fixture

AUTOWELD FIXTURE (2 GUNS) Subassembly	Part Count	Height	Width	Length	MAX AREA
1 STYLE DOOR 45 JPH	9	3	4	0.5	12
1 STYLE DOOR 80 JPH	8	3	4	0.5	12
DASH	9	2	7	3	21
TIEBAR	8	1	1	5	5
2&3_BAR_FLOORPAN_MARRIAGE	22	6	2	7	42
ROCKER_INNER	3	4	1	4	16

Table 3.2: Subassemblies that can be Handled by the 4 Gun Autoweld Fixture

AUTO WELD FIXTURE (4 guns) Subassembly	Part Count	Height	Width	Length	MAX AREA
DASH	9	2	7	3	21
TIEBAR	8	1	1	5	5
2&3_BAR_FLOORPAN_MARRIAGE	22	6	2	7	42
4BAR	3	4	1	6	24
REAR_RAILS	37	4	1	6	24
REAR_SEAT_BACK	11	3	1	3	9
REAR_WHEELHOUSE	7	2	1	3	6

the minimum and maximum part counts and subassembly sizes each fixture could handle. These points become the criteria with which the algorithm runs against.

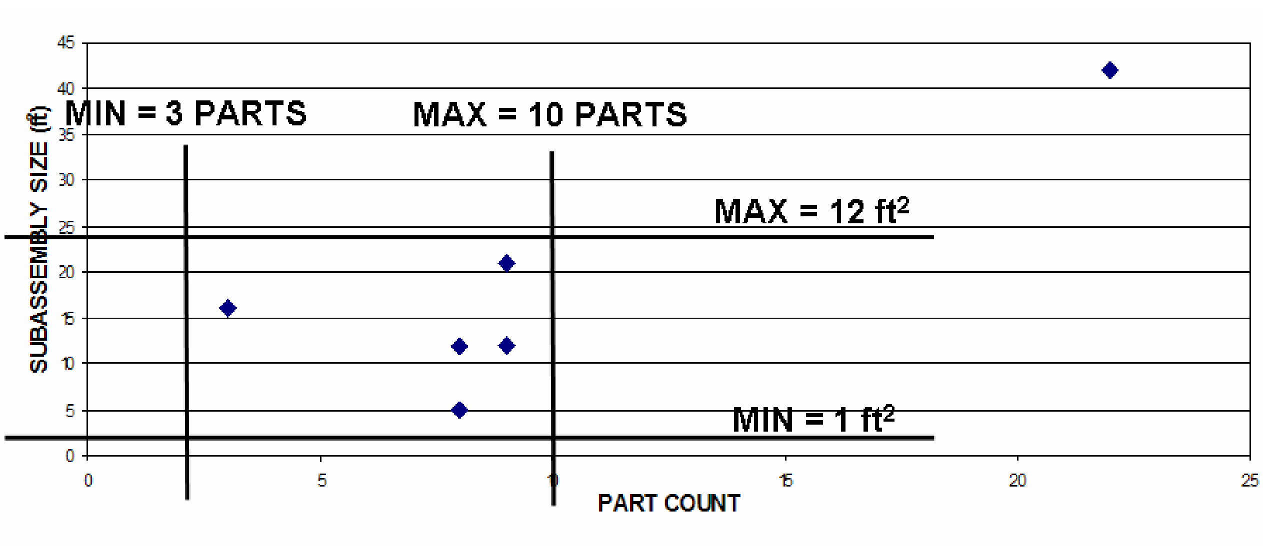

Figure 3.4: Auto weld 2 guns

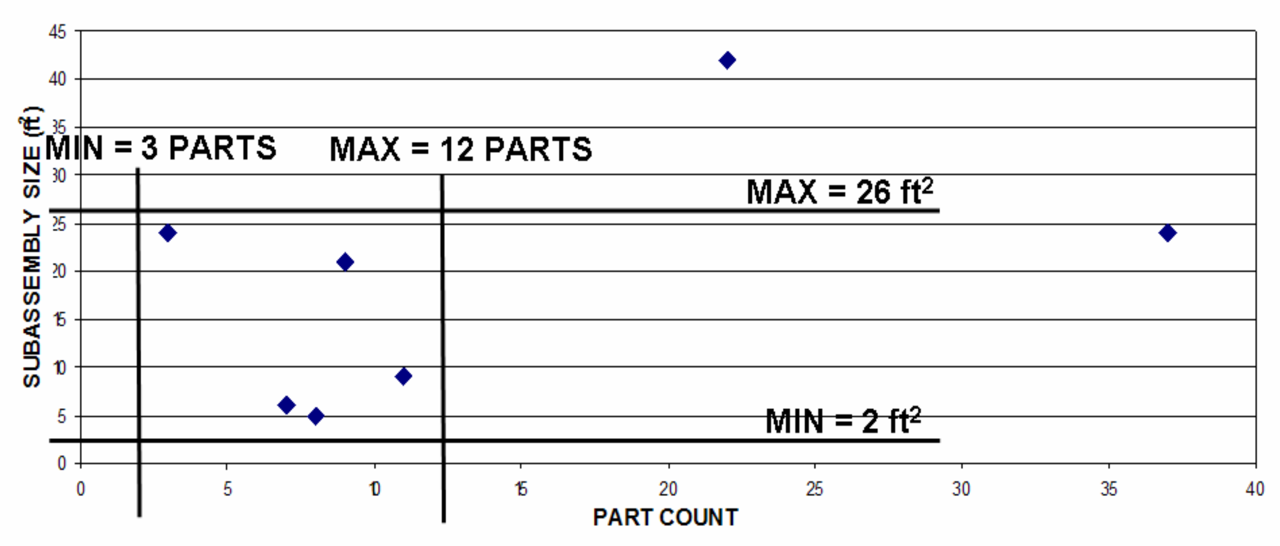

Figure 3.5: Auto weld 4 guns

As one can see, there is a large amount of overlap in at least the two auto-weld fixtures shown in Figures 3.4 and 3.5. Therefore, there cannot be cut and dry boundaries between each fixture size. Initially it was assumed that an autoweld fixture with 2 weld guns could hold a smaller range of sizes and part counts while the four gun autoweld fixture would hold the next range of sizes and part counts. It was suggested by an automotive manufacturing expert that the algorithm would run better if the criteria match was based on join intensity, rather than part count. However, in the interest of time the overlap of size and part count criteria was the best option.

Once the criteria were set, the algorithm needed to run with actual data input from a completed autobody program that produced three vehicle styles at the same time. This would allow for a good comparison to see if first, the algorithm is choosing tools correctly and secondly, the any opportunity for cost savings if flexible tools are used as opposed to single style tools. To make the analysis easier, three subassemblies were chosen from the program: Bodyside Right Hand (RH), Bodyside Left Hand (LH), and the Door. Two sets of all three subassembly inputs were used in order to test the method level sharing strategy and overrides. The first set for the three involved a single subassembly and would be split up at the method level; the ideal situation. However, there are some problems with these particular subassemblies that forced a second set of inputs where each method was considered a separate subassembly. In the bodyside production, there are two sharing strategies present: one for the geoset process and one for the respot process. In the geoset process, each vehicle has its own set single style tools combined with a common material handler for which to transport the subassemblies. The respot process, on the other hand, can occur on a single line but with alternating PRRT and pedestal weld stations. Pedestal weld fixtures work by keeping the weld robot stationary and the fixture moves under the gun, basically opposite to that of PRRT where the fixture remains stationary and the weld gun moves around the subassembly. The reason for the interdispersion is unknown at the moment, but one theory is that pedestal welding is relatively cheap and flexible, but not as precise as welding using the PRRT. Therefore, the joining methods are mixed to balance the precision of certain critical respots, productivity, and speed of assembly. The first bodyside data set had all the methods lumped together into one subassembly which would separate at the method level, while the second set broke up each method into its own subassembly. Similarly, the door subassembly had to be broken up in the same fashion. Although the sharing strategy is same throughout, all three styles produced on the same line, different overrides are needed for the geoset and respot processes. During the geoset portion of the assembly, the subassemblies are held by style specific tools set upon a turntable, while the respot portion occurs through the use of PRRT.

Using the data inputs, several sharing scenarios were analyzed, observing both the similarity to the actual production program as well as the differences between the scenarios, showing economic implications of flexible tooling.

4. Economic Implications

4.1. Data Scenarios

In order to examine the economic implications of flexible tooling, four data sets were created based on the number of vehicles being produced at the same time. A data set for a single vehicle, a data set for two vehicles, a data set for three vehicles, and a set for four vehicles were compiled. Each vehicle was comprised of the bodyside right, bodyside left and door subassemblies, rather than all the subs in the production to help simplify the analysis. All of the part counts, subassembly sizes, and join intensities were kept constant across all four vehicles. The total production level was kept constant at 200,000 vehicles. Therefore, if two vehicles are being produced at the same time, that means 100,000 of Vehicle 1 and 100,000 of Vehicle 2.

Next, five types of equipment and tool sharing strategy scenarios were created for these data sets to run against. The scenarios were Unshared* Equipment/Unshared Tools, Shared Equipment/Unshared Tools, and then Shared Equipment/Shared Tools with TDS as an override, next with PRRT as an override, and finally Turntable as an override. With the single vehicle production data set, however, it was only run through the Unshared Equipment/Unshared Tool scenario because a flexible tool would not be used on a single style line.

4.2. Economic Analysis 1: Product Mix

Once each of the scenarios and data sets were set up, data calculation tables were created to show how the cost changes with total production volume. Please see Tables 4.1-4.4 for the outputs of each data set as well as preliminary graphical representations of each scenario in Figures 4.1-4.5.

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* In this case, Unshared means independent sets of equipment or tools. As such, investments are replicated for each style included in the analysis (e.g. 2 styles = 2*single style investment).

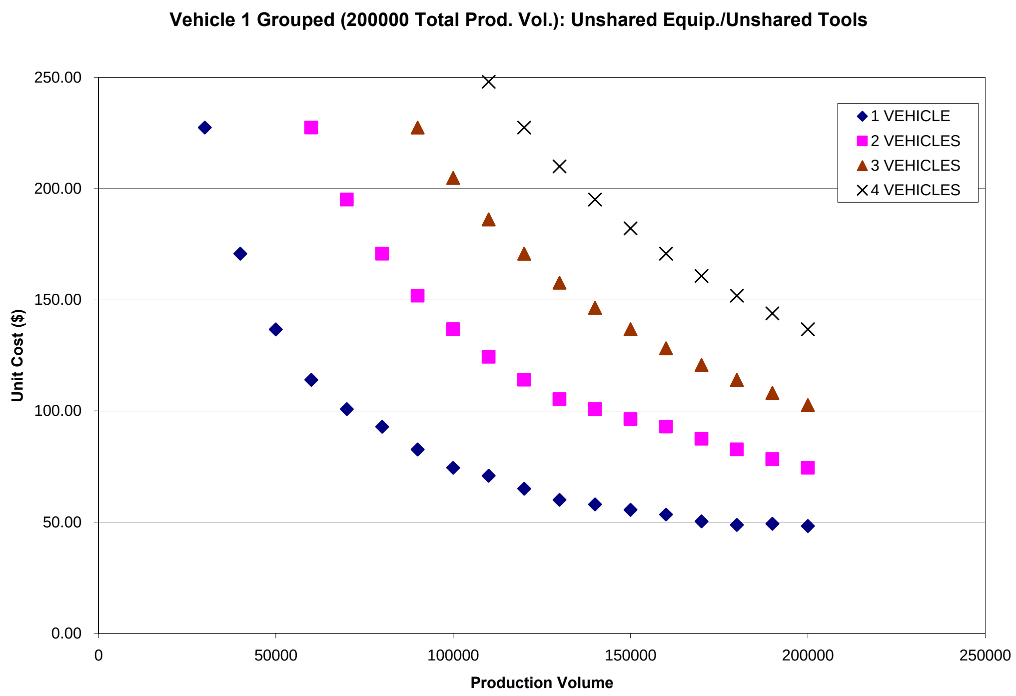

Figure 4.1: Cost outputs for the four vehicle counts with unshared equipment and unshared tools.

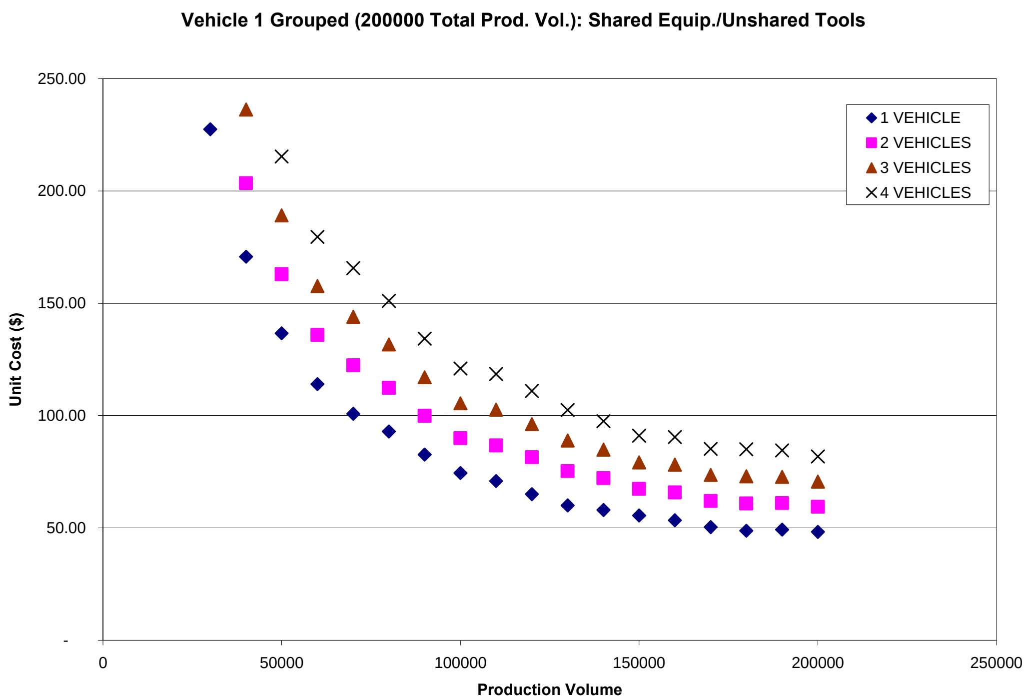

Figure 4.2: Cost outputs for the four vehicle counts with shared equipment and unshared tools.

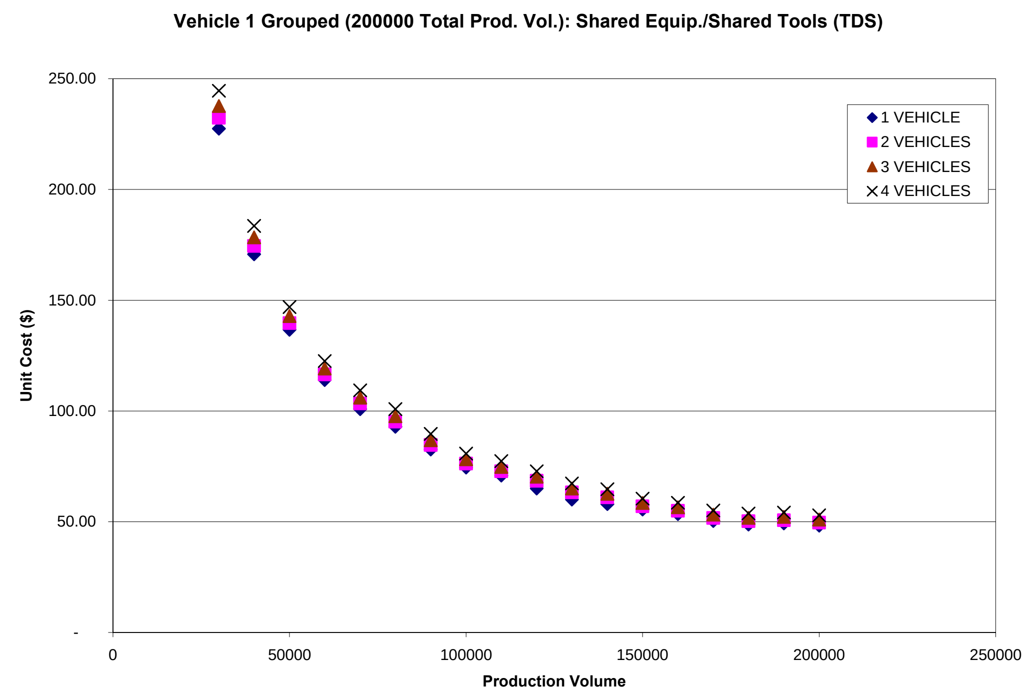

Figure 4.3: Cost outputs for the four vehicle counts with shared equipment and shared tools and TDS as the override.

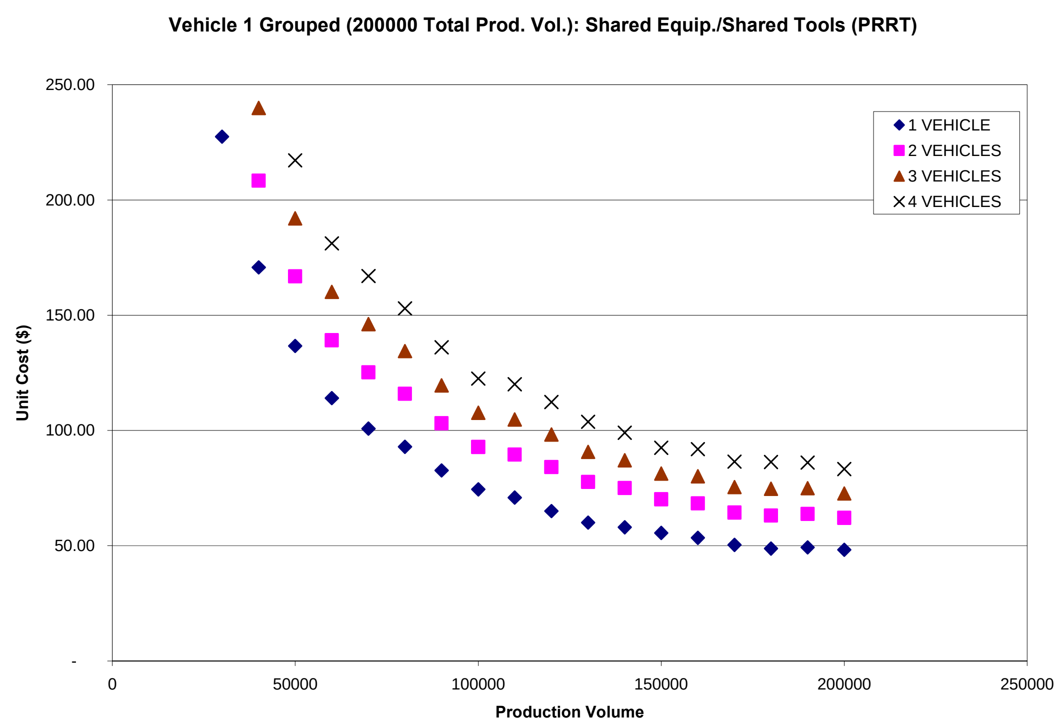

Figure 4.4: Cost outputs for the four vehicle counts with shared equipment and shared tools and PRRT as the override.

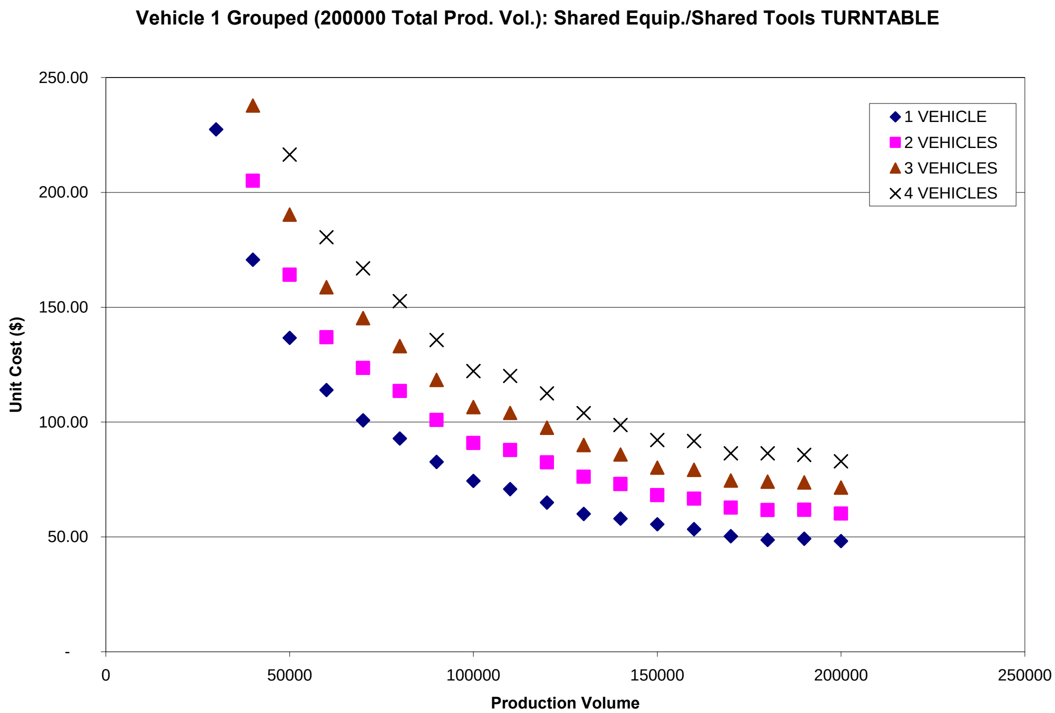

Figure 4.5: Cost outputs for the four vehicle counts with shared equipment and shared tools and turntable as the override.

At lower production volumes, the cost penalty from using completely dedicated or unshared equipment and tools is quite significant. This is because these costs can only be spread over a limited production volume. At higher volumes, these costs are not nearly as important since they can be spread over a larger number of units. This can be readily seen in Figures 4.1 through 4.5 as well as in Tables 4.9 to 4.12 (located at the end of Chapter 4. It is important to note that with the unshared/unshared strategy, the cost per vehicle 1 at 200,000 total production of two vehicles is the same as single vehicle 1 at 100,000 total production (See Tables 4.9 and 4.10 and Figure 4.1). This means that the model is correctly calculating cost because when two vehicles are being produced at 200,000 total production volume, 100,000 of each vehicle are being made.

Although the costs appear to increase with increasing vehicle style counts in all five scenarios, it is the most pronounced in the unshared/unshared case. Because tools and equipment are all unshared, individual sets of tools and equipment are needed for each style being produced. For example, if 4 vehicles are being produced, each station will need four sets of equipment and four sets of tools, greatly driving up the cost per vehicle. As the scenarios move to the flexible tool overrides, the cost per vehicle increases as the vehicle count increases for all three cases. However, the TDS cost differences are much smaller than the PRRT and Turntable costs. In order to see this effect, it best to look at the 200,000 production volume specifically rather than the entire range of production volumes (see Figures 4.6-4.8).

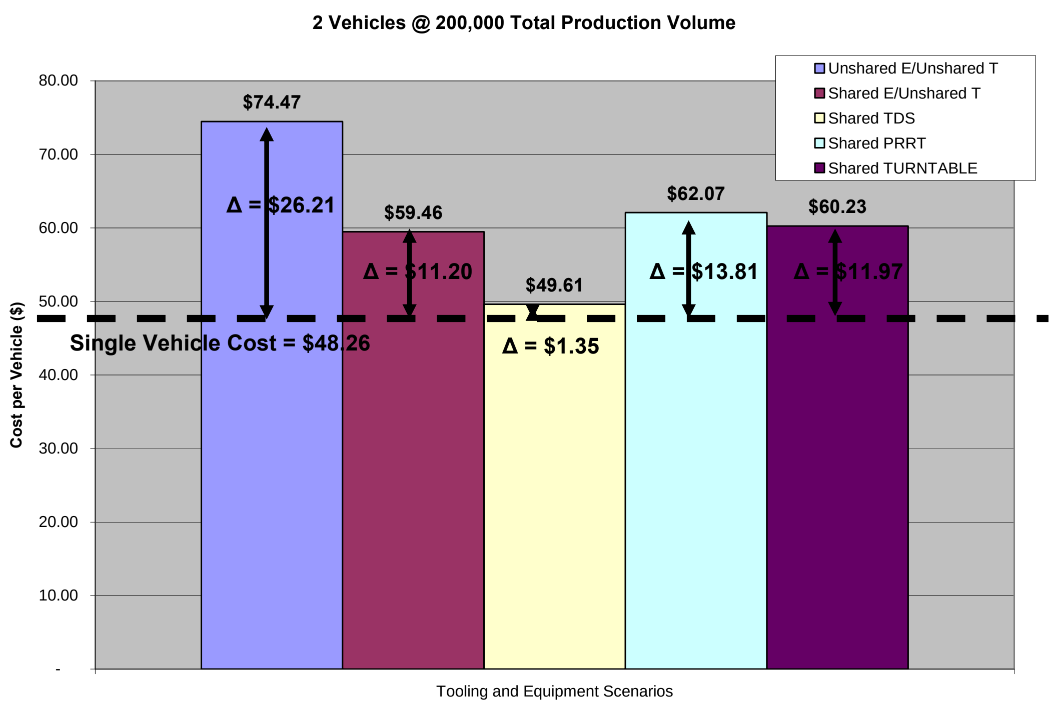

Figure 4.6: Graph of different sharing strategies for 2 vehicles at 200,000 total production volume.

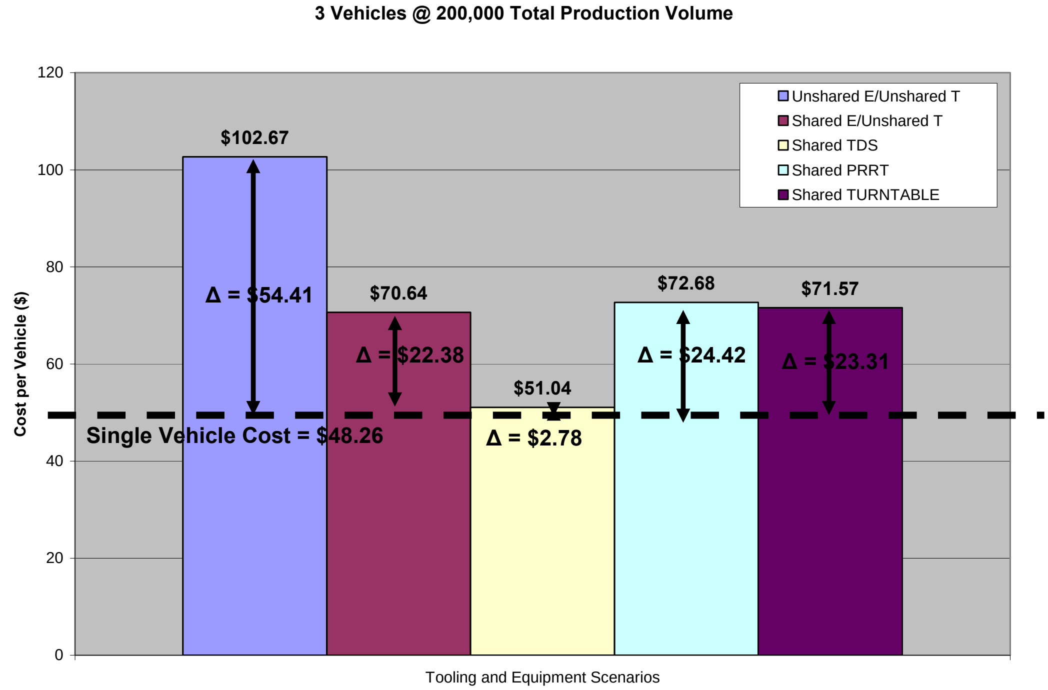

Figure 4.7: Graph of different sharing strategies for 3 vehicles at 200,000 total production volume

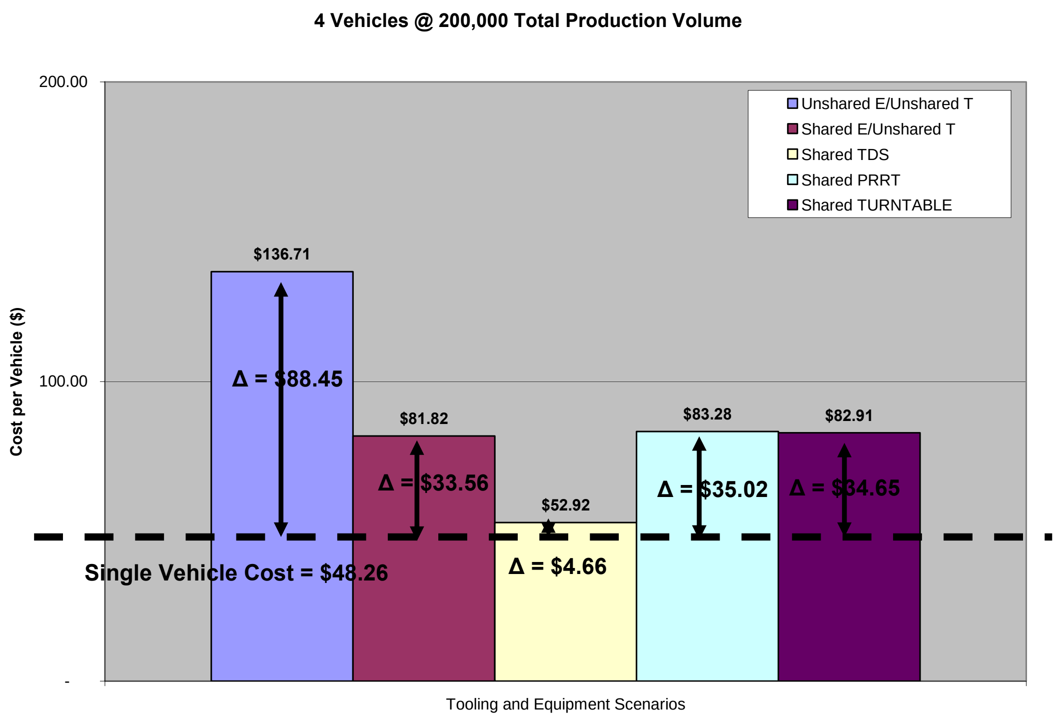

Figure 4.8: Graph of different sharing strategies for 4 vehicles at 200,000 total production volume

As the vehicle style counts increase, the change in cost from the single style vehicle appears to increase for all scenarios. This is especially true for the unshared/unshared scenario because again, this means four separate parallel lines. Again, this shows that TDS has a much lower difference in cost than the other shared/shared strategies. One important aspect to note, however, is that the delta costs for PRRT are larger than those for the turntable at lower vehicle counts, but as the count increases, the change in these delta costs gets smaller. Keep in mind that the when using a turntable as a flexible tool, as the style count increases, the number of single style tools increases as well. Therefore, the cost to add another fixture is less than the cost to expand the PRRT to handle one more style. This is even more apparent in Figure 4.9 and 4.10.

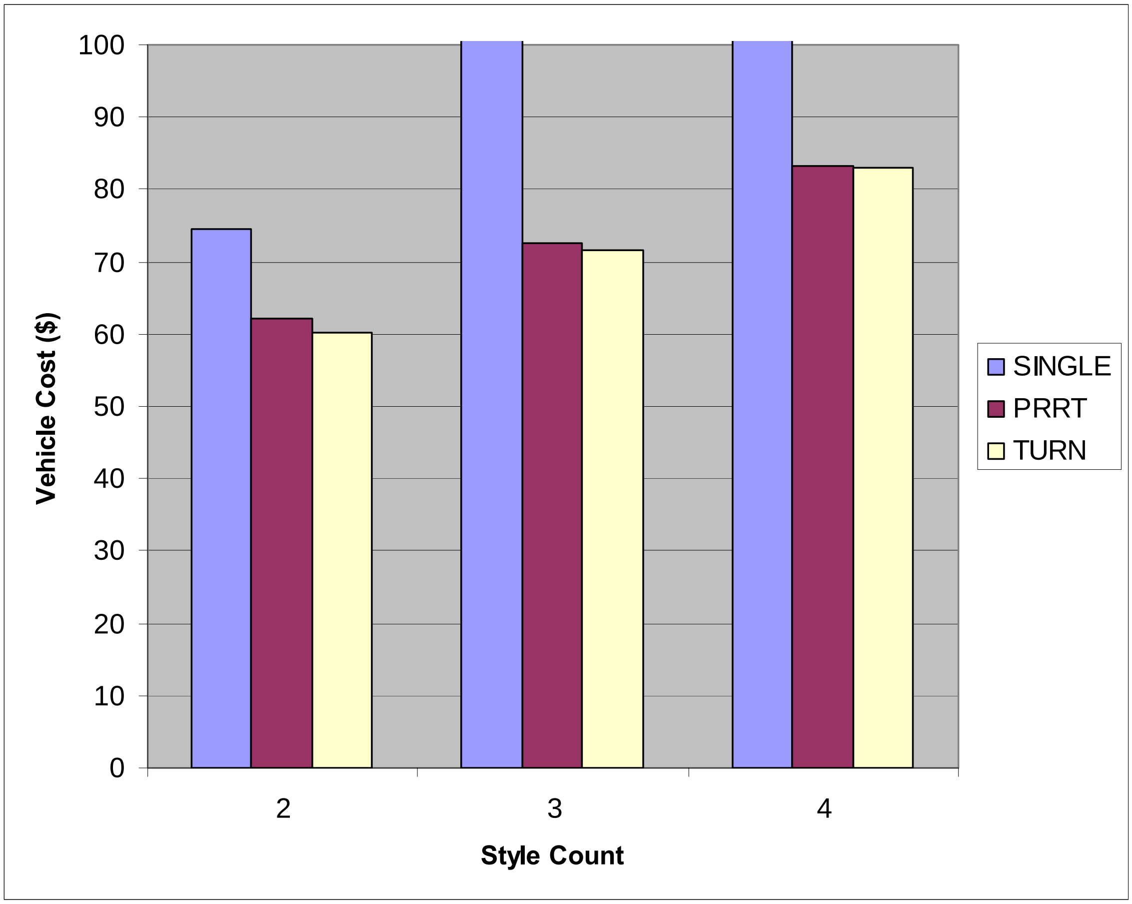

Figure 4.9: Comparison of single production, turntable, and PRRT vehicle costs vs. style count.

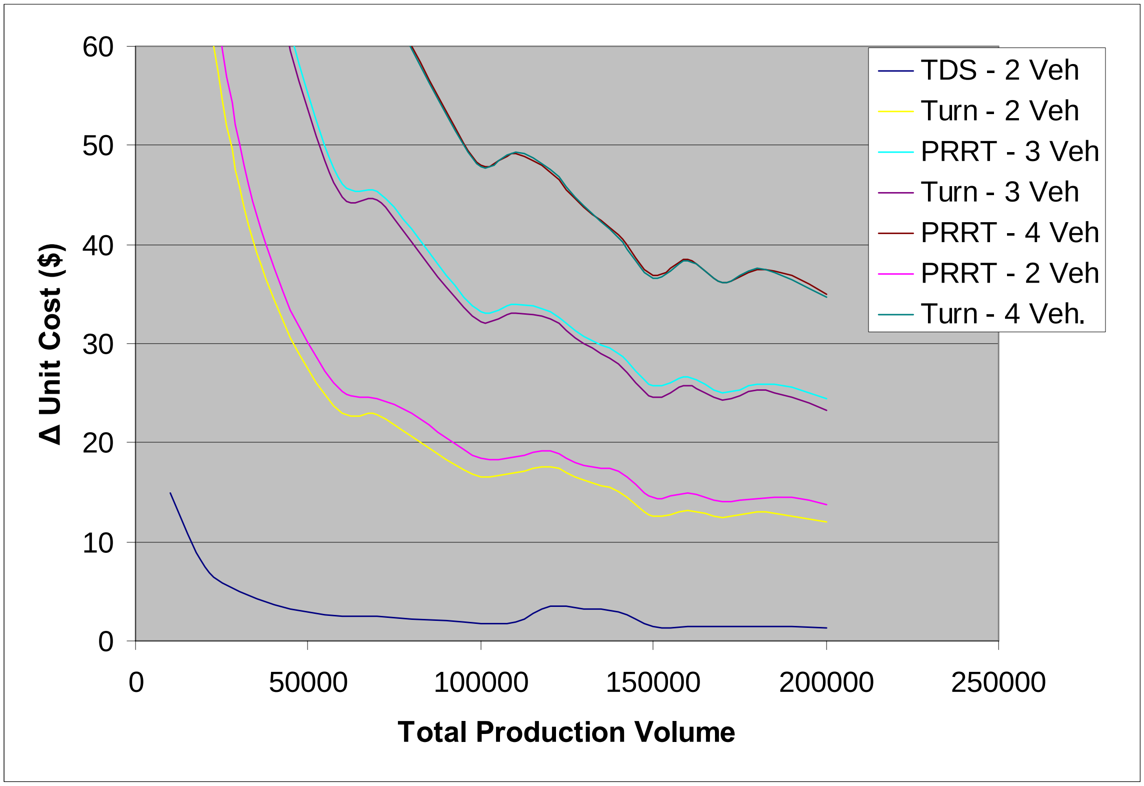

Figure 4.10: Graph showing the change in unit cost compared to single vehicle production as a function of total production volume.

In Figure 4.9, PRRT starts out higher than turntable, but gradually catches up as the style count increases. Figure 4.10 shows that at two vehicles, the turntable based vehicle costs are lower than the PRRT. However, at 4 vehicles, the costs appear equal as the lines are overlapping significantly.

Although these are interesting trends, the analyses completed so far keep suggesting that TDS is the least expensive option for flexibility. However, in many cases a TDS system is not possible at high style counts because a single style fixture can only be manipulated so much. Also, the subassemblies chosen for this analysis are comprised of some methods for which PRRTs can not be used. For example, in the case of the bodyside, the geoset welds are completed using hard-auto tooling. A hard-auto fixture is composed of multiple weld guns that apply their welds at the same time, as opposed to a robot which lays its welds down one at a time. For now, the PRRT is unable to accommodate the hard-auto welding process and the model has been designed according to that idea. The same problem happens with the pedestal weld process method which is also present in the bodyside subassembly. The pedestal weld process occurs opposite of that of robotic welding in that the weld equipment stays stationary and the fixture moves according to the location of weld placement. These two methods are perfect examples why an override option is necessary at the group method level. In some cases different sharing strategies may need to be considered within a group. Each hard-auto and pedestal method was denoted as having completely separate lines, so multiple single style fixtures would be chosen, thereby driving up the cost per vehicle. The result is correct, but it is now imperative to see if the cost savings during a changeover using PRRT is worth the initial investment.

4.3. Economic Analysis 2: Changeover Cost Savings

4.3.1. Net Present Value

Fixtures used in the automotive industry will not last forever seeing that parts wear out and vehicle styles may change drastically over the years. Typically, there is a product changeover approximately every 5 years. As stated before, the hope is PRRT will help in decreasing the cost resulting from changeover, because instead of needing an entirely new fixture like in a single style line, the major costs incurred are for reprogramming the PRRT. These reprogramming costs are much lower than those of the fixture. In order to analyze the benefits of using PRRTS when considering product changeover, the Net Present Value comparison among the tooling options must be calculated.

Net Present Value (NPV) is defined as the difference between the present value revenues and the present value costs utilizing the following equation[4]:

$$P = F(1+r)^{-N}$$

where P is the present value, F is equal to the future value, r is the discount rate, and N is the number of periods. Calculations like these are necessary because money has a time value. The discount rate causes an amount of money now to be worth more than that same amount in the future[4]. Therefore one cannot simply subtract costs now from revenues later.

When comparing the net present costs of using PRRTs vs. single style tools, there are several factors to be considered. Please see Figure 4.11 for a schematic of costs incurred during changeover when a single style is being produced. A discount rate of 5% was chosen and it was assumed that the PRRT reprogramming cost was $100,000. First, the fact that there is such large difference in the original installation costs make it seem like it is not worthwhile to use PRRT. This has been shown in the analysis up to this point. However, when looking at the costs for changeover, the reprogramming costs for PRRT are less than those of installing a new single style fixture. Because the PRRT scenario is comprised of both PRRT and fixed tooling costs, they are denoted on the graph with similar colors. At each changeover the fixed tools in the PRRT scenario need to be replaced just like in the single style scenario, but the PRRT costs are incurred through reprogramming. Results from this analysis show that when producing a single style of vehicle, PRRT does not create any cost savings because the NPV calculations come out negative (see Figure 4.11).

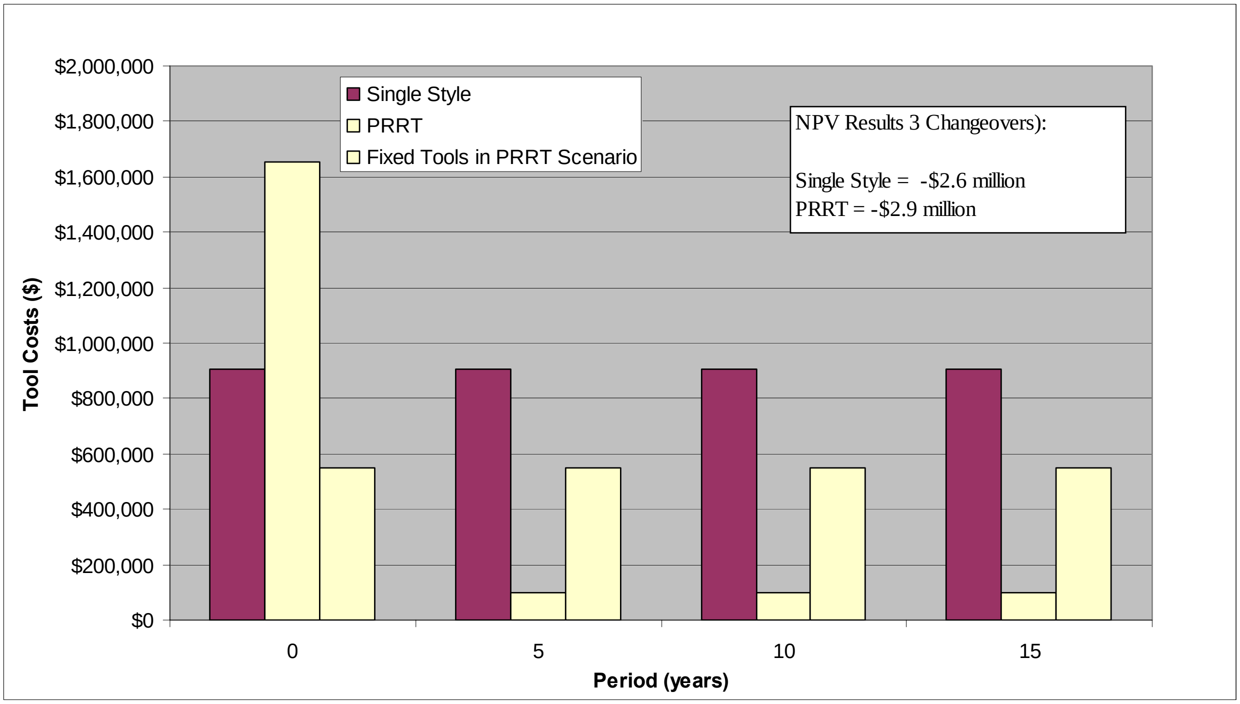

Figure 4.11: Example of costs incurred during changeover plus NPV results for single styles production.

Sensitivity analysis can be conducted which looks at how changes in the reprogram cost and discount rate affect result of changeover savings.

4.3.2. NPV of PRRT vs. Single Style Line

Because PRRTs do not offer significant savings during changeover in the bodyside subassemblies due to the large investments in the required autoweld/fixed tooling, the focus of this analysis was on the door subassembly. More importantly, the doors had minor costs for fixed tools relative to the cost of the flexible PRRT that would have to be paid again at changeover. As stated previously, the door subassembly was composed of methods shared on the PRRT and methods that need their own separate fixtures. Therefore the costs need to be broken down accordingly, because the two sets will have different NPV results. Total production volume was held constant at 200,000 vehicles across all style counts at a discount rate of 5%. The reprogram cost was estimated at $100,000 per changeover. Table 4.1 shows the resultant data from the model to be used in the NPV calculations.

Table 4.1: Cost results from model to be used in NPV calculations

	Single Style	2 Styles	3 Styles	4 Styles
Reprogram Cost	$100,000	$100,000	$100,000	$100,000
Single Tool Cost	$905,000	$1,641,000	$2,462,000	$3,282,000
PRRT Cost	$1,652,000	$2,203,000	$2,743,000	$3,322,000
Fixed Tools in PRRT approach	$550,000	$1,050,000	$1,550,000	$2,050,000

Costs were analyzed at initial investment, first changeover, second changeover, and third changeover, with the assumption that a changeover happens every 5 years. Analysis stops after 3 changeovers because the assumption was that PRRT would wear out by then. This was repeated for two, three, and four style vehicle production. Tables 4.2-4.5 show the results of these calculations. At the single style, it appears that there is never any savings from using PRRT

Table 4.2: Costs associated with changeovers for the single style vehicle case (r= 0.05).

Single Style	0 changeover	1 changeover	2 changeovers	3 changeovers
Reprogram Cost	$100,000	$100,000	$100,000	$100,000
NPV Single Tool	$(905,000)	$(1,614,091)	$(2,169,683)	$(2,605,003)
NPV PRRT	$(1,652,000)	$(2,082,939)	$(2,420,592)	$(2,685,151)
PRRT Savings	$(747,000)	$(468,848)	$(250,909)	$(80,148)

Table 4.3: Costs associated with changeovers for the 2 style vehicle case (r= 0.05).

2 Styles	0 changeover	1 changeover	2 changeovers	3 changeovers
Reprogram Cost	$100,000	$100,000	$100,000	$100,000
NPV Single Tool	$(1,641,000)	$(2,926,766)	$(3,934,198)	$(4,723,547)
NPV PRRT	$(2,203,000)	$(3,025,702)	$(3,670,311)	$(4,175,379)
PRRT Savings	$(562,000)	$(98,936)	$263,887	$548,168

Table 4.4: Costs associated with changeovers for the 3 style vehicle case (r= 0.05).

3 Styles	0 changeover	1 changeover	2 changeovers	3 changeovers
Reprogram Cost	$100,000	$100,000	$100,000	$100,000
NPV Single Tool	$(2,462,000)	$(4,391,041)	$(5,902,496)	$(7,086,760)
NPV PRRT	$(2,743,000)	$(3,957,466)	$(4,909,031)	$(5,654,608)
PRRT Savings	$(281,000)	$433,576	$993,465	$1,432,152

Table 4.5: Costs associated with changeovers for the 4 style vehicle case (r= 0.05).

4 Styles	0 changeover	1 changeover	2 changeovers	3 changeovers
Reprogram Cost	$100,000	$100,000	$100,000	$100,000
NPV Single Tool	$(3,282,000)	$(5,853,533)	$(7,868,396)	$(9,447,094)
NPV PRRT	$(3,322,000)	$(4,928,229)	$(6,186,751)	$(7,172,836)
PRRT Savings	$(40,000)	$925,304	$1,681,645	$2,274,258

because all of the results are negative. This follows the logic that a flexible tool will never be used for single production lines. As the style count increases, more and more positive cost differences appear which means that PRRT is becoming cost effective. Sensitivity analysis can be done to investigate the effects of both changing reprogram costs and discount rates for each style count. Outputs from this analysis indicate the number of changeovers required before the PRRT becomes cost effective. See Tables 4.6-4.8 for the results of these sensitivity analyses.

Table 4.6: Data Table Outputs for Single Style Vehicle Production

Single Style	r= discount rate				
PRRT Reprogram Cost ($)	r= 0.02	r= 0.04	r= 0.06	r= 0.08	r= 0.1
25000	3	not possible	not possible	not possible	not possible
50000	3	not possible	not possible	not possible	not possible
75000	not possible	not possible	not possible	not possible	not possible
100000	not possible	not possible	not possible	not possible	not possible
125000	not possible	not possible	not possible	not possible	not possible
150000	not possible	not possible	not possible	not possible	not possible
175000	not possible	not possible	not possible	not possible	not possible
200000	not possible	not possible	not possible	not possible	not possible
225000	not possible	not possible	not possible	not possible	not possible
250000	not possible	not possible	not possible	not possible	not possible
275000	not possible	not possible	not possible	not possible	not possible
300000	not possible	not possible	not possible	not possible	not possible
325000	not possible	not possible	not possible	not possible	not possible
350000	not possible	not possible	not possible	not possible	not possible
375000	not possible	not possible	not possible	not possible	not possible
400000	not possible	not possible	not possible	not possible	not possible

When producing one vehicle, it shows that the only opportunity for cost savings with PRRT is at a low reprogram cost combined with a low discount rate. Unfortunately, even then PRRT is only cost effective after the third changeover. Therefore, it agrees with the fact that multi-style tools will not be used when producing a single vehicle.

Table 4.7: Data Table Outputs for Two Style Vehicle Production

Two Styles	r= discount rate				
PRRT Reprogram Cost ($)	r= 0.02	r= 0.04	r= 0.06	r= 0.08	r= 0.1
25000	2	2	2	2	2
50000	2	2	2	2	3
75000	2	2	2	2	3
100000	2	2	2	3	3
125000	2	2	2	3	3
150000	2	2	2	3	not possible
175000	2	2	3	3	not possible
200000	2	2	3	3	not possible
225000	2	3	3	not possible	not possible
250000	2	3	3	not possible	not possible
275000	3	3	not possible	not possible	not possible
300000	3	3	not possible	not possible	not possible
325000	3	not possible	not possible	not possible	not possible
350000	3	not possible	not possible	not possible	not possible
375000	not possible	not possible	not possible	not possible	not possible
400000	not possible	not possible	not possible	not possible	not possible

In the case of two vehicle production, there is a much greater chance of cost savings when using PRRT. At lower reprogram costs and lower discount rates, the cost savings begin happening at the second changeover. As both get larger, the cost savings begin to occur during the third changeover. At high reprogramming costs and high discount rates, it is not possible to reduce overall costs under 3 changeovers.

Table 4.8: Data Table Outputs for Three Style Vehicle Production

Three Styles	r= discount rate				
PRRT Reprogram Cost ($)	r= 0.02	r= 0.04	r= 0.06	r= 0.08	r= 0.1
25000	1	1	1	1	1
50000	1	1	1	1	1
75000	1	1	1	1	1
100000	1	1	1	1	1
125000	1	1	1	1	1
150000	1	1	1	1	1
175000	1	1	1	1	1
200000	1	1	1	1	1
225000	1	1	1	1	1
250000	1	1	1	1	1
275000	1	1	1	1	1
300000	1	1	1	1	1
325000	1	1	1	1	1
350000	1	1	1	1	1
375000	1	1	1	1	1
400000	1	1	1	1	1

The three vehicle production case showed the best results in that the money savings will occur in the first changeover regardless of the discount rate and reprogramming cost. Because the first changeover was the dominant answer for all possibilities, it was unnecessary to calculate the four style changeover savings.

From the analysis it was found that the cost per vehicle increases as the style count increases, regardless of scenario. Other tool options are more cost effective than PRRT even at high style counts. However, when one considers the cost benefits that accompany product changeover together with product mix, PRRTs begin to provide a cost effective solution.

Table 4.9: Single Vehicle Data Set

1 VEHICLE: 200,000 TOTAL PRODUCTION VOLUME	
VEHICLE 1 COSTS	
TOTAL PROD VOL	UNSHARED EQUIPMENT UNSHARED TOOLS
10,000	$681.23
20,000	$340.89
30,000	$227.44
40,000	$170.72
50,000	$136.69
60,000	$114.00
70,000	$100.82
80,000	$92.92
90,000	$82.66
100,000	$74.45
110,000	$70.86
120,000	$65.00
130,000	$60.04
140,000	$58.00
150,000	$55.55
160,000	$53.44
170,000	$50.33
180,000	$48.74
190,000	$49.24
200,000	$48.26

Table 4.10: Two Vehicle Data Set

2 VEHICLES: 200,000 TOTAL PRODUCTION VOLUME					
VEHICLE 1 COST					
TOTAL PROD VOL	UNSHARED EQUIPMENT UNSHARED TOOLS	SHARED EQUIPMENT UNSHARED TOOLS	SHARED EQUIPMENT SHARED TOOLS		
			TDS	PRRT	TURNTABLE
10,000	$1,361.91	$812.26	$696.09	$831.76	$818.72
20,000	$681.24	$406.42	$348.33	$416.17	$409.64
30,000	$454.35	$271.13	$232.41	$277.63	$273.29
40,000	$340.91	$203.49	$174.45	$208.37	$205.11
50,000	$272.84	$162.91	$139.67	$166.81	$164.20
60,000	$227.46	$135.85	$116.49	$139.10	$136.93
70,000	$195.05	$122.45	$103.35	$125.23	$123.62
80,000	$170.74	$112.30	$95.18	$115.89	$113.57
90,000	$151.83	$99.89	$84.67	$103.08	$101.01
100,000	$136.71	$89.96	$76.26	$92.83	$90.97
110,000	$124.33	$86.76	$72.76	$89.49	$87.86
120,000	$114.02	$81.50	$68.48	$84.11	$82.54
130,000	$105.29	$75.27	$63.26	$77.68	$76.24
140,000	$100.83	$72.16	$60.99	$75.05	$73.04
150,000	$96.27	$67.39	$56.96	$70.08	$68.21
160,000	$92.94	$65.80	$54.93	$68.33	$66.68
170,000	$87.51	$61.96	$51.73	$64.34	$62.79
180,000	$82.68	$60.86	$50.22	$63.10	$61.73
190,000	$78.36	$61.02	$50.67	$63.76	$61.85
200,000	$74.47	$59.46	$49.61	$62.07	$60.23

Table 4.11: Three Vehicle Data Set

3 VEHICLES: 200,000 TOTAL PRODUCTION VOLUME					
VEHICLE 1 COST					
TOTAL PROD VOL	UNSHARED EQUIPMENT UNSHARED TOOLS	SHARED EQUIPMENT UNSHARED TOOLS	SHARED EQUIPMENT SHARED TOOLS		
			TDS	PRRT	TURNTABLE
10,000	$2,042.79	$943.37	$712.00	$957.91	$949.54
20,000	$1,021.53	$471.90	$356.23	$479.17	$474.98
30,000	$681.24	$314.81	$237.69	$319.65	$316.86
40,000	$511.09	$236.25	$178.42	$239.89	$237.79
50,000	$408.96	$189.11	$142.84	$192.02	$190.34
60,000	$340.91	$157.69	$119.13	$160.11	$158.72
70,000	$292.29	$144.07	$106.01	$146.14	$145.32
80,000	$255.82	$131.66	$97.59	$134.43	$133.13
90,000	$227.46	$117.10	$86.81	$119.55	$118.41
100,000	$204.77	$105.45	$78.19	$107.66	$106.62
110,000	$186.21	$102.65	$74.76	$104.78	$103.99
120,000	$170.74	$96.25	$70.35	$98.22	$97.53
130,000	$157.65	$88.90	$64.98	$90.71	$90.07
140,000	$146.43	$84.82	$62.58	$87.04	$85.88
150,000	$136.71	$79.20	$58.45	$81.28	$80.19
160,000	$128.20	$78.15	$56.50	$80.09	$79.24
170,000	$120.69	$73.58	$53.21	$75.42	$74.61
180,000	$114.02	$72.96	$51.77	$74.69	$74.07
190,000	$108.05	$72.77	$52.17	$74.91	$73.78
200,000	$102.67	$70.64	$51.04	$72.68	$71.57

Table 4.12: Four Vehicle Data Set

4 VEHICLES: 200,000 TOTAL PRODUCTION VOLUME					
VEHICLE 1					
TOTAL PROD VOL	UNSHARED EQUIPMENT UNSHARED TOOLS	SHARED EQUIPMENT UNSHARED TOOLS	SHARED EQUIPMENT SHARED TOOLS		
			TDS	PRRT	TURNTABLE
10,000	$2,723.25	$1,074.30	$732.59	$1,083.88	$1,080.16
20,000	$1,361.91	$537.43	$366.58	$542.22	$540.37
30,000	$908.13	$358.48	$244.58	$361.67	$360.43
40,000	$681.24	$269.00	$183.58	$271.40	$270.47
50,000	$545.11	$215.32	$146.98	$217.23	$216.49
60,000	$454.35	$179.53	$122.57	$181.12	$180.50
70,000	$389.53	$165.68	$109.36	$167.05	$167.01
80,000	$340.91	$151.03	$100.81	$152.97	$152.70
90,000	$303.09	$134.31	$89.67	$136.03	$135.80
100,000	$272.84	$120.94	$80.76	$122.49	$122.28
110,000	$248.09	$118.54	$77.35	$120.07	$120.13
120,000	$227.46	$111.01	$72.82	$112.33	$112.52
130,000	$210.01	$102.51	$67.26	$103.73	$103.91
140,000	$195.05	$97.48	$64.70	$99.04	$98.73
150,000	$182.08	$91.02	$60.43	$92.47	$92.18
160,000	$170.74	$90.50	$58.53	$91.86	$91.80
170,000	$160.73	$85.21	$55.12	$86.49	$86.43
180,000	$151.83	$85.06	$53.73	$86.27	$86.41
190,000	$143.87	$84.53	$54.14	$86.06	$85.72
200,000	$136.71	$81.82	$52.92	$83.28	$82.91

5. Market Penetration

The analysis in Chapter 4 has shown that flexible tooling has great potential for cost savings during changeover in the automotive industry. But what is the potential for savings in other industries of large-scale production?

At least one example of flexible tooling outside of automotive manufacturing exists in the aerospace industry. Bombardier has developed two forms of flexible tools which can hold different sizes and shapes of fuselages. This technology involves tricept tooling (Figure 5.1a) and axis nacelle tooling (Figure 5.1b). Each system has moveable pistons which can move to the shape

Figure 5.1: Bombardier Aerospace technology: **a)** tricept tooling and **b)** axis nacelle tooling[3].

of the fuselage, keeping it steady during resistance spot welding or adhesive application.

Flexible tooling, like PRRT, could have a major impact on any industry where there is large scale resistance spot welding; for example, trains and naval architecture. The demand for trains and ships is most likely lower than that of particular vehicle styles, but there are still costs associated with changeovers that can be greatly reduced as shown by this analysis.

6. Conclusions and Future Work

6.1. Conclusions

Because demand is always changing, it is hard for vehicle manufacturers to predict which product will see as well as the amount that will sell. To combat the uncertainty, companies have been pushing to become more and more flexible, first with common subassemblies in the different styles of vehicles, and now with flexible tooling, such as PRRT. Companies hope that the tooling will help curb the lead time that accompanies volume-mix changeover and ultimately full product changeover.

The actual tool choice algorithm created in this project is correctly selecting tools based on part count, subassembly size, group method applicability, and type (geoset, idle, respot). The cost outputs for 2 styles at a 200,000 vehicle production level where both tools and equipment are unshared are equal to the cost outputs for a single vehicle at 100,000. It appears to be choosing correctly based on sharing strategy inputs because the correct amount of tools show up as outputs.

When looking at production at the volume-mix level, PRRT does not appear to be the least expensive option. However, as the vehicle count increases, the cost difference as compared to single vehicle production begins to decrease. By the fourth style, it almost mimics the turntable cost difference. Again, the PRRT scenario is comprised of methods that had to run on their own sharing strategy which highly influenced the cost.

The most positive results came from the analysis of changeover cost savings due to PRRT using NPV calculations. It was found that PRRT will become cost effective after the first changeover for three vehicle production and higher. For the two vehicle production, PRRT is cost effective for low discount rates and low reprogramming costs, but only after the second or third changeover.

6.2. Future Work

Now the criteria for the tool choice algorithm run off of subassembly size and part count. However, the validation showed that there is a large amount of overlap with the range of part numbers each fixture can hold, namely with the auto-weld fixtures. It was proposed by an automotive manufacturing expert that running off the join count might be a better criteria option. Analysis should look to see if this is only necessary for the auto-weld fixtures, or if this needs to be adapted for all fixtures.

Also, while the tool choice algorithm has been constructed to handle five vehicles, the assembly model is only able to analyze four at a time. Because the automotive manufacturers are considering five or more styles on a single body assembly line, the model needs to be able to produce results on that style count.

In order to get better cost results, it would be interesting to see what happens when full vehicle assembly characteristics are analyzed with the model. This will provide more cases where PRRTs can be utilized with a reduced reliance on fixed tooling. Furthermore, the cost outputs would be more realistic if an entire set of vehicle subassemblies were analyzed.

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