A TECHNICAL AND ECONOMIC ANALYSIS OF STRUCTURAL COMPOSITE USE IN AUTOMOTIVE BODY-IN-WHITE APPLICATIONS

by

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Department of Technology and Policy on May 8, 1998 in Partial Fulfillment of
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and Engineering and Master of Science in Technology and Policy

ABSTRACT

A polymer composite body-in-white (BIW) design was analyzed to determine its competitive position in relation to the industry standard steel design. Three types of polymer composite materials were studied: glass reinforced vinyl ester composite, carbon fiber reinforced vinyl ester composite and sheet molding compound. The glass and carbon fiber reinforced composites are manufactured using the resin transfer molding process. A current steel vehicle design was chosen

To study the manufacturing and assembly costs of the body-in-white designs, technical cost models were used. The analysis showed that a carbon fiber reinforced BIW is cost effective only at very low production volumes (5,000 vehicles per year), primarily due to the cost of the reinforcement material. Glass reinforced designs using the SMC and RTM processes can be competitive up to about 35,000 vehicles per year because of relatively low capital investment costs. In addition to the analysis of the complete BIW, subsystems within the design were also studied. The subsystem analysis indicates that polymer composite materials could be competitive at production volumes as high as 75,000 per year, primarily due to parts consolidation.

Thesis Supervisor:	Professor Joel Clark
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Table of Contents

List of Figures

List of Tables

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Chapter 1: Introduction

INDUSTRY OVERVIEW

Alternative materials technologies promise increased design flexibility, improved damage resistance and lighter weight (among others) over the steel designs that are currently in production. To understand why such features are desirable and why a composite intensive vehicle may become an attractive platform for an automaker to consider, the state of the automobile industry must be analyzed. There are three factors driving the research and development efforts of the industry: competition, government legislation and consumer forces.

Competition

Imports began to gain a foothold in the market in the 1960's by offering an alternative in styling and design to American consumers. The small, economical European design, led by the Volkswagen's Beetle, represented a definitive departure from large, expensive American cars. By introducing their own scaled-down models, the US car makers were able to repulse this first attack on the market they had dominated. However, the 1970's provided transforming forces to the domestic automobile market that even the Big Three could not control.

The oil shocks of 1973-74 and 1979-80 allowed European and Japanese auto-makers to gain inroads into a market previously dominated by the Big Three (General Motors, Ford and Chrysler) by offering smaller, less gas-hungry vehicles. From the 1960's onward, the Japanese automakers had used superior manufacturing practices to win significant portions of market share away from the domestic and European manufacturers. The oil crises only accelerated the flight of consumers away from the domestic product to Japanese imports. In 1955, the Big Three accounted for 95 percent of all sales; in 1994, US automakers' total market share was only 64 percent. [Womack, 1990] [Fine, 1996]

During the 1980's, the domestic automakers struggled to change their manufacturing methods, which could not compete economically with the Japanese method of lean production because of quality, efficiency and waste problems. Through radical reforms in their manufacturing processes and organizational inefficiencies, the US car makers staged a comeback during the mid-1990's, offering a more competitive product and winning back customers. However, the Japanese and resurgent European companies have also kept pace; as a result, the current market is intensely competitive and there are enormous pressures on each company to innovate with improvements in technology, cost and quality.

Legislation

Legislation has long been an influential force in the auto industry. The 1966 Motor Vehicles Safety Act has placed strict guidelines on the crash worthiness of all vehicles. In addition to safety, environmental concerns about vehicle emissions have resulted in legislation. Governmental policy makers established CAFE (Corporate Average Fuel Economy) requirements in 1976, setting minimum standards for fuel efficiency of each auto-maker's product line and penalizing manufacturers not meeting this standard. Currently, the fleet of each auto-maker must average at least 27.5 miles per gallon. For every 0.1 miles per gallon below this minimum standard, the automaker is required to pay a $5 fine for every vehicle in its fleet. Although increasing the CAFE threshold has been considered in Congress recently, the requirement has remained unchanged for the past seven years due to lobbying pressures by the automotive industry. In addition to CAFE, the Clean Air Act of 1973 and its amendments allowed the government to strictly regulate automotive exhaust emissions. Finally, individual states have passed or are considering a requirement that a certain percentage of a company's sales be from zero or low emissions vehicles.

Consumer

As the industry has matured, consumers have become more sophisticated and more demanding of the manufacturer's products. The change in consumer preferences is dramatic; from Henry Ford's offering of the Model T in one color (black) to today's myriad choices of colors, features and models. Today, cars must be less costly, more technically advanced, more fuel efficient, more reliable, more stylish and more safety-conscious. In addition, cars must be able to differentiate themselves from a number of competitors offering a similar product. Between 1982 and 1990, the Japanese automakers have increases their product portfolio from forty-seven to eighty-four models and the US automakers have increased the number of their offerings from thirty-six models to fifty-three. [Womack, 1990] Adding to competitive pressures, consumers are keeping cars longer and also buying more used cars as vehicle prices continue their upward trend. This results in greater pressure and competition between automakers to create innovative products to stimulate demand.

While increasing demand in developed countries may be difficult, emerging markets offer a large potential consumer base and the automobile industry has been active in developing manufacturing capabilities in many of these markets. As profit margins decrease in mature markets, the developing nations will increase in importance for firms seeking new revenue generating opportunities.

LIGHT-WEIGHTING

One of the most effective strategies satisfying the demands of both the consumer and the government, as well as retaining a technological edge over competitors, is that of vehicle light-weighting. Weight reduction increases fuel economy by decreasing the power necessary to accelerate the vehicle. Therefore, less fuel is consumed and less particulate matter is emitted from a lighter vehicle, all else being equal. In addition to environmental benefits, decreasing vehicle weight allows the manufacturer increased design flexibility with which to meet the preferences of the consumer. A lighter vehicle enhances performance characteristics (such as 0-60 time, top speed) without any engine modifications. Weight savings in one area allows a designer to build in additional, weight increasing features in other areas, such as airbags, without adversely impacting the automaker's CAFE rating. Finally, as consumers become increasingly aware of the environmental damage caused by automobile pollution, the demands of the consumer market and government policy for more environmentally conscious products can be satisfied through vehicle light-weighting.

There are two techniques for reducing vehicle weight. The first is to decrease the size of the vehicle itself and thus decrease weight. This was the Japanese auto-maker's strategy in the 1970's, which proved successful for a time. Over the past 25 years, the average weight of a new automobile has decreased from 4000 pounds to 2500 pounds, mainly due to the shift to smaller vehicles. However, there are obvious disadvantages to decreasing vehicle size; there is an inherent limit on how small a car can be and interior space is highly valued by the consumer. An alternative is to make parts lighter through materials substitution. This strategy, among others, is currently being pursued in the automotive industry.

Generally, there are three types of functional components that comprise an automobile: powertrain, electronics and the body-in-white. While there are light-weighting opportunities in the powertrain and the electronic components, this report will focus on materials substitution for the body-in-white (BIW). The BIW is an automotive term which refers to the structural, load-bearing frame of the vehicle. The BIW comprises approximately 25% of the total vehicle weight so that materials substitution strategies in the BIW components can have a significant impact on achieving a lightweight design. There are three material classes that can meet the necessary physical characteristics of BIW parts: steel, aluminum and composite materials.

STEEL

The dominant material used in manufacturing the BIW is stamped steel. Steel is still used in the majority of vehicles today, but aluminum and composite materials are capturing small segments in the market and have the potential to be major competitors to steel. Steel's dominance is due to its low material cost, low cycle times, ease of forming and good mechanical properties. In addition, steel stamping and welding processes have been utilized in the car industry for decades, such that the knowledge base of processing characteristics and techniques is well documented for this technology.

Although there are many advantages of manufacturing with steel, alternative materials, are poised to attack steel's market position. Recognizing that future market share and profits could potentially be jeopardized, the American Iron and Steel Institute (AISI) sponsored a study in 1992 to research the feasibility of light-weighting using steel. The results of the initial study prompted a more detailed investigation and the Ultralight Steel Auto Body (ULSAB) consortium was formed in 1994. The goal of ULSAB is to reduce the weight of a steel BIW design (based on an average mid-sized sedan), utilizing current or near term manufacturing technologies. The first phase of the project consisted of producing a concept design. In the second phase, the conceptual structure was used to produce prototypes, which underwent testing and validation studies. From the results of the second phase study, the consortium claims a 25% reduction in weight, equal or improved structural characteristics and an economically competitive design.

ALUMINUM

Aluminum is generally regarded as closest to competing with steel in the near term. One of the primary benefits of aluminum manufacture is that its processing and assembly methods are similar to those employed when using steel. In addition, the design process for aluminum parts is similar to steel and therefore can draw upon an established database of design information. Aluminum's similarity to steel in the areas of manufacture and design are significant because of the auto industry's multi-billion dollar investment in steel manufacturing capabilities constrains any radical shift in the near term. While aluminum parts production will require some modifications to the current process, car makers would not have to make the difficult choice of abandoning equipment and familiarity to manufacture an aluminum BIW.

Aluminum is an attractive material to consider for potential light-weighting applications. The density of aluminum is approximately 2.7 g/cc, compared to 7.9 g/cc for steel. This advantage is somewhat tempered by the requirement that aluminum parts must be made thicker than their steel counterparts because of the differences in physical properties between the two materials. The main disadvantage of using aluminum is high raw material cost. Aluminum sheet used in automobiles costs roughly $1.50/lb while sheet steel can be purchased for approximately $0.30/lb. Although fewer pounds of aluminum are used in the BIW, an aluminum design still pays a manufacturing cost penalty relative to steel. Depending on the design of the BIW (spaceframe or unibody), studies have demonstrated that the aluminum design is economically competitive with steel at annual production volumes of 30,000 vehicles or less. [Politis, 1995]

Despite the cost disadvantages, several manufacturers have introduced aluminum intensive BIW designs, with the support of the aluminum industry (notably Alcoa and Alcan) which hopes to capture future business in the enormous automotive raw materials market. The most notable design is the current Audi A8, which utilizes an aluminum space frame design. The A8 is a high end luxury vehicle, competing with the Mercedes S class and the BMW 7 series. Other aluminum intensive designs include the Acura NSX and the Plymouth Prowler. Many, if not all, of the major automotive manufacturers are seriously researching aluminum. Ford Motor Company's Aluminum Intensive Vehicle program produced 40 prototypes based on the Taurus/Sable line to investigate the manufacturing implications of volume production.

POLYMER COMPOSITES

The first modern application of a polymer composite material was glass reinforced, phenolic-nylon material used in a fishing pole. Other industries have recognized some of the substantial benefits of composite materials and have incorporated polymer composites into their designs. Composites have been used for many years in the automotive industry because their unique characteristics make them attractive in certain applications.

Strength and Stiffness

A key to light-weighting using composite materials is that their strength and stiffness to weight ratios are superior to those of steel used in conventional automotive applications. This allows polymer composite parts to be lighter than a comparable steel part while offering similar mechanical properties. Decreased weight directly effects the energy consumption and performance characteristics of a vehicle. This is the main driving force behind the increasing popularity of composites in the aerospace industry.

Damping Characteristics

Due to the resin, vibration in composite parts are reduced, while the stiffness of the fibers give the part the required performance characteristics. Vibrations in plastic materials are damped because microcracking, viscoelastic effects and plasticity of the polymer matrix decrease the vibration transmission through the material. As a result, damping performance can be significantly higher that that of steel. Decreased vibration is desirable in the automotive industry because it allows increased NVH (noise, vibration, harshness) performance, which corresponds to consumers' perceptions about vehicle quality.

Fatigue Resistance

Fatigue resistance is the ability for a material to sustain loading over many cycles. Polymer composites have been shown to be more fatigue resistant than steel and aluminum. The fiber reinforcement serves to retard the effects of sustained loading. Cracks in the materials are blunted by the fiber and therefore, the rate of crack growth is reduced. In addition, when some fibers fail, a redistribution of stresses occurs among the remaining fibers so that fatigue is more stable and forgiving. As a result of improved fatigue resistance, the durability of load bearing mechanisms can be increased.

Ability to Tailor Properties

Polymer composites are constructed by laying down mats of fiber reinforcements. Fibers can be aligned in a specific direction so that by laying down mats at different angles, the part will accommodate stresses in different directions. Conversely, if a load is uniaxial, the fibers can all be aligned in the direction of the stress. This allows physical properties to be precisely tailored according to the expected load characteristics of the application.

Energy Absorption

Energy absorption is critical to the crashworthiness of a vehicle. There are a number of ways in which polymer composites absorb energy so that crash performance is comparable to or greater than that of steel. First, matrix microcracking serves to absorb energy through the breakage of polymer bonds. Second, viscoelastic properties of the matrix results in great energy dissipation. A dramatic example of the energy absorption capabilities of composite materials is displayed when a Formula One racing car collides into a wall or another car. The car is typically constructed from polymer composite using carbon fiber reinforcement. The material fails catastrophically, absorbing great amounts of energy and protecting the driver even at high speed.

Corrosion Resistance

Polymers generally exhibit superior resistance to a wide range of chemical attack and do not experience oxidation (rust) as steel would. This is of great benefit for automobile manufacturers who can eliminate the galvanizing and other anticorrosion processes currently used to rustproof steel parts.

However, composites are susceptible to some other forms of attack. Although the polymer resin is highly chemical resistant, the reinforcement may not be, in some instances. E-glass fiber can be attacked by mild acids and alkalis. Carbon fiber, because it is a conductor of electricity, can experience galvanic corrosion if it comes into contact with metals. However, if properly manufactured, the polymer resin can act as a barrier to these agents; these coatings can also be used to provide further protection. Therefore, the environment and the types of agents that a composite part comes into contact with must be carefully considered to choose the correct formulation.

Complexity of Design

Another important benefit of composite materials use is its inherent design flexibility. Steel stamping uses a downward force to form a steel sheet into the shape of the mold. This method of forming constrains the design of the part since there are geometric and material limitations. However, liquid molding processes used to produce composite parts are not limited in this way and allow more radical shapes to be produced. In addition, design flexibility potentially allows the consolidation of multiple steel pieces into a single composite part. Reducing the number of parts through parts consolidation results in lower tooling and assembly costs.

Chapter 2: Problem Statement

The body-in-white (BIW) is defined as the set of parts in an automobile that bear static and dynamic loads and also impart torsional stiffness. With very few exceptions, the body-in-white is composed of a number of stamped steel parts that are welded together. Although steel has long been the dominant material, viable alternative materials technologies, in particular, aluminum and polymer composites, are gaining attention in the automotive industry. This study will concentrate on an analysis between polymer composite and steel BIW designs.

There are a number of advantages to using steel in the manufacture of the body-in-white. First, its strength and stiffness characteristics are suitable to make a rigid vehicle structure. Second, steel is relatively easy to form into parts and its forming characteristics have been studied for many years, building familiarity through experience for engineers and factory workers. Third, the cycle time to stamp out a steel part is on the order of seconds. Finally, steel raw material is relatively inexpensive.

Despite steel's beneficial properties, composite materials have a chance to compete with steel due to some of its drawbacks. First, it is very difficult to form complex parts in steel without having to decompose the larger part into a set of smaller parts that are welded together. The additional forming and assembly steps add to the overall manufacturing cost. Second, steel is vulnerable to corrosion, prompting additional steps during the painting process to provide a measure of corrosion resistance. Third, steel parts are relatively heavy compared to polymer composites. Finally, the capital expenditure required for equipment and tooling for steel manufacture is significantly greater than for the composites manufacturing process.

Although steel is an excellent material in many respects, composite materials offer promising improvements. Most obviously, polymer composites offer significant potential for weight savings over steel. Composites use also has other potential benefits, such as improved strength and stiffness characteristics, increased corrosion resistance and greater parts consolidation opportunities. However, the major concern regarding polymer composites (and other alternative materials) is the economic aspect. Since material costs tend to be higher than for steel and processing times slower, it is questionable whether polymer composites can effectively compete in the cost arena with parts fabricated from steel. Because the automotive industry is so competitive, cost is a major decision factor.

There have been attempts to study materials selection decisions by comparing the economics of a direct part-for-part substitution of composite materials for steel. [Hendrichs, 1989] However, this is an incomplete analysis; substituting a different material for a part that had been designed in steel does not take into consideration all of the new material's potential advantages. For example, polymer composites can be easily formed into almost any shape and size. Therefore, a system consisting of multiple parts in a steel design can potentially be incorporated into one piece using polymer composites. In order to compare different materials more rigorously, the final part should be functionally identical while fully utilizing all of the advantages of each material. A composites-specific design allows engineers to fully incorporate the capabilities of polymer composites.

Given a design intended for composite materials, the thesis will attempt to answer the following questions:

- What is the economic performance that can be achieved with composite materials against the steel base case?
- Under what scenarios (factor price changes, technical progress, etc.) will the composite BIW be less expensive than the steel design?
- Given the results of the economic analysis, what other factors will effect the status of composite parts as a viable substitute for steel?
- What are the general technology and strategy implications of this analysis?

The thesis will concentrate on a cost comparison between polymer composites and steel for manufacturing the body-in-white. The composite body-in-white design will be based upon the Composite Intensive Vehicle project at Ford Motor Company. The original design used glass fiber reinforced polymer composite; however, the design can be modified to use sheet molding compound material and also carbon fiber reinforced polymer composites. The Honda Odyssey, a comparable minivan, will be used as the steel base case in which to compare the performance of the steel design against composite materials.

Manufacturing and assembly cost performance will be the primary measure to compare the designs. These costs will be estimated using technical cost models (TCM). The TCM is a spreadsheet based model which uses inputs about part characteristics and the manufacturing environment in order to output an estimate of total manufacturing cost. Four TCM's will be required to estimate the costs of the designs. Three models for SMC, steel stamping and assembly have been previously developed and the resin transfer molding (RTM) model was constructed to perform the cost analysis for the thesis.

Because of the competitive nature of the automotive industry, cost often drives most material selection decisions. Therefore, the majority of the work is dedicated to an analysis of the cost implications of materials. However, it is also important to take into account other decision criteria for acceptance of new materials technologies; to neglect these other factors would form an incomplete analysis. A discussion of the other factors influencing the business policy decisions of the automobile manufacturers will also be included.

Chapter 3: Technical Cost Modeling

Technical cost modeling is a methodology analyzing the economics of manufacturing technologies by capturing the key engineering and process characteristics which relate to the total production cost of a component (e.g., body-in-white parts). Technical cost models (TCM's) improve upon traditional cost estimating techniques by relying less on rules of thumb, past experience and specific accounting practices. In addition, spreadsheet-based TCM's are much more flexible in allowing the analysis of the effects of a wide range of operating conditions on the final manufacturing cost. As a result, TCM's are especially valuable for strategic decision making. The use of TCM's can give insight into the economics of competing material technologies and allow strategists to focus research and development efforts into a few, critical areas that can have significant impact on cost performance.

The central concept of technical cost modeling is that the total cost of a manufactured part can be broken down into contributions from various elements. Once the total cost is broken down into separate components, the task of analyzing costs becomes much simpler.

A natural segregation of cost elements is between those costs which are independent and those which are dependent on the amount of parts produced within a given time frame (typically, one year). Variable costs are independent of the number of parts produced on a per piece basis. For example, assume that some amount, X, of raw material is required to manufacture a part. If 100 parts were produced that year, 100*X pounds of raw material are required. However, for each individual part, the variable cost does not change since the amount of material, X, required is the same for each part, regardless of the production volume.

Conversely, fixed costs are capital investments which are distributed over the parts produced. Therefore, fixed costs per piece vary according to production volume; as production volume increases, fixed costs are lowered because the investment can be spread over more parts. For example, the cost of the building in which to operate is not influenced by how many parts are made in it annually (up to the capacity of the building); however, on a per piece basis, the investment cost of a building can be spread over the number of parts produced and thus increases or decreases as production volume changes.

FIXED AND VARIABLE COSTS

Variable Costs

On a per piece basis, variable costs are those cost components which remain the same regardless of production volume. Variable costs are composed of the following three elements:

1. Materials
2. Labor
3. Energy

Material Cost

The total material expense is the sum of all of the primary and secondary materials used in the operation. Primary materials are the raw and semi-finished material components of the fabricated part. The cost of these materials depends on the final part weight, engineering scrap, weight percents of raw material and the unit cost of material. In some instances, scrap can be resold to lessen material cost; recycling of steel scrap is common practice in the steel stamping factories. However, composite materials are typically thermosets, which cannot at the present time be economically recycled due to the irreversibility of the polymerization reaction. (The issue of recycling will be discussed in a later chapter.) Secondary materials are those used in the production process, such as cleaners and lubricating agents, which aid in the part manufacture but do not contribute to the material content of the final part. Secondary material cost is a function of the amount used and its unit cost.

Labor Cost

Labor costs include only those workers who are directly involved in the manufacturing process. Other personnel, such as managers and clerical staff, are not considered part of labor cost. Instead, they are accounted for as part of overhead. Labor costs are determined by the number of working hours, the number of laborers required per operation and the wage paid. Wage includes not only salary but also all benefits, such as health insurance and training.

Energy Cost

Energy cost accounts for the power requirements that arise from operating equipment. Generally, the machines run on electricity so that energy cost is a function of the machine's electricity usage, the amount of operating time and the unit cost of electricity. Other utility costs, such as gas and oil heating, are also captured in the energy cost calculation.

FIXED COSTS

Fixed costs are the investment costs that are necessary for the manufacturing facility. On a per piece basis, fixed cost components vary with the number of parts produced. These costs are labeled as fixed because they are typically a one time capital expenditure which is necessary to begin production (e.g., purchasing a stamping press). In the TCM's, there are seven fixed cost components:

1. Main Machine
2. Tooling
3. Overhead
4. Building
5. Auxiliary Equipment
6. Maintenance
7. Cost of Capital

Main Machine Cost

The main machine costs consist of the investment cost of a machine plus an additional cost of installation. The main machine refers to the primary piece of equipment in which value adding operations are carried out. Equipment cost mainly depends on the level of sophistication and the size of the equipment required. The characteristics of the part and the production volume are directly related to the cost of equipment. Bigger and more complex parts generally require larger, more sophisticated and more expensive machines. Increased production volumes require an investment in more machines to satisfy this demand. When purchasing a machine, installation costs are usually quoted by the vendor, usually as a percentage of equipment cost or a fixed amount. Since installation pricing varies by vendor, this cost is calculated in the model as a fixed percentage of the investment cost of the main machine.

Tooling Cost

The cost of tooling is an important element of the total cost for a process. Unfortunately, it is one of the most difficult components to model. Each individual part has geometric complexities which are only fully captured in a computer model or prototype. Only the most experienced tool fabricators will be able to estimate the effects of specific geometries on cost, and these relationships are not easily defined. As a result, the tooling cost equation is derived from a statistical analysis of tooling cost for various parts.

The tooling cost per set is a function of the part geometry and of the tool material. These relationships are determined through a regression analysis of industry data, relating cost to specific part characteristics. In addition, the relationships change for the various types of tool materials. Generally, more durable tool materials (such as steel) are costlier to produce relative to softer tool materials (such as epoxy). The number of tool sets required is a function of the production volume, productive tool life and the number of machines in the line.

Overhead Cost

Overhead cost accounts for those workers who are not classified as direct laborers, but are part of the production process. Indirect labor can include managerial, clerical, janitorial, security, etc. While the case can be made that overhead expenses are variable costs, assigning a janitor's number of hours worked per part produced is difficult. Therefore, overhead cost is simplified by assuming it to be a percentage of fixed costs.

Building Cost

Building cost accounts for the space requirements of the manufacturing line. Each operation requires a certain amount of floor space, which is a function of the size of the machine and the number of machines required per operation. The cost per unit area of floor space is based upon real estate values in a particular geographic region.

Auxiliary Equipment Cost

Auxiliary equipment is much like overhead labor; it is equipment not directly involved in the manufacturing process but necessary for production. Examples of auxiliary equipment can include transportation and storage equipment. Since the amount, cost and types of auxiliary equipment vary widely for each manufacturing facility, this cost is approximated by assuming it to be a percentage of main machine cost, which itself is a function of part characteristics and production volume.

Maintenance Cost

Maintenance costs result from performing upkeep on main machines, tools and auxiliary equipment. Predicting the cost of maintaining a piece of equipment is difficult, since there are many unexpected occurrences during a machine's lifetime. The cost of unscheduled maintenance varies according to the duration, frequency and timing of downtime. To avoid these complexities, maintenance is estimated by assuming a percentage of capital investment is allocated for maintenance expenses.

Cost of Capital

Whenever there are investments costs, the time value of money must be taken into account, since there are other potential uses for this money. For instance, instead of using the capital to buy equipment and tooling for a manufacturing facility, a bank account can be opened and interest payments can be collected. The cost of capital can be calculated as a payment on a loan or lost opportunity cost of money over this period of the loan. The cost of capital is a function of the expected machine life and the interest rate during this period. In some cost models, the cost of capital can be incorporated into the annual cost calculation of main machines and tooling; in other models, the cost of capital is a separate line item expenditure.

GENERAL INPUTS

The separation of cost components into fixed and variable costs provides a foundation for analyzing the total manufacturing cost. As shown in figure 1, the technical cost model employs user-supplied inputs and other assumptions about the operating environment in order to arrive at a calculation for fixed and variable costs.

Component Description

The general component description specifies the physical characteristics of the part to be produced. The description consists of part geometry (size, shape, weight), material requirements and material characteristics. For composites manufacturing, parts require several different raw materials, so that quantities and relevant material characteristics for each must be inputted.

Process Conditions

For each operation in the manufacturing process, processing conditions must be specified. These include the labor requirement, engineering scrap rates, rejection rates and required production volume for each operation.

Parameter Estimation Data

Estimations must be made for equipment capacity, equipment and tooling cost, energy usage, building space requirements and production rates. In the models, most of these production parameters are calculated using inputted equations and data from the other sets of inputs. Equations are based on engineering and scientific relationships, regression analyses and empirical data collected from industry.

Exogenous Cost Factors

Exogenous cost factors are the set of economic and production inputs that describe the manufacturing environment in which the part is produced. Production inputs include wages, available working time, maintenance cost, auxiliary equipment cost, building cost, utility prices and overhead costs. Economic inputs include the cost of capital, the capital recovery period and the building recovery life.

Dedicated / Non-dedicated Status

In addition to the above inputs, exogenous cost factors also include the dedicated/ non-dedicated status of machinery. Dedicated machinery is defined as machinery which exists solely to produce a specific part. The cost of machinery is then attributed to that part. On the other hand, non-dedicated machinery can produce many differentiated parts, so that each part "rents" the machine for a period of time and is charged accordingly. It should be noted that, regardless of whether a machine is dedicated or non-dedicated, tooling is always classified as dedicated, since the tooling is designed to manufacture only a specific part.

For the sake of simplicity, the composite processing models will assume that all machines are dedicated. This is a justifiable assumption, since composites manufacturing machinery produces parts for special applications unlike steel stamping, where a number of different kinds of parts can be manufactured using the same machine (although with different tooling). For manufacture of steel parts, machines will be considered non-dedicated. By designating a non-dedicated machine, equipment costs are lowered since the machine is always assumed to be fully utilized. On the other hand, a dedicated machine can have leftover time in which it is not being used to produce parts. This cost of the machine during this time must also be allocated to the part.

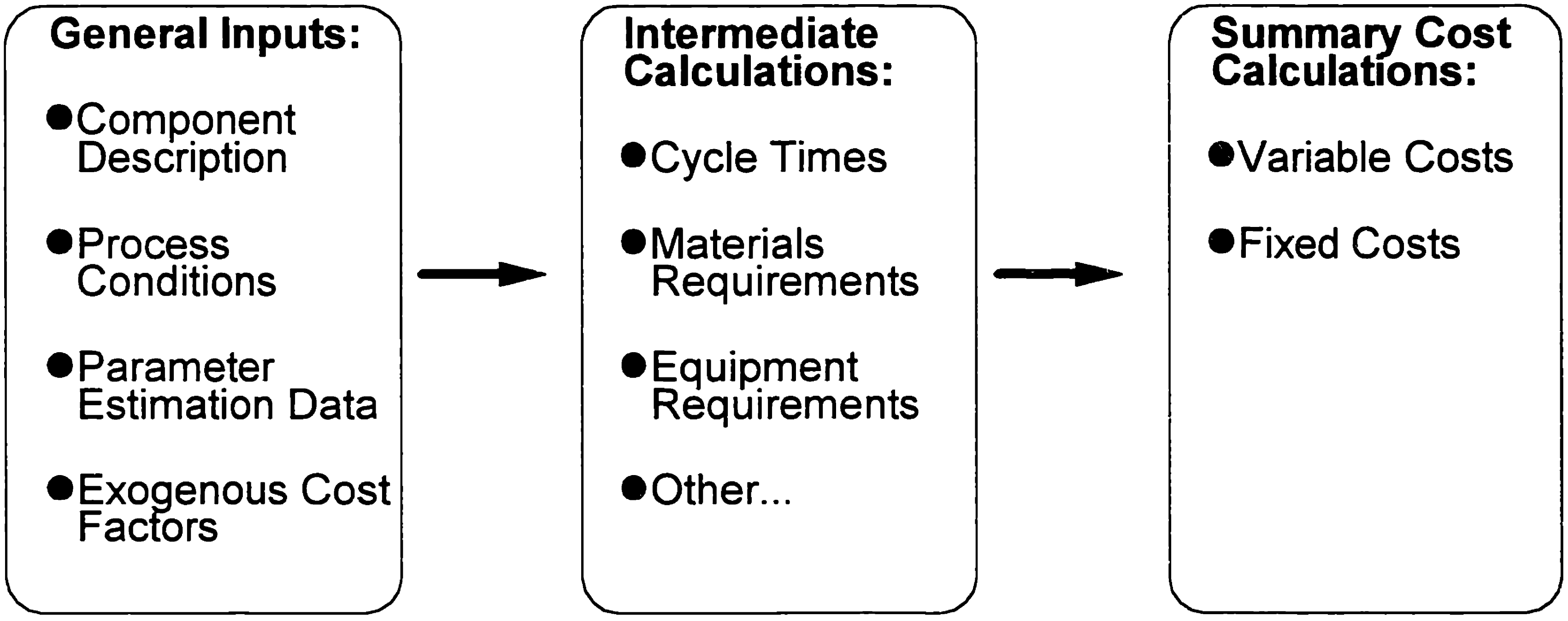

Figure 1: Conceptual Technical Cost Model

Chapter 4: Steel Stamping

PROCESS DESCRIPTION

Steel stamping has been studied extensively at the Materials Systems Laboratory for a number of years. References have been provided for a more comprehensive explanation of steel stamping processes and the associated cost models. [Han, 1994] [Park, 1988] This section will give a brief overview of the process and the cost model that has been used to formulate the economic analysis of the steel vehicle.

Parts are formed by the use of stamping presses which press steel sheet into the desired shape and trim off extraneous material. The presses are fitted with tools that perform a number of different operations, depending on the requirements of the final part. The operations can be divided into two main functions: blanking and stamping. A process diagram for steel stamping is shown on figure 2.

Blanking refers to the initial cutting of the sheet from the coil form in which steel arrives from the manufacturer. Coil is fed into blanking presses, where it is unrolled and cut into blanks, which are the input materials for the stamping operations that follow. Blanking generally occurs at a much faster production rate because the cutting operation is simpler and less demanding.

The blank then undergoes stamping operations to complete a finished part. Stamping involves a number of different operations including trimming, forming, drawing and flanging. The desired shape of the part determines the number and type of operations that must occur.

STEEL STAMPING COST MODEL

The steel stamping cost model is divided into modules based on the process description given above. To calculate costs, the model assumes that the user has knowledge about the part geometry and complexity of forming operations. As shown in Appendix A, the user inputs these part characteristics. Based on these inputs, the cost model then calculates the manufacturing cost required to produce the parts. The part geometry allows the model to calculate the amount of material required and the amount of scrap that can be recycled and credited toward the material cost incurred by the part. The part geometry and complexity inputs together determine the cost of tooling and stamping presses, how many presses are required and how long the forming operations will take. As part complexity increases, more stamping operations are required, thus increasing fixed costs as well as the time required to produce the part.

The steel stamping cost model has undergone continual refinement and adjustment as more information has been made available to improve the model. More detailed descriptions about the cost model are available in the Han and Park theses. There are two major assumptions used in the steel stamping cost model. First, it is assumed that the cost of the stamping presses are a function of the tonnage rating and bed size of the press. The tonnage rating indicates the amount of force that can be applied to a piece of steel. The bed size indicates the size limit that the press can accept. As the tonnage rating and the bed size increase, the cost of the press should also increase by some amount. To quantify this relationship, regression analysis of the press cost as a function of these two variables is used. Information about the cost of various types of presses was collected from manufacturers and used to provide data for the regression analysis. One of the major differences between the previous and current steel stamping models is that the calculations for equipment cost in current version has been simplified. For instance, the press tonnage, bed length and bed width were previously calculated using regression equations. However, press manufacturers sell presses in specific sizes and therefore, the equation can be simplified to account for only the standard press sizes that are available.

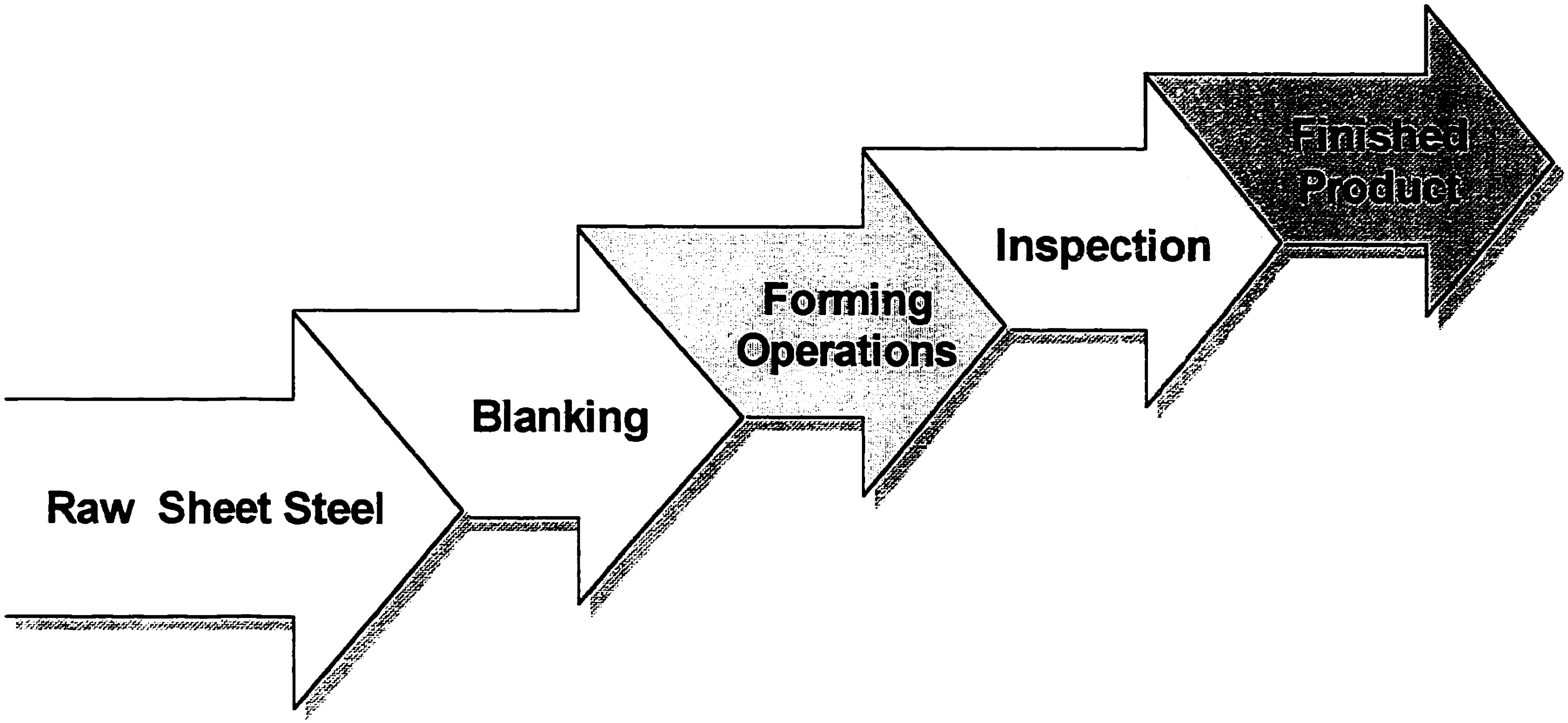

Figure 2: Conceptual Steel Stamping Process Flow

The second major assumption is that tooling cost is a function of the part geometry and the number of forming operations required to produce the part. The tooling cost regression equation takes into account three factors in determining cost. First, the number of forming operations determines the total number of tool sets required to outfit the press line. Next, the ratio of projected surface area to stamping surface area reflects a measure of the complexity of the tool. Finally, the length and width are measures of the size of the tool.

Chapter 5: Assembly

RESISTANCE SPOT WELDING

The methods used for attaching steel parts are very different from those used to attach composite parts. Resistance spot welding is the most common method used to join steel parts. In resistance spot welding, two parts are held in contact with each other between two electrodes. An electrical current is passed from the electrodes through the two parts. The steel parts produce a resistance to the flow of current at the interface, generating enough heat to produce a small melt pool of material. When the electric current ceases, the melt pool solidifies and creates a bond between the two parts.

Joining together a typical body-in-white requires 4,000 to 5,000 spot welds. As parts are attached, the type of spot welding done can be differentiated by the length between welds. Tack welding is used to hold parts in place during assembly and therefore fewer welds are required per unit length. While tack welding allows parts to stay together during the joining process, they must be reinforced by additional spot welds to produce a structurally sound join. In a typical length of join, there are 9.5 tack welds per meter and 29 spot welds per meter.

ADHESIVE BONDING

Composites are joined by applying adhesives at the interface between two parts. There are a number of adhesive formulations that exist and the aerospace industry has used adhesive joining techniques extensively in the assembly of airplanes. Epoxy adhesives are commonly used to join composite materials.

Adhesives can be classified as one or two stage. One stage adhesives have the curing agent premixed into the formulation. In contrast, the curing agent is mixed in just before the application of the adhesive for a two stage adhesive.

An adhesive bond is formed by applying an adhesive on the surfaces of the two parts. The surfaces must be clean and free of grease, dirt and other contaminants that would compromise the bond. The surfaces can also be roughened prior to the application to increase the bonding effectiveness of the adhesive. Roughening the surface increases the surface energy and the surface area to improve the bond between surfaces. The adhesive wets the surfaces when the two parts are joined together and a permanent bond is established, as the adhesive solidifies through the application of pressure and/or heat. A holding fixture is used to keep the surfaces in close contact as the adhesive cures.

When applied, the adhesive is in a liquid state and through heat or pressure, the adhesive is converted to a solid material. The conversion process can occur either by the evaporation of solvent or by the linking of many molecules within the material to increase density. The conversion from a liquid to a solid state is a complex reaction depending upon a number of factors such as temperature, chemical constituencies of the adhesive compound and pressure.

Unlike spot welding, adhesive bonding allows for a continuous join between two parts. In addition, the cost of adhesive material can be as expensive as $30 per pound. Therefore, the assembly design must consider and minimize the length of the join and adhesive material used per length in order to lower costs. However, because the join is continuous, it can be of exceptionally high strength and stiffness. In addition, the adhesive bond absorbs shock and vibration, which improves the NVH (noise, vibration harshness) characteristics of the automobile.

ASSEMBLY COST MODEL

The assembly model developed at MSL is used in developing cost estimates for the assembly of the three body-in-white material technologies. Marti and Jain, in their theses, have given a detailed description of the fundamentals and equations of the assembly model.

[Jain, 1997] [Marti, 1997] This section provides a brief summary of the more important aspects of the assembly process.

The assembly of an automotive body-in-white is accomplished by attaching various subassemblies together. A subassembly is a grouping of various parts which form a portion of the body-in-white. The subassembly groupings are chosen in order to facilitate and maximize the efficiency of the assembly process. In each subassembly step, a number of different techniques can be utilized to join parts together. These subassemblies are then joined together at the final assembly station to form the completed body-in-white. (Figure 3)

The assembly model calculates cost using relational databases to capture the relevant information needed to for each joining method. Sets of data are grouped into three tables; Parts, Groups and Group-Methods. The Parts table functions as an inventory of all parts included in the process. It identifies each part of the body-in-white and assigns a number to the part, denoting the subassembly grouping to which the part belongs. The Groups table then determines the method, join length and order in which the various subassemblies are to be joined. The Group-Methods table stores all of the information used to calculate costs for each joining method. Some examples of information stored in the Group-Methods table for each joining method would be equipment costs, number of laborers, material costs and process speed. In addition, the standard economic factors (wage, building prices, etc.) are also included in the Group-Methods table.

In order to calculate costs, the assembly model selects the necessary information stored within each table as inputs for the calculation. The Parts table allows the model to determine the number of parts to be joined in a particular subassembly. To join these parts, the Groups table contains information about the specific join methods and join lengths required to attach that particular subassembly. Finally, the Group-Methods table supplies the necessary cost information for the particular joining process to calculate the cost for that operation.

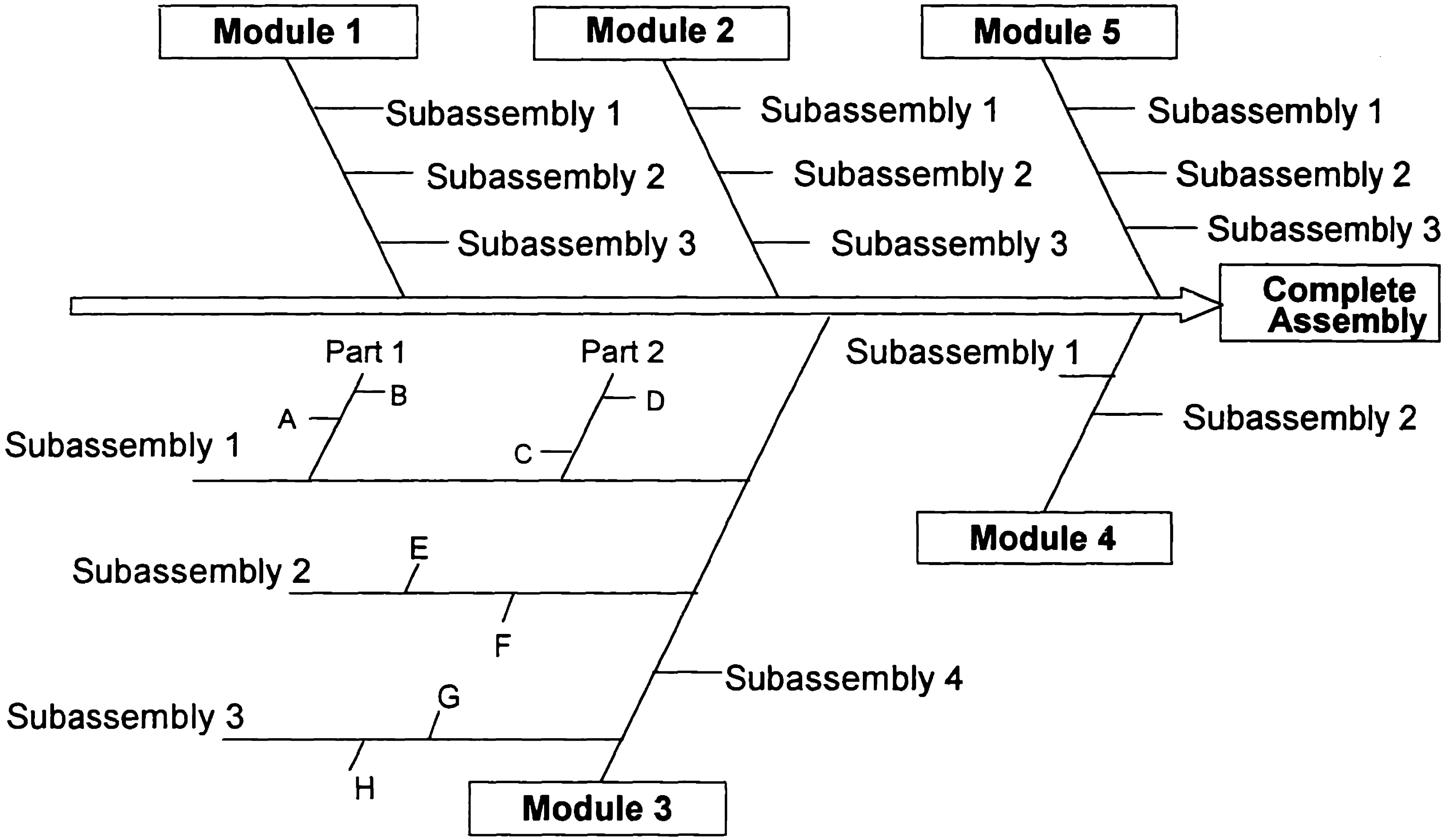

Figure 3: Conceptual Assembly Process

Chapter 6: Sheet Molding Compound

DESCRIPTION OF PROCESS

Sheet Molding Compound (SMC) is a composite material in which the resin, initiator, filler and reinforcement have already been pre-assembled in sheet form. SMC was developed in the mid-1960's and has been used primarily for body panel applications in the automotive industry; the most famous SMC application is the body paneling on the Chevrolet Corvette. To manufacture the SMC material, a resin/initiator mixture is first placed between two rolls. Chopped fiberglass is mixed into the resin by the rotating action of the resin. Thickening agents, such as magnesium oxide, can be added to the mixture in order to keep sheets together. The material then passes through a series of compaction rolls, which mixes the components and wets the fibers, and then is rolled into sheet form. The material is then aged, usually one day, resulting in a rubbery texture that is easy to handle and ship. Because of the initiator and thickener present in the resin mixture, the material has a finite shelf-life (usually two weeks, depending on storage conditions).

The process of manufacturing parts using SMC is shown in figure 4. When SMC is ready to be used, it can be cut into the desired shape. The protective plastic film is peeled off and the material can be placed into a preheated mold. Usually, multiple plies of the SMC are used to reinforce specific areas where greater strength is required. The completed pattern is called the charge. The mold closes onto the charge and the pressure (1000 to 5000 psi) applied in the mold causes the charge to flow and conform to the mold shape. At the same time, heat applied through the mold results in the activation of the initiator to begin the curing process, in addition to decreasing the material viscosity for better flow. The heat produced by the exothermic curing reaction is absorbed by the mold. The total molding cycle runs approximately three minutes at a typical temperature of 270 °F, depending on the thickness of the part and its material formulation. When the part is adequately cured, it can be taken out of the mold to undergo final finishing/trimming operations.

DESIGN CONSIDERATIONS

Ribs

Ribs are incorporated into the design to efficiently increase the part stiffness. However, there are several considerations to make before utilizing ribs. First, the thickness of the rib will be determined by the surface quality desired. If thick ribs are incorporated, stiffness will be increased significantly but due to variations in cooling rates, warpage and sinks may occur. Therefore, it is advisable to use ribs with thicknesses no greater than the thickness of the part itself. In addition, tall ribs are harder to fill in the molding process and may result in misoriented fibers and resin rich areas.

Uniformity of Thickness

Uniform thickness is ideal in an SMC part because it results in similar cooling and curing rates in all areas, minimizing warpage and shrinkage problems. However, if thickness variations are required, it is advised to gradually change the thickness to reduce potential warpage and fiber misalignment.

Thickness Constraints

The part thickness is a strong determinant of the molding cycle time. Heat must be added to the charge to promote flow and initiate the cross-linking reaction. Afterward, this heat must be removed to finish the curing cycle. Since composites are generally poor conductors of heat, the thickness of the part will determine the length of the molding step. Therefore, the part should be thick enough to adequately meet the performance requirements but no greater to minimize cycle time.

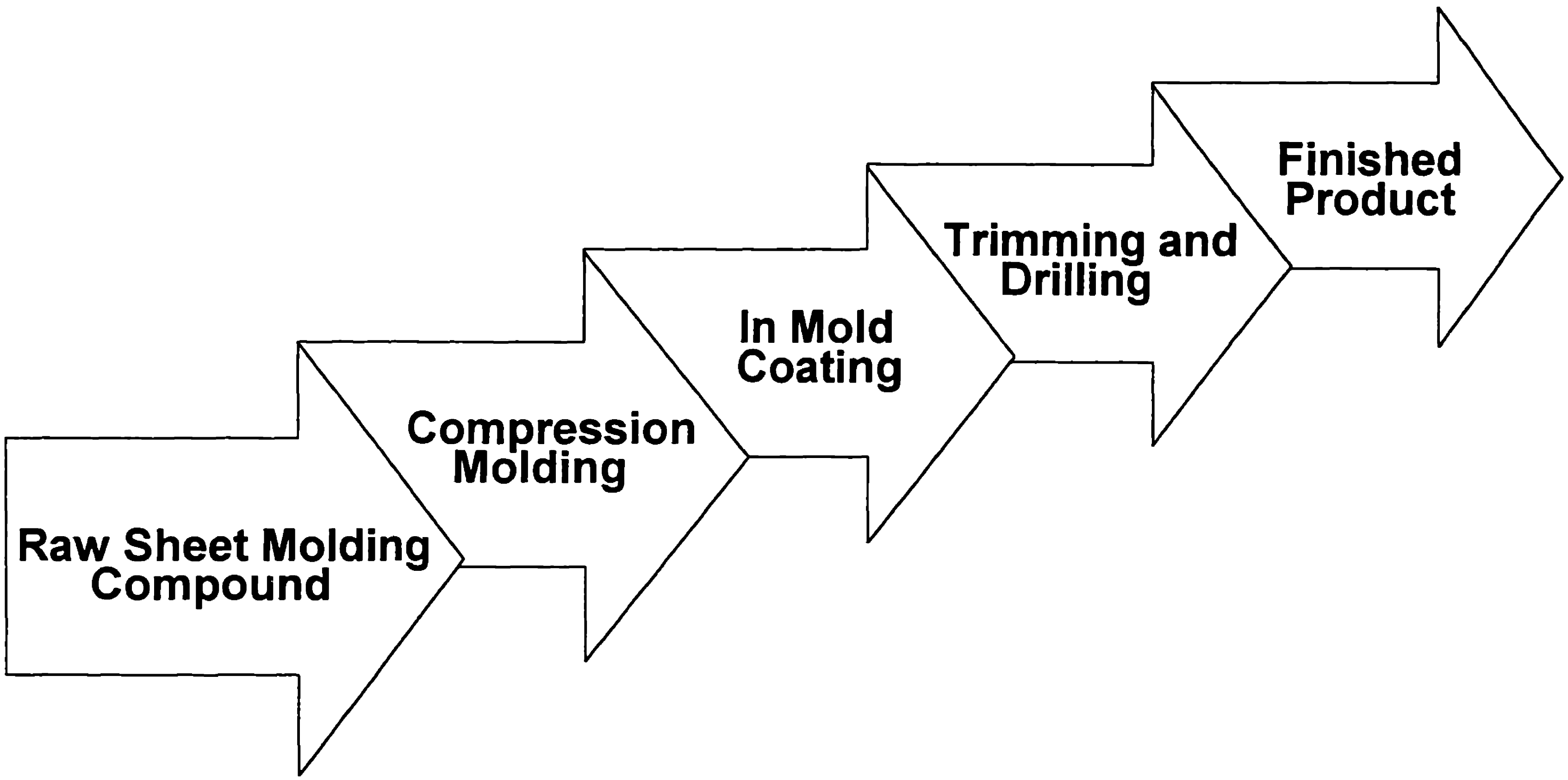

Figure 4: Conceptual SMC Process Flow

SMC COST MODEL

The SMC cost model requires the user to input part characteristics which are then used to calculate costs. A detailed description of the model is available; this section will cover the more important calculations involved in the cost model. [Busch, 1983]

The underlying assumptions of the SMC model are very similar to that of the steel stamping model; part characteristics (geometry, complexity) determine the manufacturing cost of the SMC process. Because the SMC process is very similar to a stamping process, the equation for press cost also depends on the capacity of the press (although with different regression variables and constants). In the SMC process, the press exerts a certain amount of pressure per unit area of the part; therefore, press capacity is determined by the size and number of the parts in the mold. In addition, the cost of the mold is determined by the geometry of the part (surface area, weight) and by the difficulty of the forming operation (denoted by the number of tool actions).

Unlike the steel stamping model, cycle time is not an inputted variable in the SMC model. It is calculated using a regression equation that considers the thickness of the part. Mold cycle time is strongly dependent on the part thickness because the resin initiates the curing cycle through the application of heat. This heat must be conducted to the interior in order to fully cure the part. Because SMC is an insulator, the thickness of the part has a strong influence over how quickly the cross-linking reaction can be initiated. In addition, the model also considers the effect of different formulations on the cycle time. Because different formulations have different heat conductivities, the material adjustment factor is used to adjust the cycle time calculation in accordance with the type of material used.

Chapter 7: Resin Transfer Molding

Resin transfer molding (RTM) is a method of producing structural composite parts using a combination of polymer resin, fiberglass reinforcement and foam cores. The fundamental RTM operation is the injection of polymer resin into a closed mold containing glass reinforcements and foam cores. The polymer infiltrates the glass fibers and solidifies, creating a solid polymer/glass matrix surrounding the foam core. This technology is promising as a competitive alternative to steel stamping because it offers the following advantages:

1. Ability to mold large complex parts in one operation.
2. Flexibility in reinforcement and foam core usage dependent on desired performance characteristics.
3. Potential for parts which are mechanically superior to steel.
4. Ability for substantial parts consolidation, reducing assembly requirements.
5. Lower investment costs relative to steel stamping and SMC processes.

However, the main disadvantages of the RTM process are long cycle times relative to steel stamping (minutes compared to seconds) and high material costs. Although additional machines can be added to increase throughput, the extra expense offsets some savings from lower investment costs. In addition, as more parts are produced, the investment costs reduce to an asymptotic minimum value since these costs are distributed over a large number of parts. As a result, the effect of high material cost becomes more pronounced as production volume increases. At high production volumes, RTM's material cost disadvantage relative to steel is readily apparent. The main question concerning a comparison between steel stamping and the RTM process is how the benefits and disadvantages of the RTM process effect its cost performance relative to the steel comparator. The purpose of this section is to provide a detailed inspection of the process and equations incorporated into the cost model.

PROCESS DESCRIPTION

The operation sequence of the RTM process is shown on figure 6. The operations that produce the reinforcement material and foam core are performed concurrently and merge at a subassembly operation before the RTM step. The following section will describe the individual operations in greater detail.

Preforming

The preform is the glass fiber reinforcement which has been shaped to fit into the RTM mold. The reinforcement is shipped as roll stock cut to a certain width. In the first fiber cutting operation, the reinforcement is unrolled and cut to the desired length. The cut piece is then shaped into the preform at the next operation. There are multiple methods of manufacturing the preform; however, thermoforming is chosen for body-in-white applications. Thermoforming requires the glass mat to be preheated before the forming operation. The heating allows the thermoplastic binder that is present in the material to soften and become pliable. After heating, the mat is press-formed into the preform shape. The thermoplastic then solidifies, allowing retention of the new shape. (Figure 5) Any trim scrap is removed subsequent to thermoforming. The finished preform is sent to the subassembly operation.

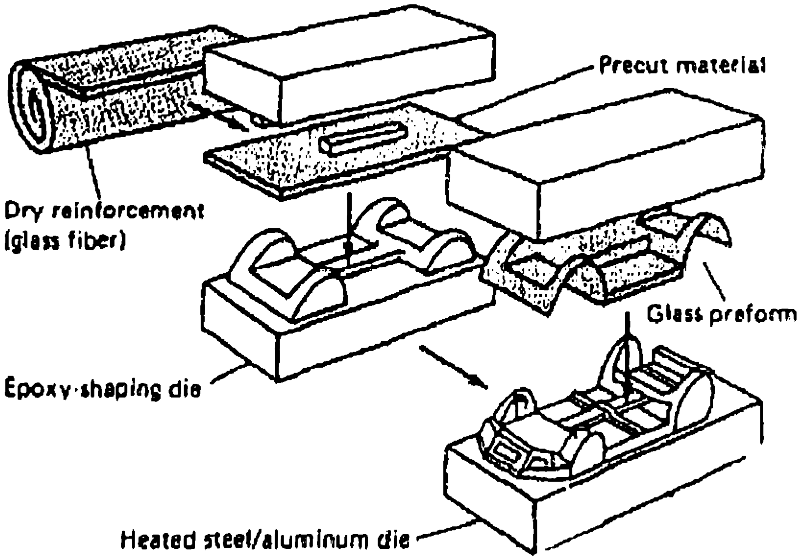

Figure 5: Preforming Operation[1]

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[1] Source: http://isl.cps.msu.edu/trp/rtm/tech_stm.html

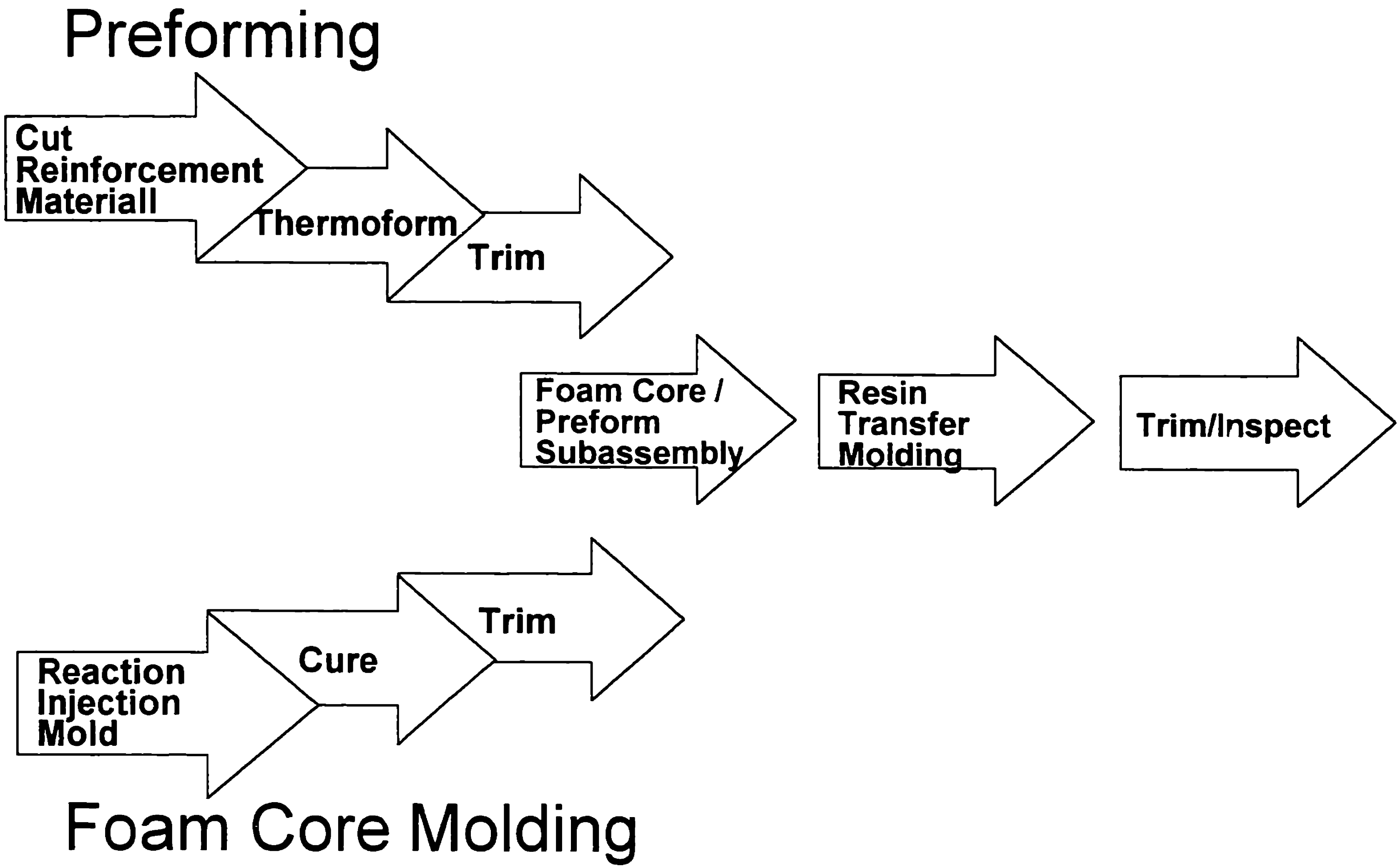

Figure 6: Conceptual RTM Process Flow

Foam Core Manufacturing

Polyurethane foam is used as a lightweight core material in RTM parts where thick cross-sections are required. Solid resin/glass fiber parts are undesirable for thick cross-sections for three reasons. First, the resin and glass fiber materials are relatively expensive and therefore should be efficiently used. Second, the cycle time of filling and solidifying the part would increase beyond a feasible limit if thick sections were filled entirely with glass and resin. Finally, foam cores are much less dense compared to the resin/fiber mixture, presenting an opportunity for weight savings.

The foam core is molded in a reaction injection molding (RIM) machine. Reaction injection molding is similar in concept to resin transfer molding in that resin is injected into a closed mold to produce a part. However, there are two key differences between RIM and RTM. First, there are no glass reinforcements in RIM. This means that parts made from RIM do not possess the same structural, load bearing capabilities as RTM parts. Also, the absence of reinforcements results in a cycle time reduction since the polymer does not have to infiltrate the glass fiber. The resin can be formulated for exceptionally fast cure and can also be injected into the mold at high flow rates. The other difference is that RIM polymer resins depend on a chemical reaction instead of heat to solidify. The resin usually consists of two or three components. The components are mixed just before injection into the mold. Since the mixed resin is extremely reactive, solidification time is very low. As a result, RIM parts can be molded much more quickly than a comparable RTM part.

After the reaction injection molding operation, the part undergoes an additional post-curing reaction. Essentially, the part is subject to heating in an oven so that all polymerization reactions will be taken to completion and that the desired material properties will be achieved. After post-curing, any unwanted trim is removed and the completed foam core is sent to the subassembly station.

Preform / Foam Core Subassembly

The subassembly operation combines the preform and the foam core into a consolidated unit before the resin transfer molding operation. The subassembly operation allows a reduction in setup time in the RTM operation since the consolidated assembly can be quickly and easily placed into the mold.

Resin Transfer Molding

The equipment required in the RTM step consists of a press outfitted with a mold and a resin injection system. The size of the mold press varies in relation to the pressure requirements to fill the mold. The injection system can be a single or multi-component system, depending on the type of resin used. (Figure 7) The RTM process begins with the placement of the preform/foam core assembly into the lower half of the mold. The mold is then closed and resin is injected into the mold. The length of the fill sequence is a function of the part geometry, injection pressure and the material properties of the resin and glass fiber. Essentially, the process can be described as steady laminar flow through a porous medium. The empirical equation that governs this flow is called D'Arcy's law. (A more explicit treatment of D'Arcy's Law will be given in later sections.) While accurate flow modeling requires finite element analysis to take into account the effects of non-isothermal conditions, fill times can be estimated using flow equations that assume a Newtonian resin, isothermal flow and homogeneous reinforcement.

Once the mold is filled, the part must be cured for a time that allows enough dimensional stability for removal. After the cure, the part is demolded and brought to the trim/inspection station where excess material is removed and the part is inspected.

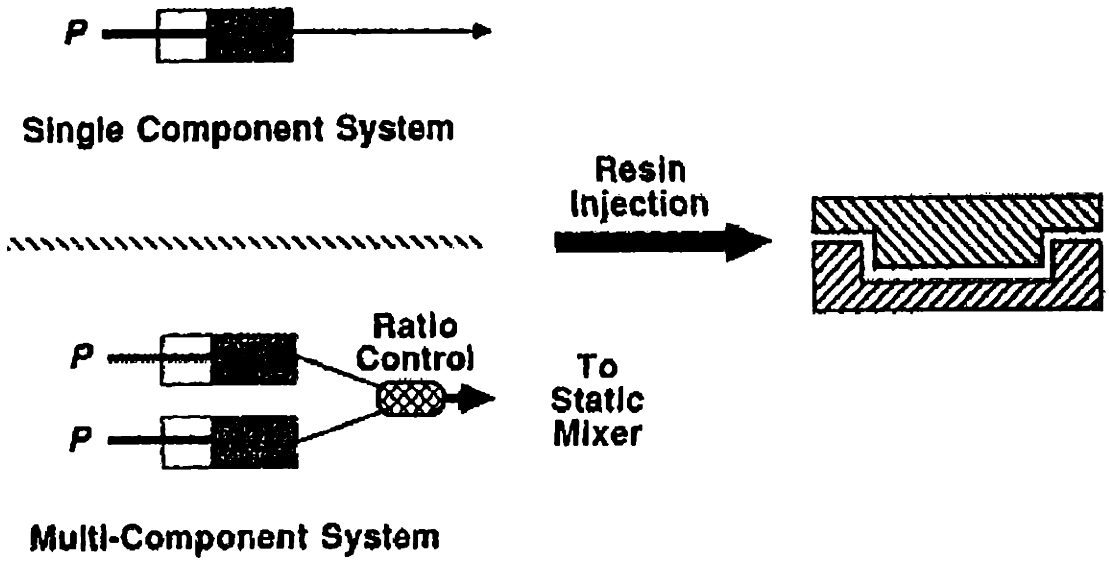

Figure 7: RTM Injection Configurations[2]

RTM COST MODELING

The RTM cost model was developed in order to analyze the composite vehicle design. As in the steel and SMC cost models, the underlying principle remains the same in terms of press and tooling cost. However, there are some unique characteristics of the RTM process that require a more detailed explanation.

The major hurdle in developing the cost model for the RTM process was to adequately approximate cycle times for the foam core molding and resin transfer molding process steps. The resin transfer molding step requires an estimation of the time required to fill the mold with resin and both process steps required equations to approximate the curing time. The following sections will provide a more detailed analysis of the cycle time calculations involved.

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[2] Source: http://isl.cps.msu.edu/rtm/inj_eqip.html

FLOW MODELING

One of the main limitations of liquid molding processes is its relatively long cycle time. Filling and curing times (accounting for the greatest percentages of overall cycle time) are on the order of minutes, depending on the geometry of the part and the processing conditions. In comparison, a steel part can be stamped in seconds. Therefore, any significant improvement in cycle time performance must come from the filling and curing stages. While curing can be optimized using a system of catalysts to accelerate reaction times, optimal filling of the mold requires an accurate model representing the flow of resin in the mold. The following sections will allow the reader to gain a better understanding of the theory behind processing modeling for the filling cycle time in the RTM process and the cure cycle time for the RTM and RIM processes.

D'ARCY'S LAW

There are a number of parameters that should influence mold filling; injection rates, part geometry, gate locations and injection pressure are immediately apparent. Additionally in the RTM process, the resin encounters resistance to flow due to the fiber preform. The ease at which fluid flows through the mold is associated with the amount of resistance incurred by the preform in addition to the viscosity of the resin itself.

The problem of flow through porous media was studied by Henry D'Arcy in 1865. His analysis of the flow of water through a bed of sand led to the following equation, relating the parameters of flow rate, pressure and resistance to flow (see Appendix D for symbol notation):

$$Velocity = \frac{Q}{A} = -\frac{K}{\mu} \nabla P$$

The permeability, K, is a measure of the ease with which the fluid flows through the fiber preform and can be determined from Kozeny's equation for fibrous structures. The equation requires as inputs the diameter of the fibrous media (d_p), the porosity (ϕ).

$$K = \frac{d_p^2\phi^3}{180(1-\phi)^2}$$

where $\phi = (1 - v_f)$. The constant 180 is called the Kozeny constant which is experimentally determined.

Using D'Arcy's law, the pressure acting on the mold and the mold filling times can be derived. In the RTM technical cost model, simple relationships derived from D'Arcy's law are used to calculate the clamping force needed to hold the mold halves together, in addition to the filling time. There are inputs that allow the user to specify the nature of the flow so that the appropriate equations can be used.[3] In order to use D'Arcy's Law to generate the equations used in the cost model, a number of simplifying assumptions are made:

- Flow is Newtonian and the resin is incompressible
- Flow occurs under isothermal conditions
- Flow is laminar and does not undergo shear thinning
- Geometry is thin shell, such that flow in the thickness direction can be ignored
- The flow path is one-dimensional, accounting only for the maximum length between the injection point and the end of the mold
- Resin viscosity is constant and does not vary with pressure or temperature
- Pressure at the gate is constant
- Reinforcement permeability is isotropic
- The reinforcement is an incompressible medium; permeability is not a function of mold pressure

RTM CYCLE TIME ESTIMATION

Mold Filling

There are a variety of methods that can be used to fill the mold. The RTM cost model allows the user to select from a number of mold filling strategies. The first and most basic division considers whether the resin is being delivered at a constant flow rate or at a constant

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[3] For a complete discussion of the derivation of the cycle time and mold force equations, see Kendall, *'Mould Design for High Volume Resin Transfer Moulding'*.

pressure. After this division, the cost model then calculates cycle time according to user's inputs. Figure 8 shows the process flow for cycle time calculation.

The calculations estimate both the fill time and the force required to keep the mold halves together during filling. The force on the mold correlates with the mold filling strategy that is selected by the user. For instance, if the user selects constant pressure filling, the injection pressure that is inputted will have a significant effect on how much force is applied to the mold as the resin is injected. The force is then used to estimate the equipment requirements necessary. As the force on the mold increases, larger presses will be required to maintain the downward pressure to keep the mold halves together. Therefore, filling strategies have significant implications for part cost.

CONSTANT FLOW RATE

When the mold is filled at a constant flow rate, the equation to calculate fill time is relatively simple.

$$T_{fill} = volume \div flow\ rate \div N_{inj}$$

In this case, volume is not the entire part volume but the volume taken up by the resin only, since the fiber reinforcement consumes a portion of the total volume. To calculate the resin volume, the entire part volume is multiplied by the porosity (which is the volume fraction of the resin in the part).

The force on the mold is given by the following equation:

$$F_m = \left(\frac{P_{max} P_{surf}}{2}\right) N_{inj}$$

The equation calculating mold force requires knowledge of the maximum pressure achieved in the mold. The calculation of the maximum pressure is dependent on the type of flow. To simplify the analysis, only rectilinear and radial flows were considered. Rectilinear flow is one dimensional flow from a one dimensional source. (Figure 9) The maximum pressure that occurs during rectilinear flow (under a constant flow rate) is located at the gate.

As resin fills the mold and begins to cure, more force is required to fully pack the mold; consequently, maximum pressure occurs where the resin is introduced into the mold. The equation to calculate maximum pressure at the gate is:

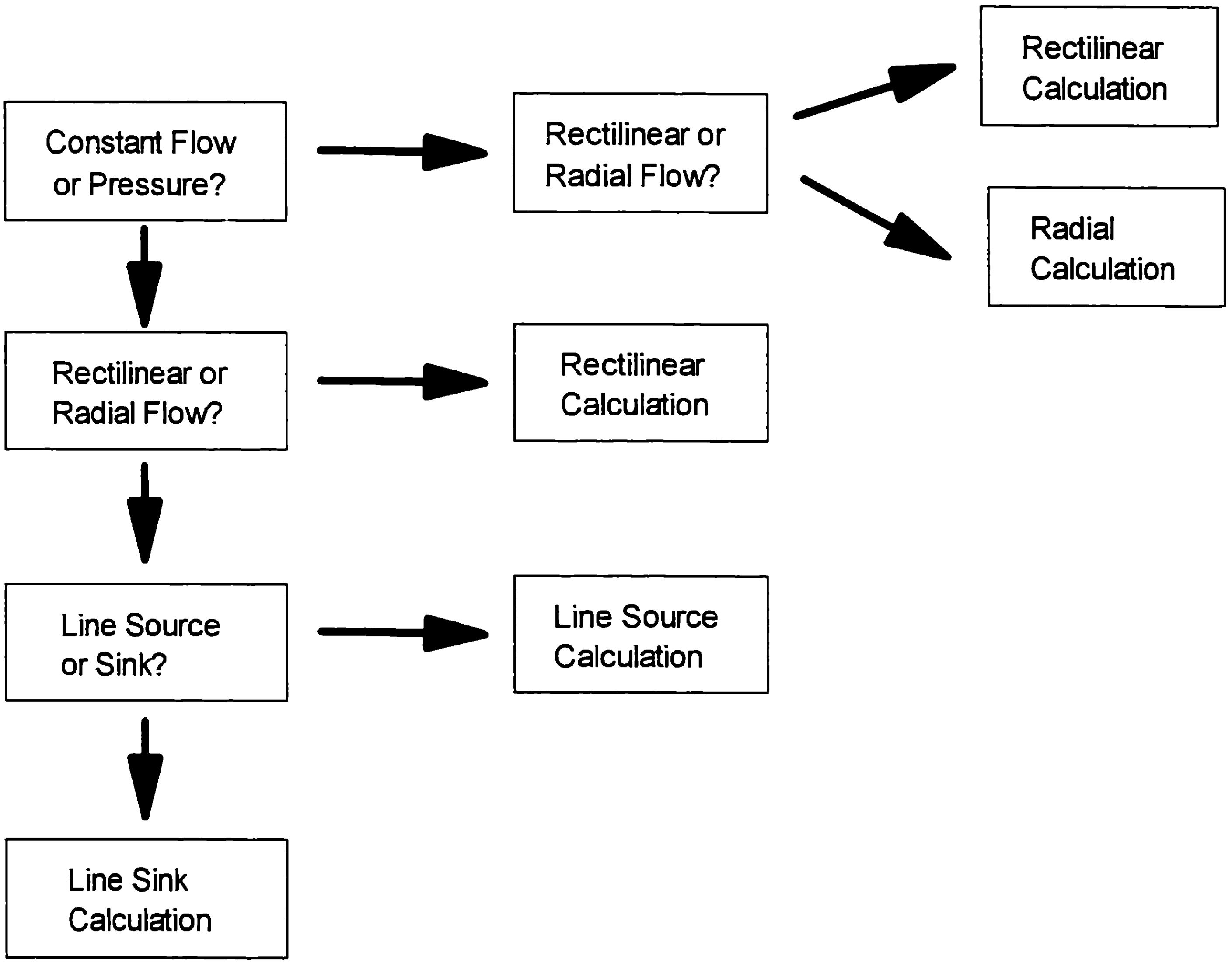

Figure 8: RTM Fill Time Calculation

$$P_{\max} = \frac{\mu Q L_{\max}}{K t w}$$

There are two types of radial flow: (1) resin moving radially outward from the source or (2) resin flow inward to the sink. The equation for maximum pressure under either of these conditions and constant flow rate is given by:

$$P_{\max} = \frac{\mu Q}{2\pi K} \ln \frac{R_m}{R_s}$$

CONSTANT PRESSURE

Instead of maintaining a constant rate of flow, molding can also be performed under a constant injection pressure.

Rectilinear Flow

For rectilinear flow with resin injected at constant pressure, the fill time is:

$$T_{fill} = \frac{\phi \mu}{2 K P_{inj}} X_m^2$$

The maximum mold force is:

$$F_m = (P_{inj})(X_m)(W)$$

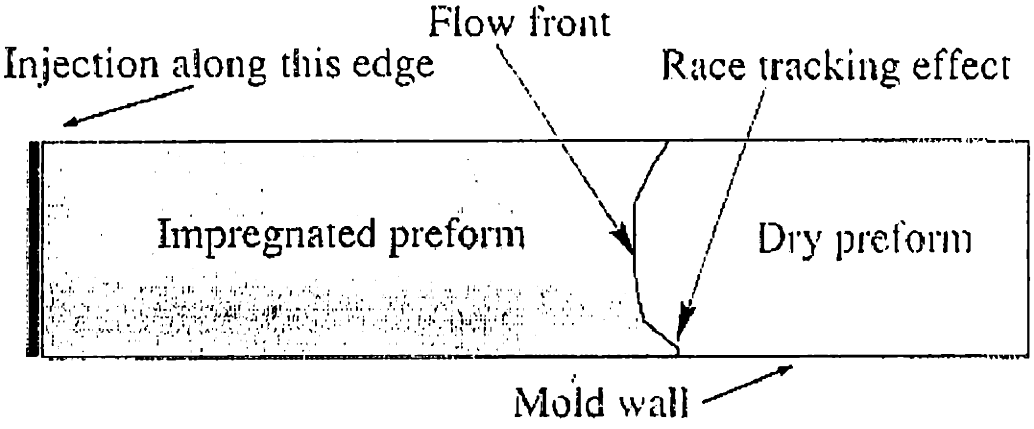

Figure 9: Rectilinear Flow[4]

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[4] Source: http://isl.cps.msu.edu/trp/rtm/mld_perm.html

Radial Flow from Line Source

Radial flow is flow that develops uniformly around a central axis. (Figure 10) Resin can flow radially in two ways: inward to a central sink or outward from a central source. For radial flow from a source, the fill time is:

$$T_{fill} = \frac{\phi\mu}{2KP_{inj}}\left[R_i^2 \ln\left(\frac{R_i}{R_o}\right) - \frac{R_i^2 - R_o^2}{2}\right]$$

and the maximum mold force is:

$$F_m = \pi P_{inj}\left[\frac{R_o^2 - R_i^2}{2\ln\left(\frac{R_i}{R_o}\right)} - R_o^2\right]$$

Radial Flow from Line Sink

For radial flow inwards towards a central sink, fill time is calculated as:

$$T_{fill} = \frac{\phi\mu}{2KP_{inj}}\left[R_o^2 \ln\left(\frac{R_o}{R_i}\right) + \frac{R_i^2 - R_o^2}{2}\right]$$

and the maximum force on the mold is:

$$F_m = \pi P_{inj}\left[\frac{R_o^2 - R_i^2}{2\ln\left(\frac{R_i}{R_o}\right)} + R_i^2\right]$$

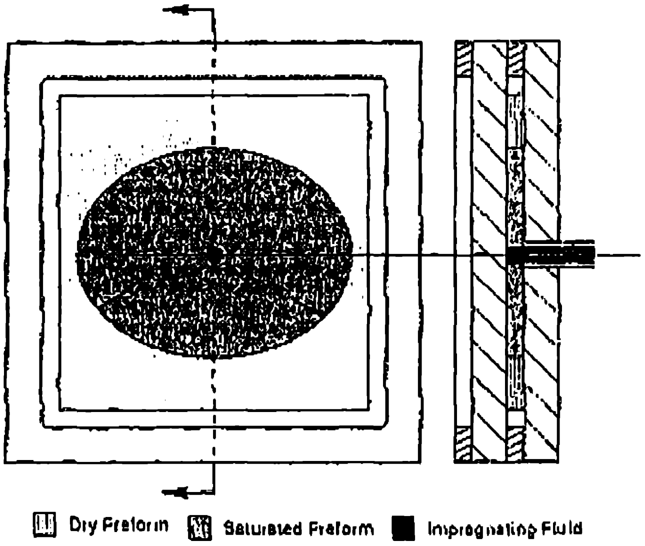

Figure 10: Radial Flow[5]

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[5] Source: http://isl.cps.msu.edu/trp/rtm/mld_perm.html

PART CURING

Overview of Cure Time Modeling

For the RTM and foam core molding process, the amount of time required for curing needs to be calculated. There are three types of cure models: n^{th} order reaction, autocatalytic reaction and a combination of n^{th} order and autocatalytic reaction. In an n^{th} order reaction, the reaction rate decreases with time, since the concentration of monomers (molecules that form the polymer chain) and initiators (molecules that produce the reactive species) decrease with time. An autocatalytic reaction represents the opposite case: the reaction rate increases with time. Most polyester, vinyl ester and epoxy resins exhibit both n^{th} order and autocatalytic curing behavior, so that the combination model is more representative. The general equations of the three models are:

$$
\begin{aligned}
&n^{th}\ order: \tfrac{dX}{dt} = k(1-X)^n \\
&Autocatalytic: \tfrac{dX}{dt} = kX^m(1-X)^n \\
&n^{th}\ order/autocatalytic: \tfrac{dX}{dt} = (k_1 + k_2X^m)(1-X)^n \\
&where\ k_i = A\exp\left(-\tfrac{E_a}{RT}\right)
\end{aligned}
$$

Most polymer resin systems contain additives such as catalysts, inhibitors and fillers that also effect the curing behavior and are extremely difficult to model. Most resin suppliers will not divulge detailed information about the resin formulation so that reaction constants used in the cure models must be found empirically. One of the most common methods is to perform isothermal DSC (Differential Scanning Calorimetry) tests to determine constants.

Estimation of Cure Time in RTM Cost Model

For the RTM technical cost model, literature searches on published reaction constants were found and used as representative values for each class of resin. Thus far, information has been collected for polyester, vinyl ester and polyurethane systems. Because of simplicity and availability of data, a second order reaction ($n = 2$, in n^{th} order equation) was assumed to model the curing behavior of these resins. Given a second order reaction, the n^{th} order model can be integrated to give the following equation to estimate cure time:

$$t = \frac{1}{A}\exp\left(\frac{E_a}{RT}\right)\frac{c_{cr}}{1-c_{cr}}$$

where c_{cr} is the conversion percentage at which the part exhibits enough strength and stiffness to be removed from the mold without damage. This conversion percentage is a user input into the cost model. Table 1 shows the kinetic rate constant and the activation energy used in the cure equation:

Resin	**Kinetic Rate Constant (sec^{-1})**	**Activation Energy (J/mol)**
Polyester	1.61×10^8	75,100
Vinyl Ester	8.0×10^7	76,550
Polyurethane	1.27×10^5	38,900

Table 1: Polymer Resin Kinetic Parameters

NON-ISOTHERMAL MODELING

For more precise flow simulation, some of the simplifying assumptions can be relaxed so that the simulation is a more accurate representation. One of the most constricting assumptions is that of isothermal flow. When molding parts in RTM, the environment usually varies greatly in temperature, because of heat transfer between the resin and reinforcement. The mold is heated to activate catalysts which help to minimize the cure time. Then the mold is cooled to draw heat out of the resin to allow for faster demold times. Because of temperature gradients, the resin also experiences changes in viscosity, which effect the length of the molding cycle. Temperature gradients also affect the length of the cure cycle, since the degree of cure is dependent on temperature. Therefore, non-isothermal flow modeling is a more accurate predictor of the molding cycle.

However, to simulate non-isothermal flow, there are a number of other models that must be constructed. First, a heat transfer model must simulate the energy flow that occurs in a non-isothermal environment between the different constituents. Second, a cure model of the resin must then take the information from the heat transfer model to use as inputs to determine the completeness of resin cure. Finally, using information from the heat transfer and cure models, the change in viscosity can be determined. The value for viscosity can then be used in the D'Arcy equation to determine the velocity at which the resin flows through the mold and the pressure distribution.

Utilizing all of the elements of the non-isothermal flow model, resin flow can be predicted using numerical methods to obtain solutions to the energy, cure and viscosity models. A finite element/control volume technique is used to solve the complex set of equations that model the behavior of the resin. In the finite element method, the space inside of a mold is divided into a set of control volumes. As flow advances into the mold, resin fills some of these control volumes. The temperature and degree of cure are calculated for each control volume using the energy and cure models. Then viscosity and flow rate can be determined so that the model is able to adjust the speed of the resin in addition to the pressure exerted. This procedure is performed iteratively. At each step of the fill, the parameters for the models are readjusted and recalculated, until all control volumes have been filled.

Incorporating a flow model can give a precise estimate of the fill time for the RTM process. More importantly, non-isothermal flow models are mainly used to determine whether certain processing conditions will result in a completely filled mold and to predict potential knit lines in the part. However, for the purposes of estimating manufacturing cost, the more simplistic analysis based on isothermal conditions is a reasonable way to capture the RTM cycle time.

ADDITIONAL CONTRIBUTORS TO CYCLE TIME

In addition to the filling and curing steps, there are additional steps that also contribute to the total cycle time. Before the mold closes and begins to fill with resin, the mold must undergo maintenance and preparatory operations in order to ensure an acceptable part. The operations consist of mold cleaning, release agent coating and gel coating. The assumptions for the rate and frequency of these operations are given in table 2. The units of frequency are given as parts per operation, meaning that the given number of parts are molded for every operation. To illustrate, a value of 20 for frequency for the mold cleaning operation means that the mold is cleaned after every 20 molded parts.

Operation	**Rate (sec/m^2)**	**Frequency (parts/operation)**
Mold Cleaning	20	20
Release Agent Coating	40	20
Gel Coating	20	1
Operation	**Cycle Time (sec)**	
Placement	30	
Mold Open/Close	30	
Demold	20	

Table 2: RTM Operation Assumptions

Mold cleaning is a periodic cleansing of the mold surface, removing excess material left behind after the part is removed from the mold. Excess material left behind on mold surfaces can degrade the surface quality of the part. In order to reduce the amount of cleaning that is necessary, a release agent is also coated onto the mold surface to promote an easier demold. The release agent is used to aid the ejection of the part after the molding step. Release agents can be internal, meaning that it is included as part of the resin formulation, or external, which requires a coating directly onto the actual mold surface. In the cost model, the release agent coating step refers to an external coating operation. However, internal release agents should be evaluated to determine the optimal performance. Finally, gel coating is used primarily to increase the part's surface quality and increase tool life. The gel coat aids in decreasing the surface porosity and can also be used to add color to the part. However, applying color to a part using a gel coat has not been proven to give a Class A quality finish and will not replace the painting operation. A painting process will probably be required subsequent to the molding operation in order to give the desired surface finish.

In addition to the maintenance operations, there are also three additional segments of the molding cycle that contribute to the total cycle time. The model allows users to input estimates of the placement time, mold open/close time and demold time. Placement time is the time required to set the preform/foam core subassembly into the mold. Mold open/close is the time required for the mold halves to come together before the molding cycle and come apart after the part is completed. Demold is the process of extricating the part from the mold.

Chapter 8: Steel Comparator Vehicle

In order to develop an analysis of the competitive position of composite materials, vehicle designs using these materials and steel are required. The composite intensive body-in-white design (which will be described in the next chapter) was specifically developed for one material type and therefore has no true steel equivalent. For a suitable comparison vehicle, a currently manufactured minivan was chosen as the closest approximation for the steel design. Specifically, the Honda Odyssey (model year 1996) was selected as the representative steel vehicle for the comparison between materials technologies. The Odyssey was chosen primarily for its similar physical dimensions in relation to the CIV. Because the Odyssey is based on an Accord chassis, it is one of the smaller minivans in its market segment and thus more closely approximates an equivalent to the composite vehicle design. (Table 3)

Minivan	**Wheelbase**	**Length**	**Width**	**Height**
Chevrolet Venture	112"	186.9"	72"	67.4"
Dodge Caravan	113.3"	186.4"	76.8"	68.7"
Ford Windstar	120.7"	201.2"	75.4"	68.0"
Nissan Quest	112.2"	189.9"	73.7"	64.9"
Toyota Previa	112.8"	187"	70.8"	70.1"
Honda Odyssey	114.4"	187.2"	70.6"	64.6"
CIV	113"	161"	62"	66"

Table 3: Comparison of Minivans

COST MODELING OF HONDA ODYSSEY

The Odyssey body-in-white is composed of 148 parts. To measure each one and create individual cost models would be time-consuming and impractical. In addition, getting access to each part in the body-in-white in order to take measurements would either require extreme generosity from the manufacturer or access to a teardown facility from a competitor analyzing the Odyssey. Therefore, a simpler and less resource-intensive approach is required to estimate the cost of body-in-white designs with numerous parts.

Past research at the Materials Systems Laboratory has classified parts into distinct categories. [Han, 1994] A representative part is chosen for each category and this part is precisely measured and modeled using the steel stamping TCM. The categories are determined according to differences in part geometry, size and forming complexity. The rest of the parts of the body-in-white can then be classified into one of the categories. Assuming that all parts in a category are formed in a similar fashion, they can be costed using weight ratios and the percentage breakdowns of cost for the representative part.

For the analysis of the Odyssey, ten categories were formed, divided among rails, panels and high material cost parts. There are two categories for high material cost parts: 1. Material costs only, and 2. 90% Material cost. The Material costs only category considers solely the cost of materials in forming a cost estimate. These parts are those which are extremely simple and produced at high volume, such that they incur virtually no other costs. The 90% materials cost category represents parts which are somewhat more complex than the first category, yet are not complex enough to be classified as a rail or panel. Therefore, 90% of the total cost of the part is due to material, with the remainder of costs being divided into the other elements (labor, equipment, tooling, etc.) according to the cost breakdowns of the simple rail category.

The remaining eight categories are listed in the table below. (Table 4) The categories are separated into rails (narrower, box-shaped parts) and panels (flatter, rectangular parts) to demarcate the types of geometries of the body-in-white parts. The differences in running rate, workers per line and forming hits are correlated to the size and complexity of the representative part.

Part Category	**Running Rate (parts/hr)**	**Workers per Line**	**Forming Hits**
Simple Rail	600	3	2
Drawn Simple Rail	550	3	3
Drawn Complex Rail (Small)	500	3	3
Drawn Complex Rail (Large)	450	4	4
Drawn Panel (Small)	500	3	4

Part Category	**Running Rate (parts/hr)**	**Workers per Line**	**Forming Hits**
Complex Panel	450	4	4
Simple Panel	450	4	3
Drawn Panel (Large)	400	6	5

Table 4: Steel Stamping Part Categories

Having established the ten part categories, the rest of the body-in-white parts can then be classified into the most appropriate categories. Figure 11 shows the allocation of the Odyssey's parts into each category by weight percentage. The top three categories (by weight percentage and not number of parts) are: 1. Simple Panel (25.8%) 2. Drawn Simple Rail (20%) 3. Complex Panel (19.1%). The parts included in the Material Cost Only and Material + 10% Fixed Cost represent small fractions of the total vehicle weight because these parts are typically small brackets and attachments that contribute relatively little to the total cost of the body-in-white. In terms of number of parts included in each category, the Drawn Simple Rail category contains the most. However, Simple Panels and Complex Panels have high weight percentages because of a few, heavy parts in each. The roof and floorpan are classified as simple panels and the inner bodyside panels are included in the complex panel category.

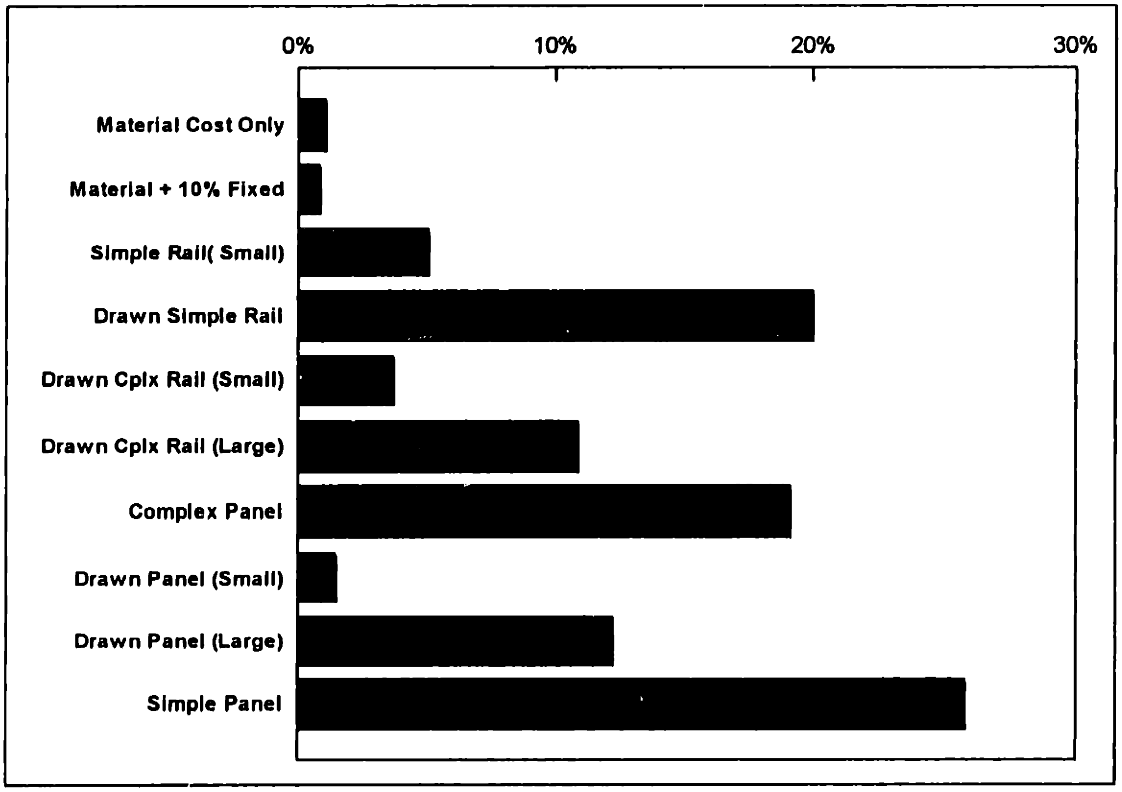

Figure 11: Distribution of Parts into Part Categories by Weight Percentage

Wage ($/hr)	$44.00
Material Price ($/kg)	$0.77
Scrap Material Price ($/kg)	$0.10
Blanking Running Rate (parts/hr)	1,200
Cumulative Reject Rate	1%

Table 5: Global Steel Stamping Model Assumptions

Each representative part was costed using the stamping model and the global assumptions are listed in the table above. (Table 5) The percentage breakdowns for each part is shown in figure 12 using a production volume of 100,000 vehicles per year. This represents the percentages that are used to calculate the cost of rest of the body-in-white parts. The allocation of cost to the various cost components vary according to the part category. For example, material cost represents the largest proportion of total cost for the simple panel.

The reason is that the simplicity of the part's geometry allows for low tooling costs so that material cost represents the largest fraction. Conversely, as parts become more complex, tooling becomes a more significant contributor and results in a decrease in material cost percentage. However, the increasing tooling cost percentage is tempered by increasing material costs for some complex parts as a result of increasing scrap losses. This effect is shown in the complex panel, where the material cost percentage is higher than other part categories.

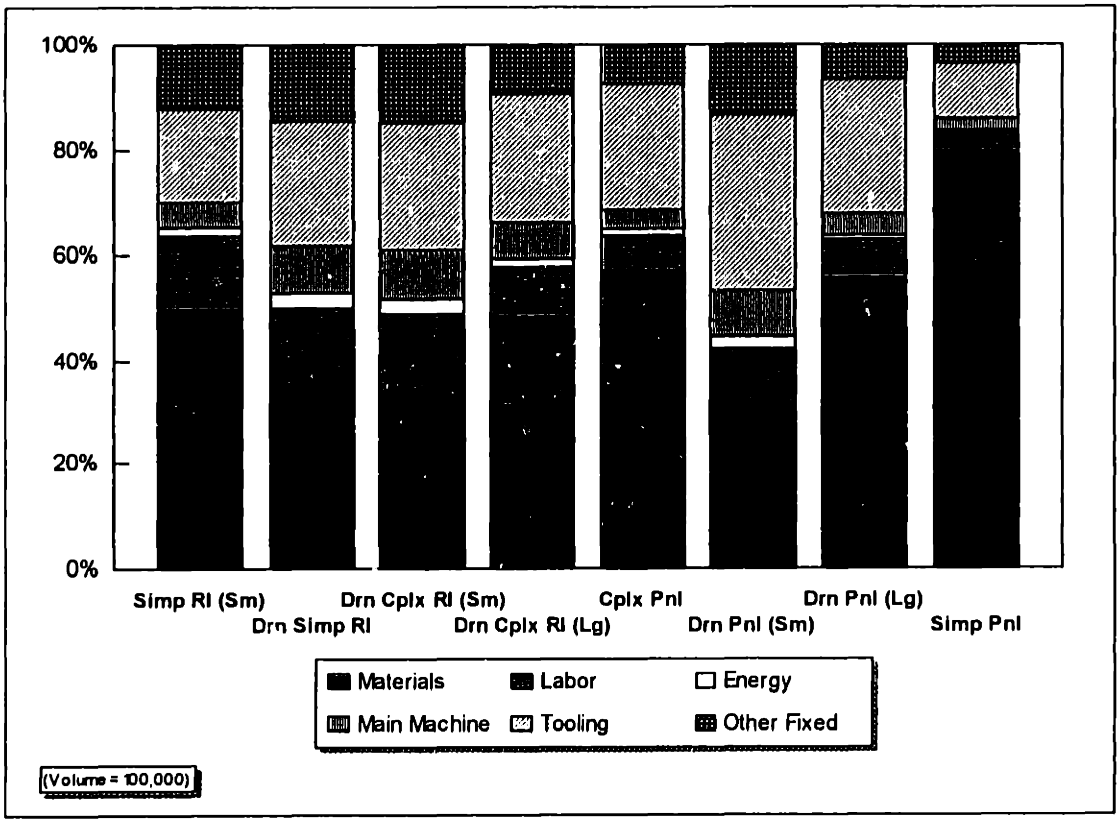

Figure 12: Cost Percentage Breakdown for Part Categories

ASSEMBLY

In addition to cost modeling the manufacturing process of the individual parts, the cost of assembling those parts together to form a completed body-in-white is significant and thus should be analyzed. The conceptual assembly process for the steel vehicle is shown on figure 13. The assembly process is envisioned as building the body-in-white beginning from the base and concluding at the top portions of the vehicle. Away from the main assembly line, subsystems are joined together. These subsystems are then brought to the main assembly line, where they are joined together to complete the body-in-white.

Assembly Processes

The assembling of the steel body-in-white mainly employs resistance spot welding and tack welding. In addition, there are some areas which require adhesive bonding and riveting but these operations are minor in comparison to the welding processes. The major assumptions for each process used in the assembly model are listed in table 6.

	Spot Welding	**Tack Welding**	**Adhesive Bonding**	**Riveting**
Equipment Costs	$120,000	$120,000	$156,000	$15,000
Start/Finish Time	2 sec	2 sec	10 sec	5 sec
Laborers	0.25	0.25	0.25	1
Joining Speed	0.33 welds/sec	0.33 welds/sec	0.36 m/s	0.67 rivets/sec
Usage	0.035 welds/m	0.105 welds/m	0.015 kg/m	0.04 rivets/m
Power/Join	46 kW	15 kW	30 kW	25 kW
Material Cost	$0.45/electrode	$0.45/electrode	$17.17/kg	$0.016/rivet
Other	Electrode Life: 8000 welds	Electrode Life: 8000 welds		Tool Cost: $198 Tool Life: 700

Table 6: Key Process Parameters for Steel Assembly

For the spot and tack welding processes, equipment costs include the cost of the welding gun and head ($20,000) plus the cost of the welding robot ($100,000). The Start/Finish time indicates the amount of time required for the gun/head to move to the part to start welding and then move away from the part when all welds in that section are complete. Because the welding process is assumed to be fully automated, one worker can operate 4 welding robots. The life of the electrode refers to the number of welding cycles that can be performed before the electrode wears out and requires replacement. Two differences between tack welding and spot welding are the usage (or connect spacing) of welds and the power required to form the join. In one meter of a weld join, there are three times as many spot welds as there would be in a comparable meter of tack welds. Since tack welds are used to temporarily hold pieces together, less power is required to preform the tack weld operation.

The adhesive bonding process assumes a two-component adhesive system. The equipment cost includes the dispenser gun ($1,000), the dispensing robot ($100,000) and the pump system ($55,000). The Start/Finish time is longer than the other processes because of the need to mix the two-component adhesive and begin pumping. The adhesive bonding operation is a continuous process so the joining speed is denoted as meters of join per second and the usage is measured in kilograms of adhesive used per meter.

Because riveting is a minor operation, it is assumed to be performed manually. Therefore, the riveting gun is the only piece of equipment necessary. In addition, only one worker can operate the gun at one time.

Assembly Modeling

The assembly model requires two main inputs. First, the user must distinguish the subassembly operations that are required and then classify the parts accordingly. The conceptual assembly diagram shown in figure 13 shows how the assembly process was envisioned and the different subassemblies that were required. Second, after the assembly process is well-defined, the type of joining methods and length of the join for each subassembly must be inputted into the model. Using the diagrams made available through a Honda repair manual, the join lengths for the resistance spot welding, riveting and adhesive bonding operations were estimated. In addition, tack weld lengths were assumed in areas where a temporary join seemed necessary. It should be noted that the assembly flow used in the analysis is based not on actual Honda assembly practices but through estimations made by researchers experienced in the area of steel assembly. Thus the analysis represents more of a generic assembly process rather than one specialized for a certain vehicle or company philosophy.

The inputs and results of the assembly model are shown in table 7. The number of laborers and stations are calculated by assuming a production volume of 100,000 vehicles per year (vpy). A case study presented in Marti's thesis demonstrates the effects of varying the number of subassemblies and changing the part groupings by analyzing the effects of three scenarios with different numbers of subassemblies. [Marti, 1997] While it is most efficient to have fewer subassemblies (as more joins are done at each station, the equipment utilization efficiency increases, decreasing the total assembly cost per part), many subassemblies are required in reality, due to the need for sequencing of parts. As a result, the assembly assumptions made in the analysis of the Odyssey recognize the need for subassembly steps and are configured as such.

Subassemblies	17
Total RSW Join Length	153.77 m
Total Tack Weld Length	127.79 m
Total Adhesive Bonding Length	5.12 m
Total Riveting Length	2.48 m
Number of Laborers (@ 100,000 vpy)	68
Number of Stations (@ 100,000 vpy)	
Resistance Spot Welding	42
Tack Welding	17
Riveting	1
Adhesive Bonding	1
Total Number of Stations (@ 100,000 vpy)	60

Table 7: Steel Assembly Model Assumptions and Results

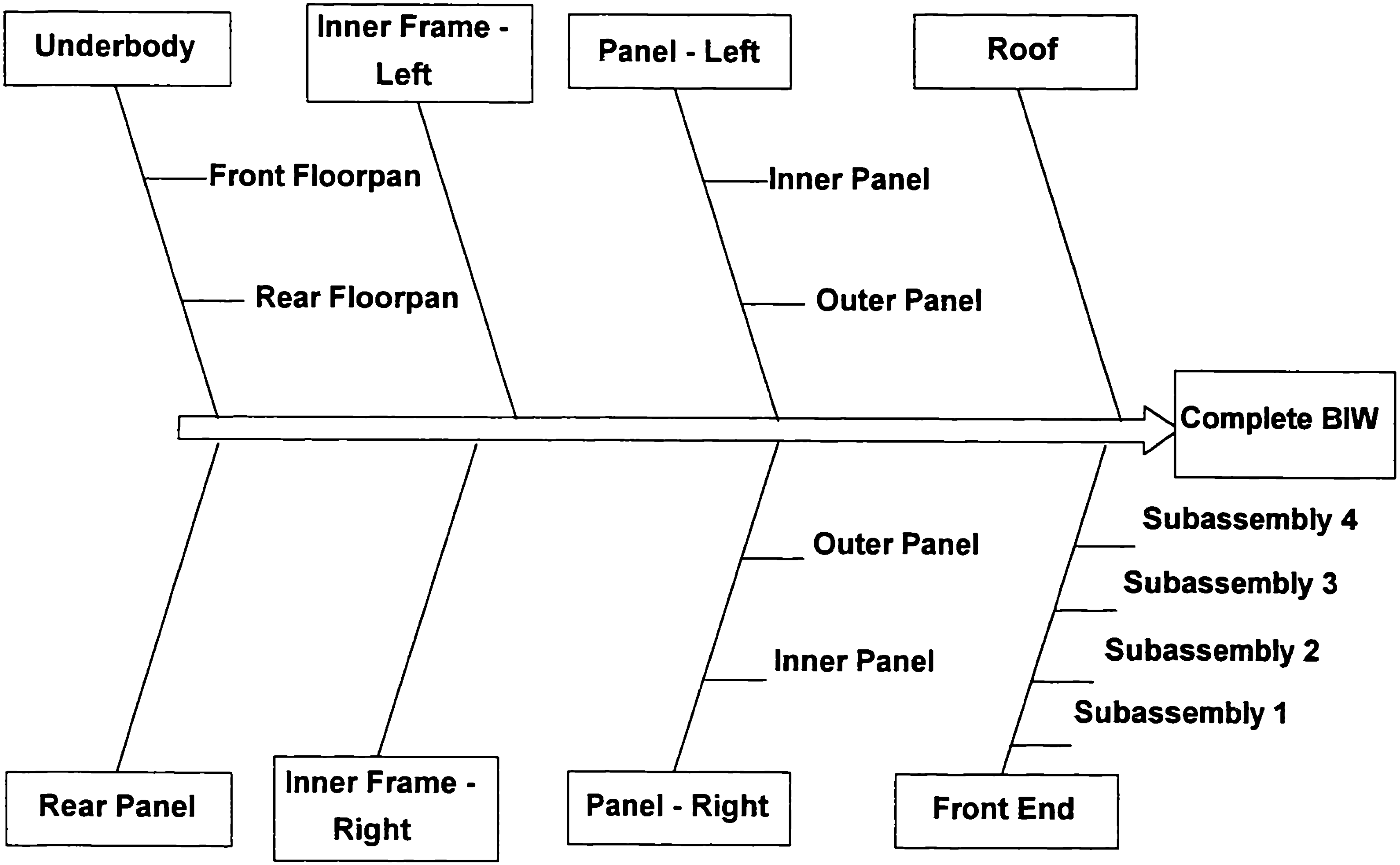

Figure 13: Honda Odyssey Assembly Process

Chapter 9: Composite Intensive Vehicle Design

DESCRIPTION

Since the days of the energy crisis, composites had long been hailed as the material of the future, replacing steel parts in vehicles because of their many advantages. However, with the exception of some minor successes, composite materials have not been able to make significant inroads into body applications. One of the main reasons is that unfamiliarity with the new material resulted in engineers designing composite parts to substitute directly for steel parts. However, a part-for-part substitution does not fully utilize the significant advantages of composites. In response, the Automotive Composites Consortium, a partnership between Ford, Chrysler, General Motors and suppliers, was formed. The main objective of the ACC was to develop the engineering expertise and processing technologies necessary for making structural composite use in automobiles feasible. One of the more recent ACC achievements has been a successful crash test of a composite front end design. [Ashley, 1996]

Building on the work of the ACC, the Ford Motor Company developed a composite vehicle design that will be used to compare the performance of composites against a steel competitor. The CIV was designed in order to utilize all of the design advantages of composite materials. The Ford CIV is a concept minivan-style vehicle originally intended to demonstrate technical and manufacturing feasibility for composite materials. The body-in-white has been designed in order to take advantage of parts consolidation opportunities. A significant reduction in part count (relative to traditional steel body-in-white designs) has been achieved.

The CIV was originally designed utilizing glass fiber reinforced polymer composites manufactured using the resin transfer molding process. In the cost analysis, the performance of alternative composite materials (SMC and carbon fiber reinforcements) will also be addressed. This section will describe the various designs used to formulate the cost analysis.

The first portion will outline the specifics of the original CIV design using glass fiber reinforcements. Next, the calculations used to convert the original design to one utilizing carbon fiber reinforcements will be presented. The final section will outline the methodology to convert the original design into a comparable SMC design.

GLASS FIBER REINFORCED COMPOSITE DESIGN

Component Design

The body-in-white design is comprised of eight components as well as 32 metal brackets. In all components, continuous swirl mat is used as the reinforcement material, vinyl ester as the polymer matrix material and where necessary, polyurethane is used as the foam core material. Continuous swirl mat, a random fiber reinforcement, is used instead of oriented fibers for three reasons. First, random fibers are less costly than oriented fibers due to the ease of fabrication of the random fiber mat. Second, random fibers are easier to mold because laying the preform into the mold is much simpler. For oriented fibers, the angle at which the preform is laid into the mold must be more carefully monitored. Finally, the body-in-white undergoes loads in many directions; although oriented fibers perform well along the direction of the preferred orientation, performance is diminished along other directions.

Foam cores are utilized for a number of structural, design and manufacturing reasons. First, the use of foam cores increases the crush resistance of beams. Without foam cores, beams fail during crush resistance testing by the local buckling of the walls. Through the use of cores, beam walls are supported and result in failure that is more stable and progressive. Second, by surrounding the foam core with the resin/fiber composite, thick sections can be molded without requiring the resin to fill the entire volume. This reduces the cycle time (shorter fill and cure times) and also decreases the weight (foam cores are much less dense than polymer resin and glass fiber).

The metal brackets are not inserts that are incorporated into the composite part during the liquid molding process. Rather, the brackets are simple stamped shapes that are joined during the assembly process of the body-in-white. The brackets are used to attach non-BIW parts to the BIW components; for instance, attaching a seat to the floorpan will require a seat track insert. In a steel design, these brackets are already incorporated into the stamped shape of the part. Therefore, the brackets are included in the analysis as part of the total cost in order to make the composite design a better functional equivalent of the steel comparator.

	Roof	Floorpan	Cross Member	Bodyside	Front End
# Cores	0	4	1	1	2
# Preforms	1	5	1	2	2
# per vehicle	1	1	1	2	2

Table 8: Subsystems Components List

The actual components of the composite BIW consist of the following subsystems: roof, underbody, bodyside and front end. Table 8 lists the various subsystems and their components. The roof subsystem contains an RTM inner and an SMC outer panel; two pieces are required because the SMC panel allows the roof to have a Class A finish while the RTM inner imparts the necessary structural characteristics. The roof has no foam cores.

The underbody subsystem consists of an integrated floorpan that incorporates the front and rear floorpans and the rear sill. In addition, the front cross-member is joined to the floorpan; the cross member provides reinforcement should a side impact occur. The underbody incorporates foam cores in the front and rear cross member, left and right rear rails, rear suspension cross member and the left and right front floor rails.

The bodyside, consisting of the right and left hand components, incorporate the A, B, C and D pillars to form a complete bodyside structure. A single foam core component provides a continuous core section throughout the entire bodyside.

Like the bodyside, the front end is composed of right and left hand parts. The Automotive Composite Consortium developed and successfully crash tested a front end design based on the Ford Escort. [Botkin, 1997] The CIV's front end is similar in concept to the ACC design; the composite apron extends to incorporate part of the A pillar and the bodyside rocker section. Each front end piece includes two foam cores.

Cost Modeling

The specific parameters used for the cost modeling of the composite body-in-white designs are found in Appendix B (SMC) and C (RTM). This section will highlight some of the more important assumptions and parameters used in formulating the cost model for the RTM process.

Table 9 shows the material formulation for each subsystem. These formulations are estimates based on the number and type of components (foam cores, preforms), the geometry of the part and the load bearing requirements. For example, since the roof has no foam core, it incorporates a higher fraction of resin and reinforcement. The bodyside, cross member and front end have continuous foam core sections, so that the weight percentage of the foam core is high. The floorpan has foam cores in selective areas and also experiences a high load; as a result, its reinforcement percentage is high.

Material	Roof	Floorpan	Cross Member	Bodyside	Front End
Resin	40.0%	39.5%	40.0%	39.5%	39.5%
Filler	14.5%	0.0%	0.0%	0.0%	0.0%
Fiber	45.0%	45.0%	34.5%	40.0%	40.0%
Catalyst	0.5%	0.5%	0.5%	0.5%	0.5%
Foam	0.0%	15.0%	25.0%	20.0%	20.0%

Table 9: Material Formulation for Subsystems

Table 10 lists the important material price assumptions that were used in formulating cost. In addition to material cost, other important assumptions should also be outlined. Steel was chosen as the tool material in the foam core molding, thermoforming and RTM steps. There are examples of past manufacture of RTM parts using alternative, cheaper tool materials such as nickel shell and epoxy tooling. However, steel, while being extremely durable, also allows parts to be molded with the best surface finish and thus was chosen as the tool material. In the later sections of the analysis, the effect of different tooling materials will also be considered. The flow strategy for the RTM step was assumed to be rectilinear with a constant flow rate. These assumptions were chosen because it allows the lowest possible fill time. However, fast mold filling results in a tradeoff with higher clamping force requirements due to the high molding pressures that build up as the mold is filled. As a result, cycle time is lowered but the press size (and therefore cost) is increased.

	Type	**Price ($/kg)**
Resin	Vinyl Ester	$2.60
Filler	Calcium Carbonate	$0.13
Reinforcement	Glass Fiber CSM	$2.00
Catalyst	Akzo Cadox	$3.24
Foam Core	Polyurethane	$2.54

Table 10: Material Price Assumptions

Assembly

The assembly steps required to join components are divided into three main categories: part loading/unloading, adhesive bonding and curing. Table 11 shows the major production parameters for each category. Curing is divided into small, medium and large sizes to recognize cost differences for curing fixtures of various sizes. For adhesive bonding, the adhesive material was assumed to cost $1.79/kg and material usage was calculated to be 0.141 kg/m, assuming a 12 mm diameter bead.

During a typical assembly step, a robotic arm picks up a component and places it into the adhesive application station. Adhesive material is then applied to the part. Finally, the parts are joined together and held in a curing fixture until the adhesive is fully solidified. In the final assembly line, to increase throughput, idle stations are designed into the process. Idle stations increase the total number of stations in an assembly line and no operations occur at these stations. However, because of the long times required for curing, a number of consecutive idle stations can divide the curing cycle time into more reasonable segments, allowing the line to move at a faster rate. While increasing throughput, idle stations increase the total cost of the assembly line, since the line length increases and more fixtures are necessary to occupy the idle stations.

	Part Loading	**Adhesive Bonding**	**Curing (Small)**	**Curing (Medium)**	**Curing (Large)**
Equipment Cost	$90,000	$145,000	$45,000	$75,000	$150,000
Start/Finish Time (sec)	0	15	10	10	10
Transport Equipment Cost ($/m)		$17,031	$17,031	$17,031	$17,031
Speed or Cycle Time	15 - 41 sec per loading	0.342 m/s	275 - 310 sec	275 -310 sec	275 - 310 sec

Table 11: Key Process Parameters for CIV Assembly

Because there are only eight body-in-white components and 32 metal brackets, assembly for the composite vehicle is much simpler than that of the steel vehicle. Figure 14 shows the conceptual assembly process for the CIV. Similar to the design philosophy for the steel vehicle, the assembly process begins with the underbody and builds upwards. Before each component can be brought to the main assembly line, the metal brackets are joined through adhesive bonding at a substation. After this subassembly, the components can be joined together to complete the body-in-white. At the final assembly line, the underbody is joined to the right and left hand bodysides; the structure is then bonded to the roof and the front end halves to complete the body-in-white. Table 12 outlines the results of the assembly model. (The number of stations and laborers were calculated from the assembly model assuming an annual production volume of 100,000 vehicles per year.)

Subassemblies	6
Total Join Length (Adhesive Bond)	106.6 m
Number of Laborers (@ 100,000 vpy)	8
Number of Stations (@ 100,000 vpy)	
Adhesive Application	8
Part Loading/Unloading	11
Curing (Small)	2

Curing (Medium)	8
Curing (Large)	4
Total Number of Stations (@ 100,000 vpy)	33

Table 12: RTM Assembly Model Assumptions and Results

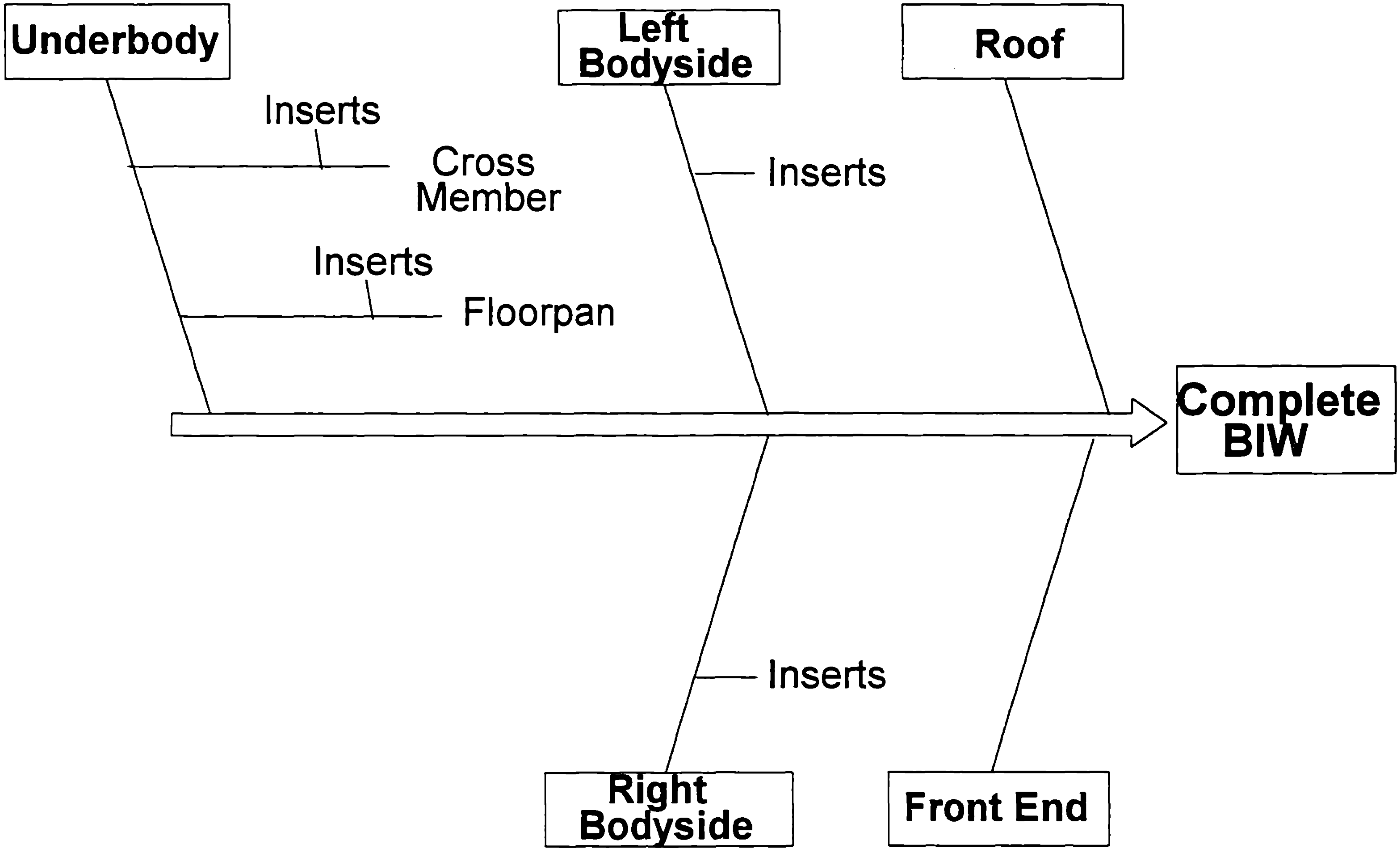

Figure 14: Conceptual RTM Assembly Diagram

Chapter 10: Alternative Composite Materials Vehicle Design

CARBON FIBER CONVERSION

Design

Carbon fibers have been used over glass fiber reinforcement in applications which demand exceptionally high performance and high strength to weight ratios. Carbon fibers are typically produced using a precursor of PAN (polyacrylonitrile) fiber or melt-spun pitch that undergoes a series of heating and stretching steps that remove non-carbon impurities and orient the fiber crystallites. Carbon fiber is much more expensive to produce than glass fiber reinforcement because of high processing temperatures and long cycle times; however, its superior physical properties allow a potentially interesting study of the cost/performance tradeoff.

In order to convert the glass fiber reinforced design to one utilizing carbon fiber, some basic design assumptions must be made. The design assumptions change the geometry of the part; there are no changes in number of components, manufacturing process or assembly process relative to the glass fiber reinforced vehicle.

Stresses that result from bending are the most common form of loading that parts experience. Therefore, stiffness can be the physical parameter in which the designs are compared. Assume that bending for a body-in-white component is similar to a beam fixed on one end experiencing a bending moment due to a force applied to the free end. This type of bending is classified as a cantilever. The equation to calculate the deflection on a cantilever beam is:

$$\delta = \frac{PL^3}{3EI}$$

where δ is the deflection of the beam, P is the applied load, L is the length of the beam, E is the elastic modulus and I is the second moment of inertia. In addition, the second moment of inertia can be expressed (for homogenous materials) as:

$$I = \frac{bh^3}{12}$$

where b is the width of the beam and h is the beam thickness. Using the two equations and the necessary material properties, beam thickness can be calculated.

To utilize the beam bending equations to convert the original CIV design into a carbon fiber reinforced design, a few assumptions must be made about material properties and part characteristics. Assume the typical carbon fiber material used in this design has an elastic modulus of 34 Msi and the typical value for E glass fiber is 10.5 Msi. [Lubin, 1982] If the part thickness of a glass fiber reinforced sheet is 3 mm, then the thickness of an equivalent sheet (same length and width) reinforced with carbon fiber which gives the same stiffness can be calculated from the above equations. The calculations result in a carbon fiber reinforced sheet thickness of 2.03 mm.

In addition to the pure carbon fiber reinforced part, a blend of carbon and glass fiber can also make an interesting study of the cost/performance tradeoff. The blend may allow a significant reduction in material cost while retaining some of the advantageous properties of carbon fiber. Given the values for elastic moduli of the carbon and glass fiber, a mixture containing 50 wt% glass and 50 wt% carbon would have a modulus of 22.25 Msi. The corresponding thickness of the blend sheet is then calculated as 2.3 mm.

The calculations produce results which state that given the superior physical properties for carbon fiber, less material can be used to give equivalent levels of performance. The calculations provide a first pass estimation of the geometry of a true carbon fiber reinforced part design. It must be noted that the assumptions made to calculate a comparable design must be more rigorously tested and proven out. However, the simple calculations used to produce the results allow a reasonable foundation to study the feasibility of carbon fiber use in automotive body-in-white designs.

Cost Modeling

Most of the assumptions that were made in the RTM model remain the same for the carbon and carbon/glass bend designs. The only major differences are in the material formulation of the subsystems. Because less reinforcement material is used, the weight percentage distributions change accordingly. Tables 13 and 14 list the material formulations for the carbon and carbon/glass designs.

	Roof	**Floorpan**	**Cross Member**	**Bodyside**	**Front End**
Resin	46.63%	42.49%	39.58%	40.75%	40.75%
Fiber	35.89%	33.12%	23.36%	28.24%	28.24%
Foam Core	0.00%	23.85%	36.56%	30.49%	30.49%
Catalyst	0.58%	0.54%	0.49%	0.52%	0.52%
Filler	16.90%	0.00%	0.00%	0.00%	0.00%
Carbon Fiber Price: $11.00/kg					

Table 13: Material Formulation for Carbon Fiber Vehicle

	Roof	**Floorpan**	**Cross Member**	**Bodyside**	**Front End**
Resin	43.04%	40.50%	39.13%	39.57%	39.75%
Fiber	40.82%	38.90%	28.45%	33.78%	33.78%
Foam Core	0.00%	20.08%	31.93%	26.15%	26.15%
Catalyst	0.54%	0.51%	0.49%	0.50%	0.50%
Filler	15.60%	0.00%	0.00%	0.00%	0.00%
Carbon/Glass Blend Fiber Price: $6.50/kg					

Table 14: Material Formulation for Carbon/Glass Blend Vehicle

SMC VEHICLE

Design Conversion

In order to convert the original CIV design into one that utilizes SMC material, a number of design assumptions must be made. SMC is reinforced through chopped glass fibers (typically one inch in length) which are randomly distributed throughout the resin matrix. The chopped reinforcements are less expensive than the continuous fiber mat used in the RTM process; however, chopped fiber is not as effective a reinforcement material as the continuous fiber. As a result, a number of design assumptions must be made in order to derive a functionally similar SMC composite vehicle from the original CIV design.

The most common form of loading in beam and sheet sections is through stresses imposed by bending. Therefore, stiffness is the most important design criteria to consider when converting the original design to an SMC one. To compensate for SMC's lower elastic modulus, the part thickness is increased from 3 mm in the original design to 4 mm for the SMC. [Jaranson, 1997] Although greater increases in thickness can allow the SMC design to meet the stiffness requirement, thickening the part requires greater material usage (which increases cost and weight). A more effective way to increase stiffness is to incorporate ribs into the part design.

Ribs are long, thin sections of material which are placed in strategic areas on the interior of the part in order to bear load. Figure 15 shows a depiction of the proposed rib structure used in the SMC design for the composite vehicle. This rib pattern was assumed to be placed uniformly throughout the parts, every 150 mm. [Elliot, 1997] The rib length was assumed to be 150 mm; the height and width of the rib would be dependent on the specific geometry of the part in which the rib was placed. It is important to note that without a proven design, it is difficult to measure the effect of ribs on part performance. These assumptions are a rough approximation of how a likely SMC part would be designed. In addition, the placement of ribs in an actual part would be much more precise in order to avoid poor surface quality and molded-in stresses.

Because ribs are located on the interior of a part and SMC molding is a stamping process, parts are designed as two halves which are bonded together to form a complete part. As a result, the SMC design faces increased tooling costs because of the increased surface area resulting from ribs and also because of the need to mold two halves. In addition, assembly costs also increase because of the additional assembly steps resulting from the bonding of the two halves.

Finally, the SMC design assumes foam cores in areas where crush resistance was necessary, specifically, the front end and floorpan. However, an actual SMC molding process may incorporate foam by injecting it directly into the part, rather than placing pre-manufactured foam cores between two halves. The foam injection manufacturing process was not modeled due to the fact that it is a highly specialized application without sufficient information available to build a cost model. An approximation using reaction injection molded foam cores was deemed to have sufficient accuracy in terms of cost.

Cost Modeling

Taking the results of the design assumptions, the SMC cost model can be used to estimate the cost of manufacturing the body-in-white parts. The inputs for each specific part can be found in Appendix B. The more important cost model parameters and assumptions are listed in Table 15. This section will highlight some of the modeling methods used in costing the body-in-white.

Material	$1.90/kg (Vinyl Ester/Glass Fiber SMC)
Tooling	Single Cavity, Single Action Steel, plus Backup
Press Cost	
Large	$2.5 MM
Small	$0.75 MM
Molding Cycle Time	
Large	120 sec
Small	90 sec
Laborers	2 per press

Table 15: SMC Cost Modeling Parameters

Manufacturing using the SMC process is much like steel stamping in that a downward pressure applied to a sheet of material forces the material to conform to the mold shape. As a result, large presses and steel tooling are required to compression mold an SMC part. Because the SMC presses are considered dedicated machinery, equipment and tooling costs are a significant portion of the total manufacturing cost. As a result, in a real manufacturing situation, a press and tool would not be allocated to each individual part. Much effort would be made to share machines and utilize them as efficiently as possible.

In order to share machines to mold various parts, a distinction was made between large and small parts. Part geometry has a major influence on press cost, as discussed in the previous chapter on the SMC cost model. By separating parts by size, the presses can be tailored to the forming requirements of each category. Therefore, a 2000 ton SMC press will only mold those parts which require such large clamping forces while smaller presses can service less demanding applications. As a result, equipment costs decrease because of the more efficient utilization of presses.

To calculate the size of the press required, each part's equipment requirements were calculated to determine the range of press tonnages. Then, for the large and small part categories, the maximum press size was selected. To determine the number of machines required, the total amount of required machine time was calculated for each part, then all times were totaled and rounded to the nearest integer to calculate the total number of machines required. Equipment cost for each part can then be allocated according to the fraction of machine time utilized to manufacture each part.

Assembly

The assembly strategy for the SMC vehicle is similar to that of the RTM designs. Joining parts requires the application and cure of adhesives. However, there are differences in the number of process steps required to assemble the two designs. Because a complete SMC part is composed of two halves, extra assembly steps are required to first join the halves together before attaching brackets and other components. The direct result of the need for extra assembly steps is that equipment costs increase as more stations are required to join parts. In addition, material costs increase due to the increase in total join length. (Figure 16)

Subassemblies	10
Total Join Length (Adhesive Bonding)	194.3 m

Total Number of Laborers (@ 100,000 vpy)	12
Number of Stations (@ 100,000 vpy)	
Adhesive Application	12
Part Loading	15
Curing (Small)	2
Curing (Medium)	8
Curing (Large)	8
Total Number of Stations (@ 100,000 vpy)	45

Table 16: SMC Assembly Model Assumptions and Results

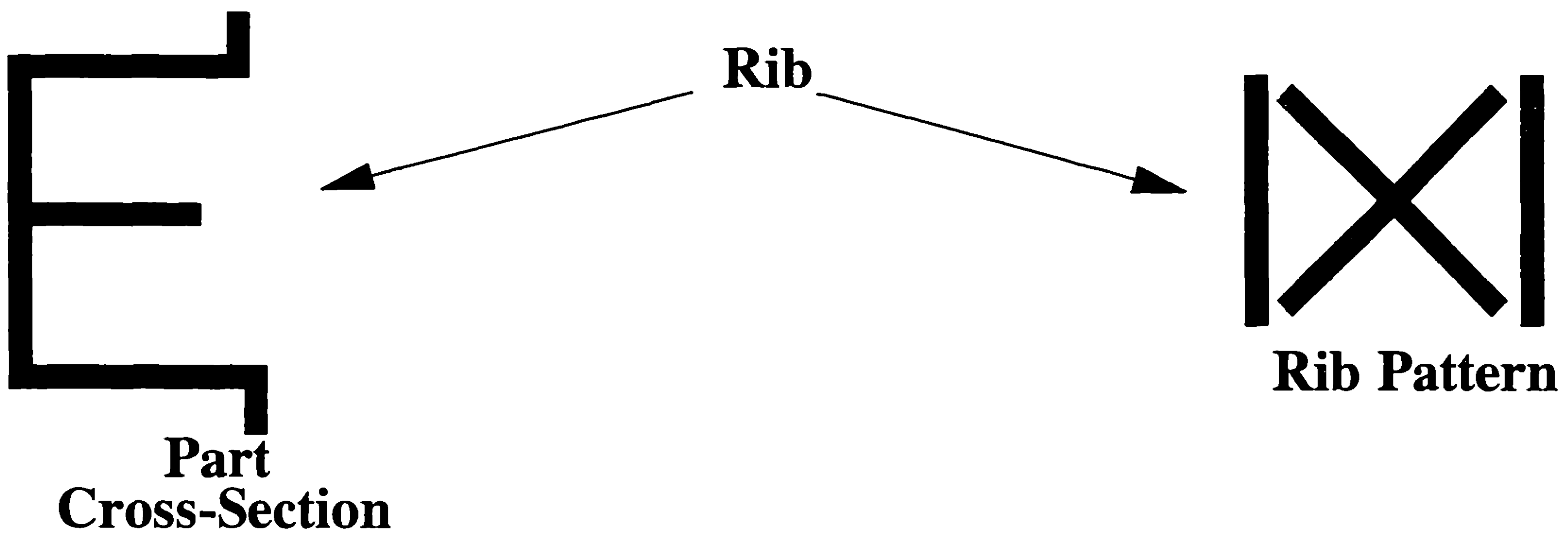

Figure 15: Representative Rib Diagram

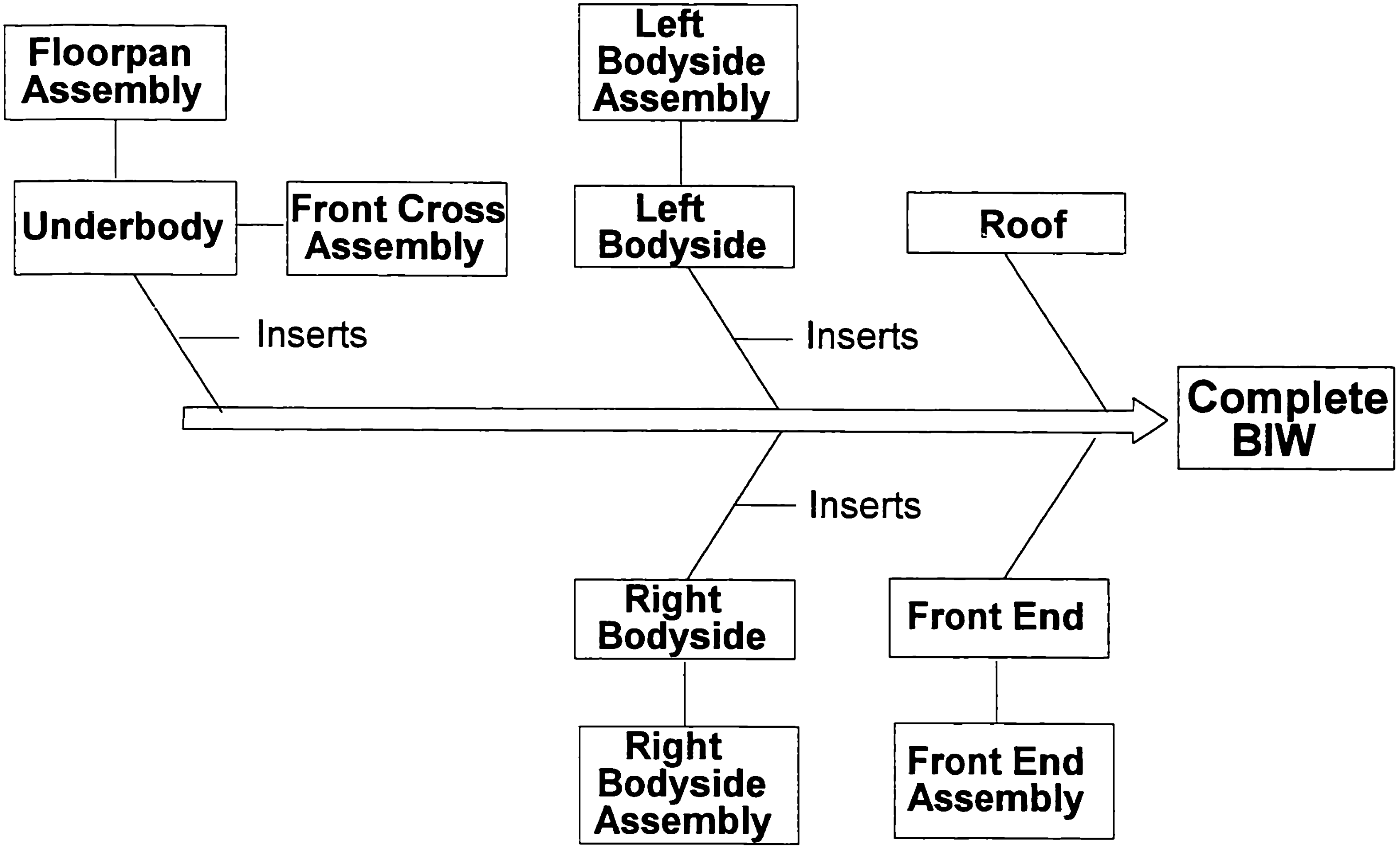

Figure 16: Conceptual SMC Assembly Process

Chapter 11: Results of Analysis

TOTAL BODY-IN-WHITE WEIGHTS

Given the design assumptions made in the previous chapter, the weights of the body-in-white designs can be derived. Figure 17 shows the results of the design calculations and measurements made for the steel and composite material vehicles. Not surprisingly, carbon fiber, with its lower density and higher strength relative to glass fiber, dramatically reduces the weight of the body-in-white. The weight of each subsystem changes significantly with each type of material used. The only exception is the roof subsystem, which only demonstrates minor weight savings with use of carbon fiber and almost no savings with the use of glass fiber. This is because for the RTM design, two roof panels are required, an SMC outer and an RTM inner. Therefore, the weight savings achieved in the RTM inner is overshadowed by the need for an additional SMC outer panel.

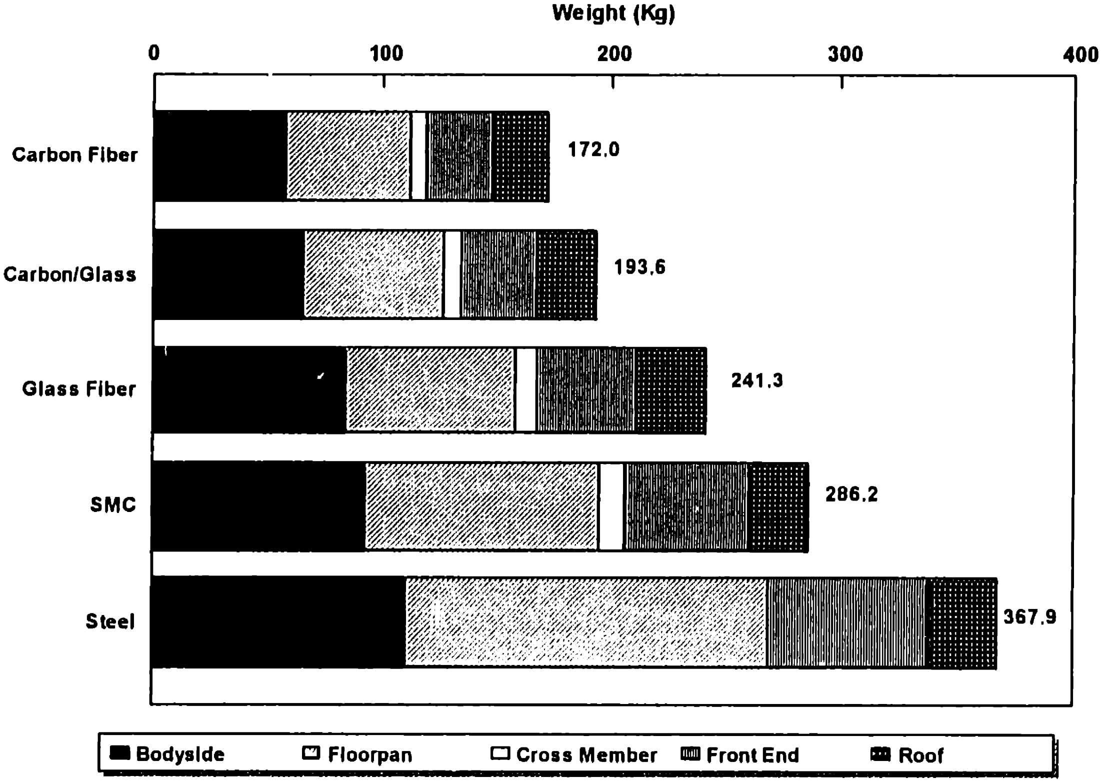

Figure 17: Comparison of Weights for Body-in-White Designs

TOTAL BODY-IN-WHITE COST

Figure 18 shows the results of the cost analysis of the entire body-in-white for the five material technologies. The RTM glass fiber reinforced vehicle cost line crosses over with the steel base case at approximately 35,000 vehicles per year, the carbon fiber vehicle crosses over with steel between 15-20,000 vehicles per year, the carbon/glass blend crosses over at 25,000 vehicles per year and the SMC design crosses over at just under 35,000 vehicles per year. Below the crossover volumes, the composite vehicle designs are more cost-effective than the comparable steel vehicle.

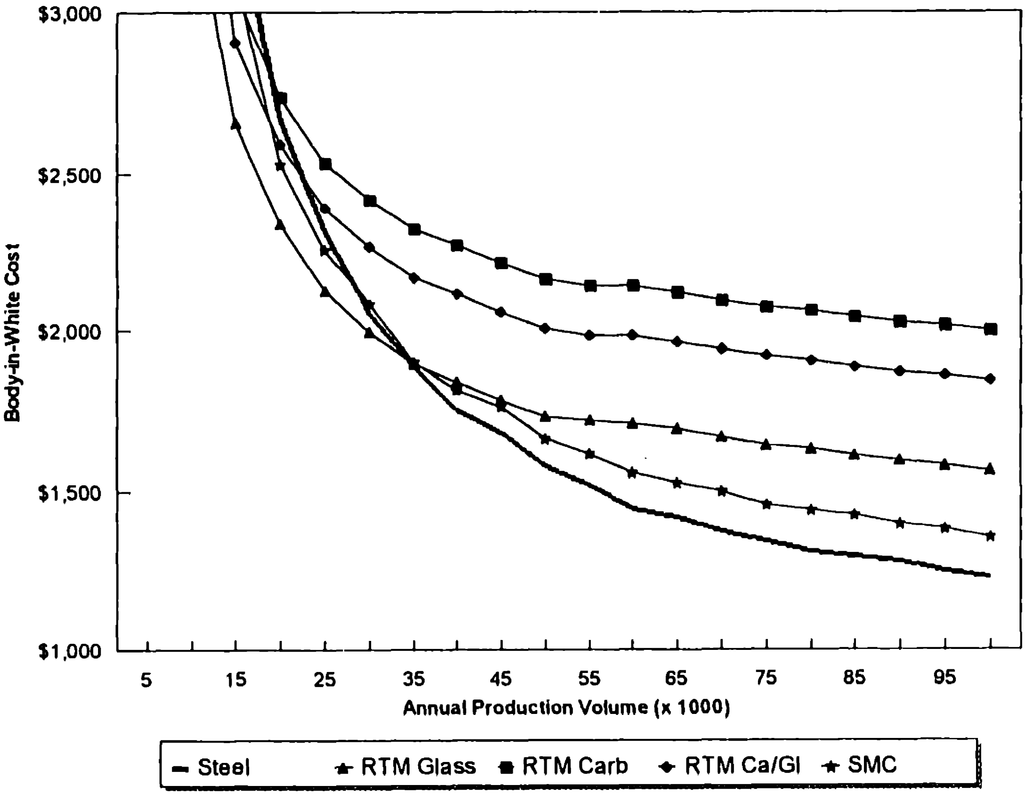

Figure 18: Total Body-in-White Cost

This result can be explained by the differences between the alternative composite materials and the steel stamping process. Fundamentally, the cost drivers for the composite processes are different from those of steel because of the requirements of the manufacturing processes. In order to manufacture parts from steel, much capital investment is required. The press lines consist of large presses and steel tooling, which are expensive to purchase. On the other hand, composite processes incur lower capital costs for two reasons. First, composite manufacturing systems do not require presses as large as those used in steel because of the lower pressure forming process. Second, even if large presses are used, multiple presses are not required since all part-forming operations occur at one press, while a steel part requires up to five presses, depending on its complexity. In addition to the cost increase from multiple presses, each press in the press line is outfitted with a tool, further increasing the capital costs. Figure 19 shows the equipment and tool cost differences between the processes at the crossover production volume.

While the steel stamping process incurs high fixed costs, its variable cost component is low relative to the composite processes. The steel stamping process is a low variable cost operation for two reasons. First, steel material is very inexpensive ($0.77 per kilogram steel) and any scrap can be resold to gain additional cost savings. Second, the cycle times are short for the part-forming operations (on the order of seconds) so that labor costs remain low. On the other hand, materials for composite parts are expensive (upwards of $2/kg for the RTM parts and $1.90/kg for SMC). In addition, cycle times are much longer than steel stamping (for example, the RTM cycle time itself is over 4 minutes) so that labor costs are high. However, the large number of steel parts offset the labor cost advantage since more people are needed in the steel manufacturing process. Figure 20 shows the contribution of variable costs to each material. The RTM cost breakdown displayed in the figure is the result from the glass fiber reinforced design.

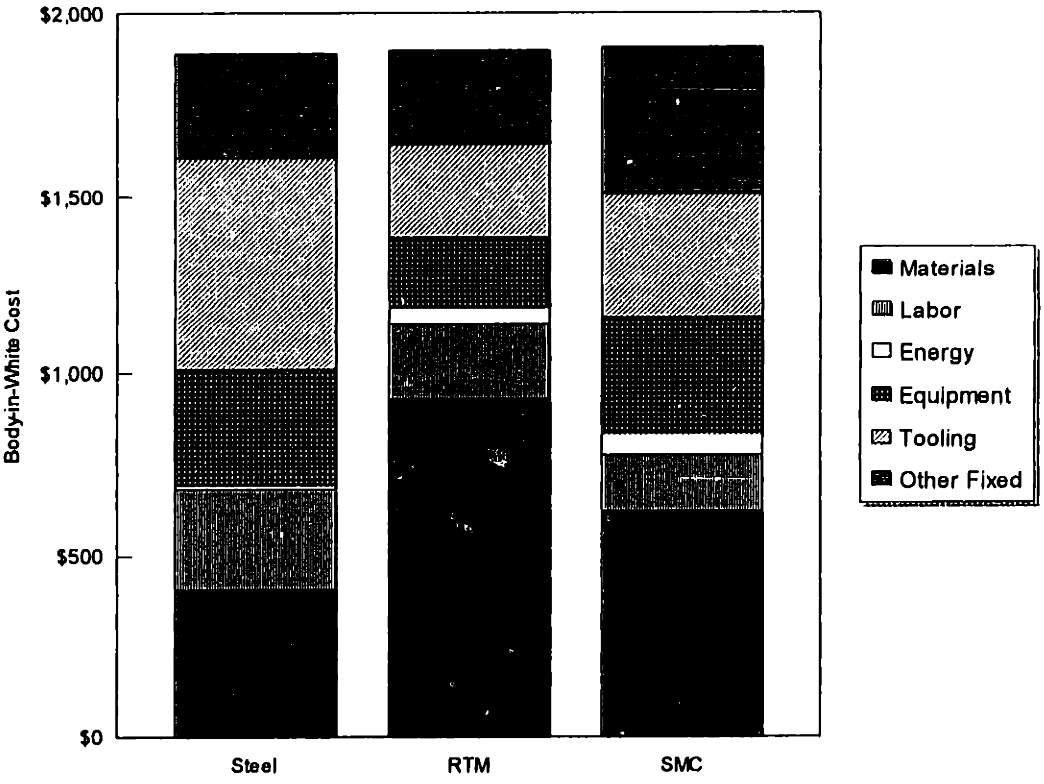

Figure 19: Cost Component Breakdown at 35,000 Vehicles/year

Therefore, at low production volumes, the composite processes can remain competitive with the steel stamping process. At low volumes, the cost of tooling cannot be distributed over many parts so that fixed costs remain high. This allows the composite processes to be competitive with steel, even though the composites' variable costs are much greater. However, as more parts are produced annually, the contribution of fixed costs to the total cost decreases and thus the steel process becomes more cost-effective. Contrasting the cost components of figures 19 and 20, the contribution of fixed costs for the steel BIW change dramatically between the low and high production volume scenarios. On the other hand, variable costs remain fixed for all processes at all production volumes, leaving the composite parts at a disadvantage at high production volumes as fixed costs become less important.

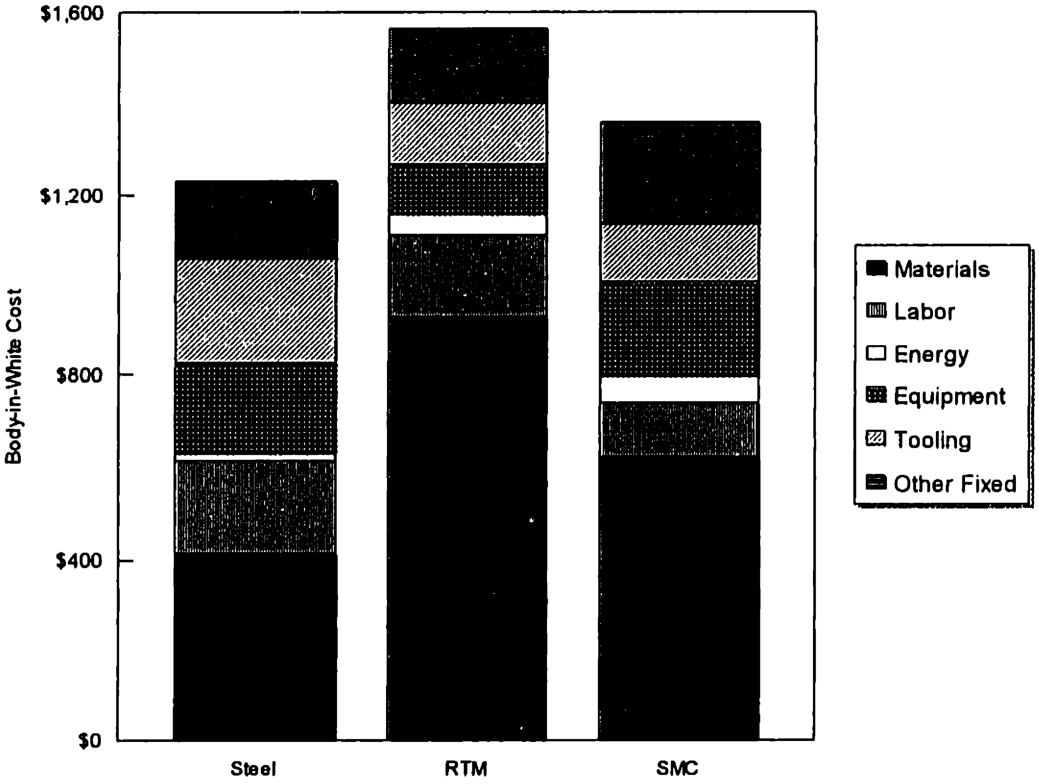

Figure 20: Cost Component Breakdown at 100,000 Vehicles/year

Another interesting result is that the SMC process represents somewhat of a compromise between the RTM and steel BIW designs. Compared to the RTM process, the SMC design has higher fixed costs for two reasons. First, more machines and tools are required because of the need to mold two halves to form one part. Secondly, the SMC process utilizes larger, more expensive presses relative to the RTM process as a result of higher relative molding pressures. On the other hand, SMC's variable costs are lower than that of the RTM process. Material cost and cycle times are both lower for the SMC process, resulting in lower material and labor costs. Therefore, at low production volumes, the SMC design is slightly less expensive than the steel design but more expensive than the RTM design. At higher production volumes, the SMC design is more cost-effective compared to the RTM vehicle but more expensive compared to the steel design.

Assembly Cost

Another method to break down the total body-in-white cost is to separate the manufacturing and assembly portions. (Figure 21) The results show a distinct advantage in cost for the composite vehicles in assembly, while the steel design has the advantage in manufacturing cost. It is expected that the steel design would incur the greatest assembly cost, since there are many more parts to assemble compared to the composite designs. For the SMC design, it is again a compromise between the RTM and steel vehicles. There are more parts to assemble relative to the RTM design, but much less relative to the steel. The process breakdown demonstrates that the cost of assembly plays a significant role in determining the overall cost effectiveness of various designs. If manufacturing cost was the only consideration, then the composites would be more expensive, even at this low production volume. However, modeling the assembly process quantifies one of the more important benefits of composites use.

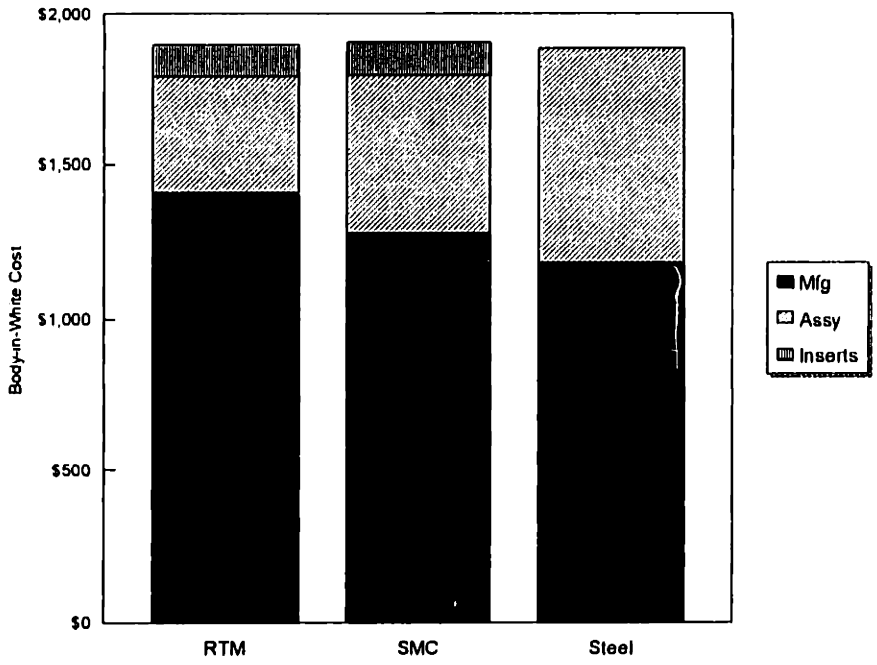

Figure 21: Cost Breakdown by Process at 35,000 Vehicles per Year

Carbon Fiber BIW

As shown in Figure 17, the use of carbon fiber results in significant weight reduction of the body-in-white. However, its use also comes at an increased manufacturing cost. Figure 22 shows the manufacturing cost breakdown of the RTM body-in-white designs using glass fiber, carbon fiber and carbon-glass mixtures. The assembly cost is not included in the breakdown because assembly is identical for all designs.

As a result of its high modulus, less reinforcement material is required through the use of carbon fiber, such that part thickness can be decreased. This design modification results in some cycle time savings in the RTM step where the resin fill time is reduced due to a smaller volume to fill. However, as the cost breakdown demonstrates, these modest cycle time advantages do not overcome the material cost penalty from the use of carbon fiber. The carbon fiber reinforcement material costs $11.00 per kilogram, compared to the $2.00 per kilogram cost assumed for the glass fiber reinforcement. While there are slight decreases in some cost components due to cycle time reductions, these gains are overshadowed by the large increase in material cost.

From the preliminary analysis of alternative reinforcement materials, the conclusions indicate that the high material cost results in prohibitive constraints on the use of carbon fiber. The assumption of $11.00 per kilogram of carbon fiber is a generous one; only low grade carbon is currently available at this price. There are two scenarios that can be envisioned where carbon fiber would be a viable reinforcement material. One is that the price drops dramatically to more competitive position. This scenario seems unlikely given the high cost of producing carbon fiber. The other scenario is that carbon fiber's superior physical properties can be utilized to achieve significant design advantages over the glass fiber design in addition to its lower material usage. While more research must be conducted to fully understand the effects of carbon fiber use on the body-in-white, the current results strongly indicate a clear advantage to glass fiber as the most competitive reinforcement material for structural automotive applications.

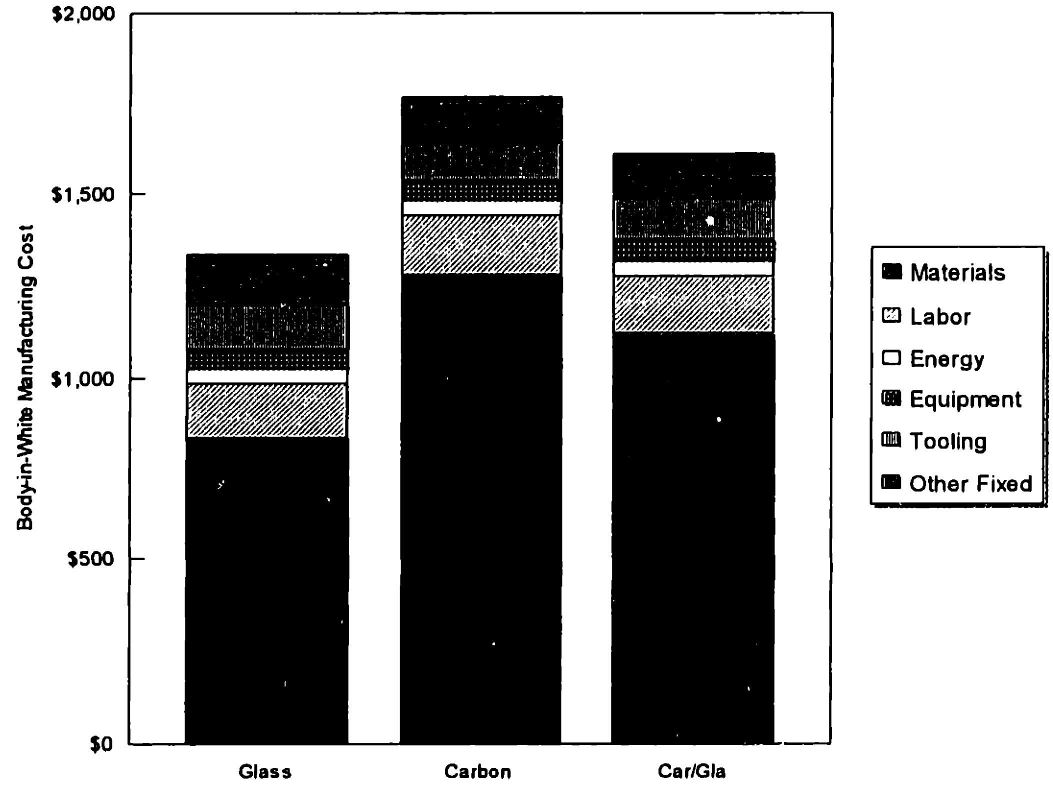

Figure 22: BIW Manufacturing Cost Breakdown at 35,000 Vehicles per Year

Another method in which to evaluate the cost competitiveness of the carbon fiber designs is to analyze the cost per kilogram weight saved. (Figure 23) The cost per kilogram saved is a metric that takes into the account the weight savings and cost of each design, relative to the steel base case:

$$\text{Cost per Kilogram Saved} = \frac{\text{Cost of Composite BIW - Cost of Steel BIW}}{\text{Weight of Steel BIW - Weight of Composite BIW}}$$

The cost per kilogram saved is negative when the cost of the composite body-in-white is lower than the steel cost, denoting that the composite design is more cost-effective at this production volume. However, as the cost of the steel design overtakes the composite, the cost per kilogram saved will be a positive number. The value can be interpreted as the additional cost incurred per kilogram of weight savings achieved by the composite design. Therefore, this metric mitigates the cost penalty incurred from the use of carbon fiber by taking into account the weight savings gain.

The analysis indicates that carbon fiber designs are still more costly, even when the weight savings are accounted for in the cost metric. The analysis reinforces the conclusion that while carbon fiber reinforcing materials do allow significant weight savings, additional process or material price gains must be realized before it merits serious consideration in body-in-white applications.

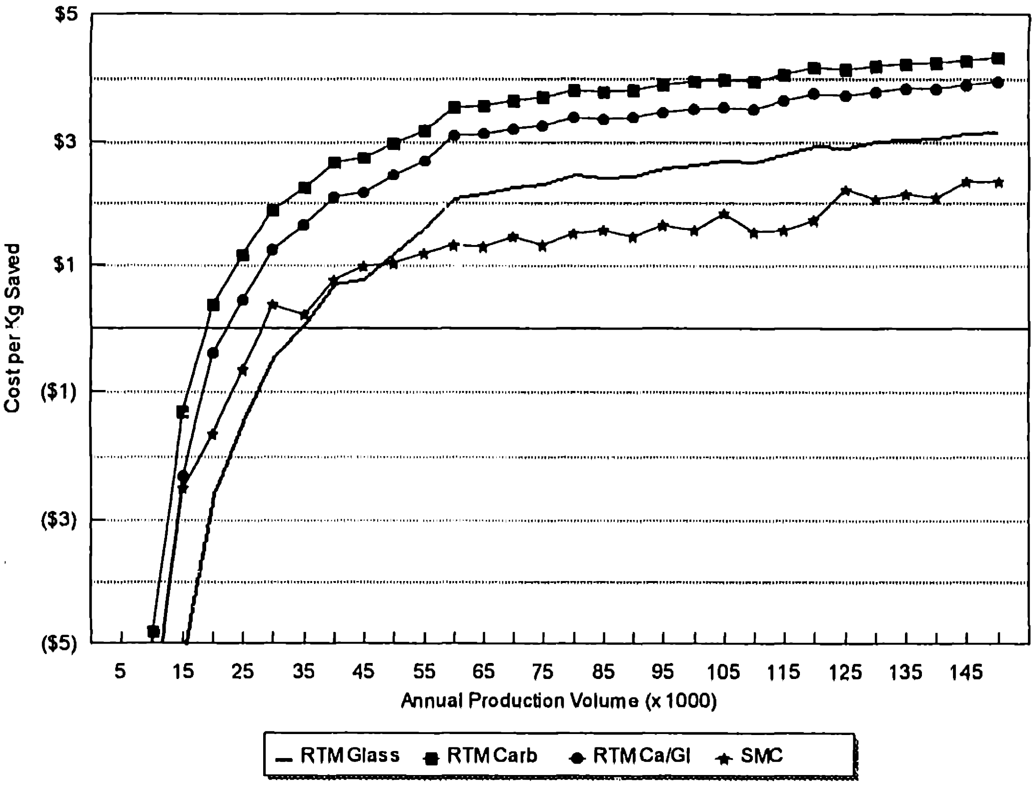

Figure 23: Cost per Kilogram Saved (Relative to Steel Base Case)

SMC SCRAP

One of the assumptions in the cost model for the SMC body-in-white was for the process scrap rate, assumed to be five percent. This assumption was grounded on the ability of the SMC charge to be laid into the mold in a pattern closely resembling the final part shape. For example, in molding a door panel, the SMC charge pattern is laid around the window opening so that scrap rates are reduced. On the other hand, cutouts of the window opening are required in the glass mat in the RTM process, increasing material waste.

However, if this assumption proved too aggressive in reality, it would be beneficial to investigate the effects of increasing scrap rate for the SMC process.

Figure 24 shows the effect on cost given a design with scrap rates ranging from 5% to 30%. As expected, increasing scrap rate increases the amount of material used and therefore increases costs. (Crossover points: SMC 5% - 30,000 vehicles per year; SMC 15% - 25,000 vpy and SMC 30% - 20,000 vpy)

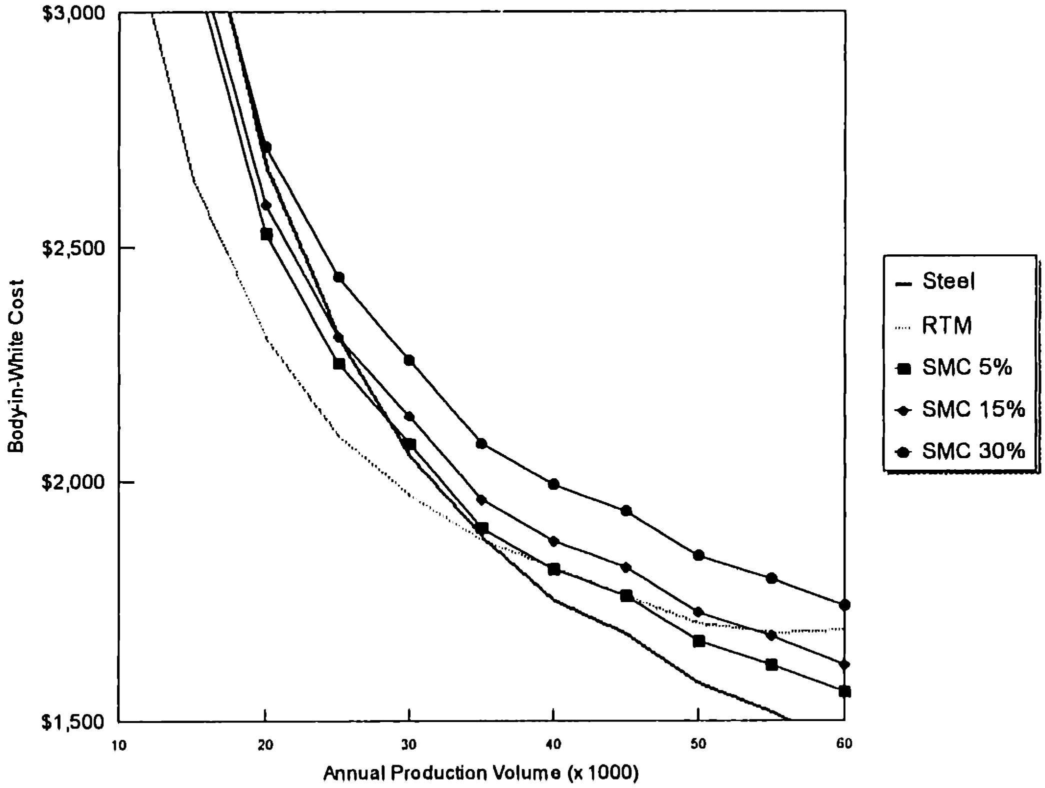

Figure 24: SMC BIW Cost with Varying Scrap Rates

EFFECT OF MATERIAL COST

The cost of materials is the most significant cost component of the RTM body-in-white designs. Table 17 shows the cost contribution of each material used in the RTM design. The "Other" category includes the cost of the filler, catalyst and mold maintenance materials. As shown in the table, the cost of the glass reinforcement accounts for over half of the total cost of materials.

Component	*Cost*	*% of Total Material Cost*
Glass Reinforcement	$449.26	54%
Resin	$221.78	27%
Foam Core	$116.00	14%
Other	$42.42	5%
Total	**$829.46**	**100%**

Table 17: Breakdown of Material Cost

Consequently, the RTM body-in-white design is very sensitive to changes in the cost of glass reinforcement. As the reinforcement price is increased from $2/lb. to $3/lb., the break-even point between the curve and the steel BIW curve declines from 35,000 vehicles per year to less than 25,000 vpy. (Figure 25) While the negative correlation between materials cost and break-even point is obvious, this analysis demonstrates the importance of materials cost to the competitiveness of a composite BIW design. Processing breakthroughs that lower the cost of producing glass reinforcement will result in significant improvement in the cost of the composite BIW.

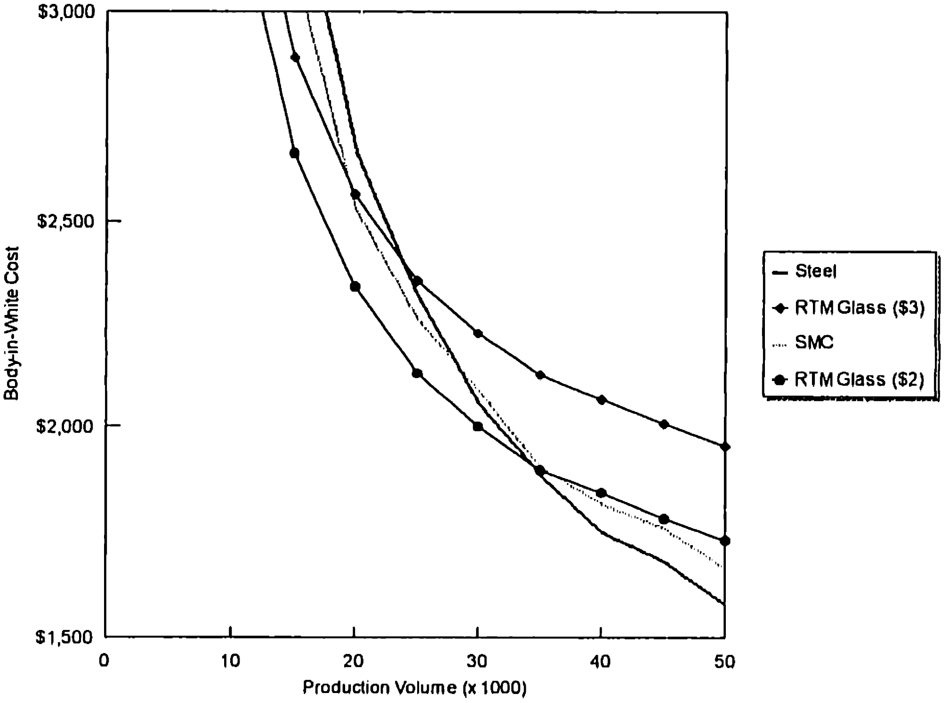

Figure 25: Effect of Reinforcement Cost

EFFECT OF TOOLING COST

An additional advantage of the RTM process is that cheaper, non-steel tooling can be used in the preforming and foam core molding steps. While steel tooling is recommended in the resin transfer molding step in order to achieve a high quality surface finish, cheaper tooling can be utilized in applications for which surface quality is not critical. An example of a less expensive tool material would be a nickel shell tool backed by cast iron. However, aside from the surface quality issues, these tools have another drawback; the life of the tool is significantly less compared with steel tool material. Steel tooling is extremely durable and with proper maintenance, steel tooling can be used to form over 1 million parts (1 million parts was the tool life assumed in the model). However, tooling such as nickel shell can be expected to last on the order of 100,000 parts. Other tool materials (such as epoxy) have an expected life in the high thousands and are used to make limited production runs or prototypes.

Figure 26 exhibits the results from the alternative tooling scenario. In the original analysis, all three steps were assumed to use steel dies. For this scenario, the preforming and foam core molding steps were assumed to have tool costs that were 25% of the original. In addition, the life of the new tool was assumed to be 100,000 parts. The tooling in the RTM step was unchanged.

The graph shows that less expensive tooling provides a marginal reduction in the cost of the BIW, increasing the break-even volume by only 3,000 to 5,000 vehicles per year. The results demonstrate the tradeoff of cost versus tool life; in addition, the results indicate that tooling is not a significant source of cost for the RTM process. As a result of major parts consolidation, the number of tools required to form the body-in-white is dramatically reduced such that tooling becomes a less important contributor to the total cost. As a result, the choice between longer lasting, more expensive tooling and less expensive, less durable tooling is not a critical issue.

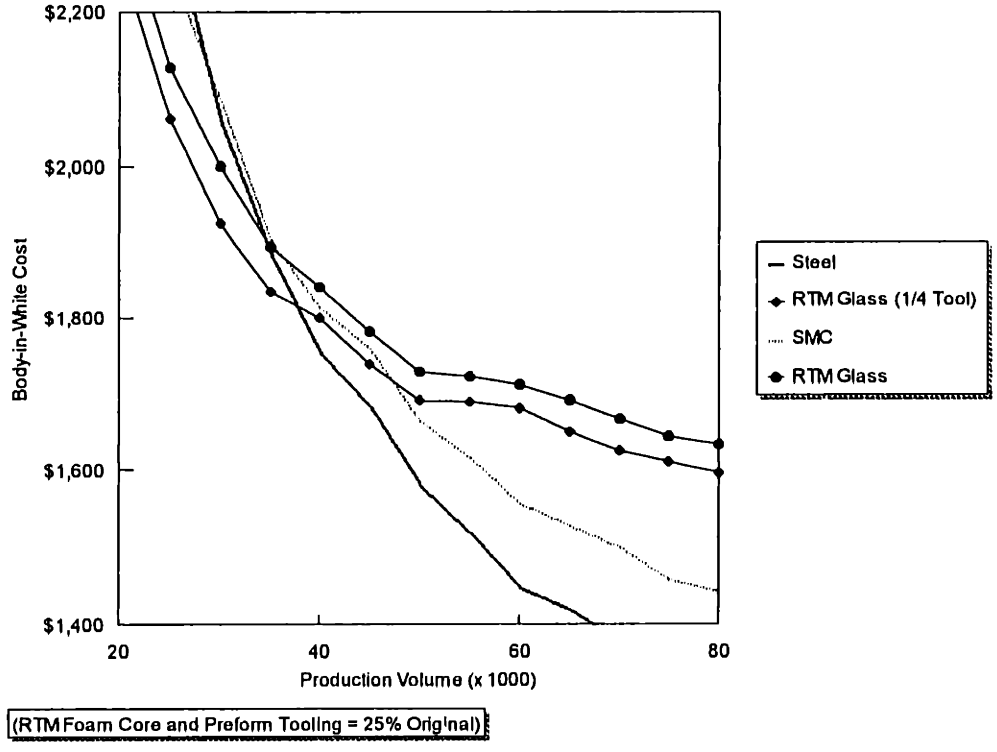

Figure 26: Effect of Tooling on RTM CIV Design

Chapter 12: Case Studies of Body-in-White Subsystems

The results of the complete BIW analysis indicate that composites are viable for low to medium production volumes (less than 40-50,000 vehicles per year). However, the body-in-white is comprised of several subsystems which contribute to the total cost. In the next section, each subsystem and its steel counterpart will be examined to determine the contribution of each to the overall cost of the body-in-white.

ROOF

Figure 27 displays the results of the roof cost analysis. The steel roof is composed of nine parts, the RTM roof has 2 parts (RTM inner and SMC outer) and the SMC roof is a one piece design. As the results show, the composite designs offer no cost advantage; the steel is the least expensive part at almost all production volumes (except at very low volumes; less than 5,000 parts per year).

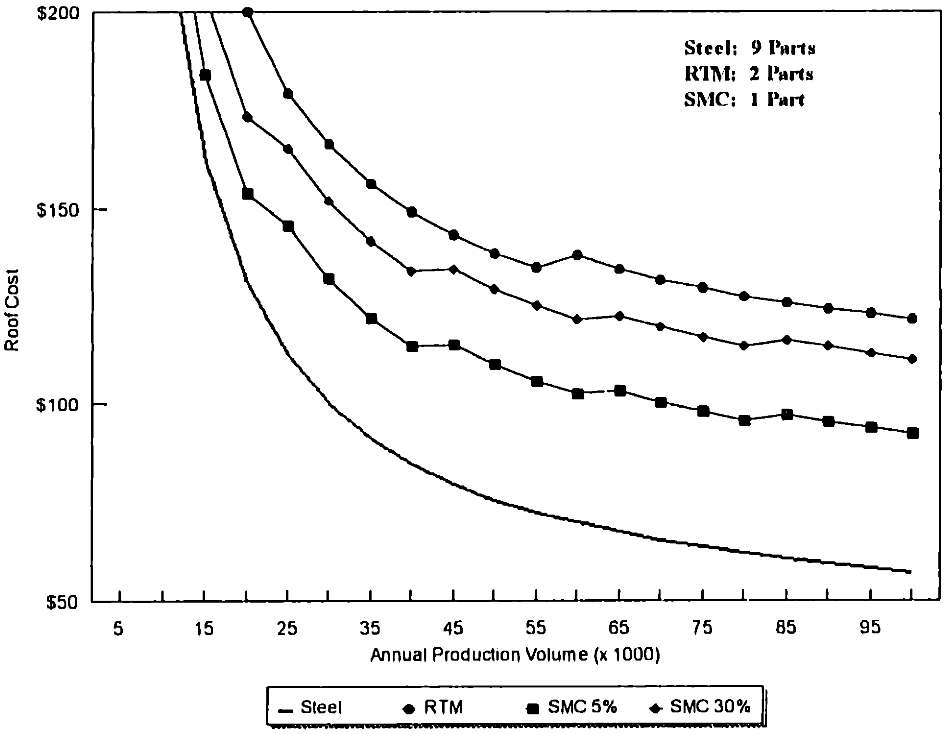

Figure 27: Roof Cost

Cost breakdowns illustrate more clearly why the roof is a disadvantageous subsystem for composite materials. Figure 28 shows the cost breakdown between manufacturing and assembly for the various designs. This highlights the first reason that the composite roofs are not cost competitive. The roof is a very simple part, consisting of one large panel and eight rails that provide structural support. There are few parts to assemble and therefore, parts consolidation is not a source of significant advantage for composite materials. In addition to a relatively simple assembly process, the length of the join for the steel roof is also minimal. The rails are only welded to the roof at the ends and not along its entire length, resulting in a short join length. As a result, assembly costs for the various designs are similar, with the composite designs holding a slight edge. The main difference lies in the manufacturing cost of the roof.

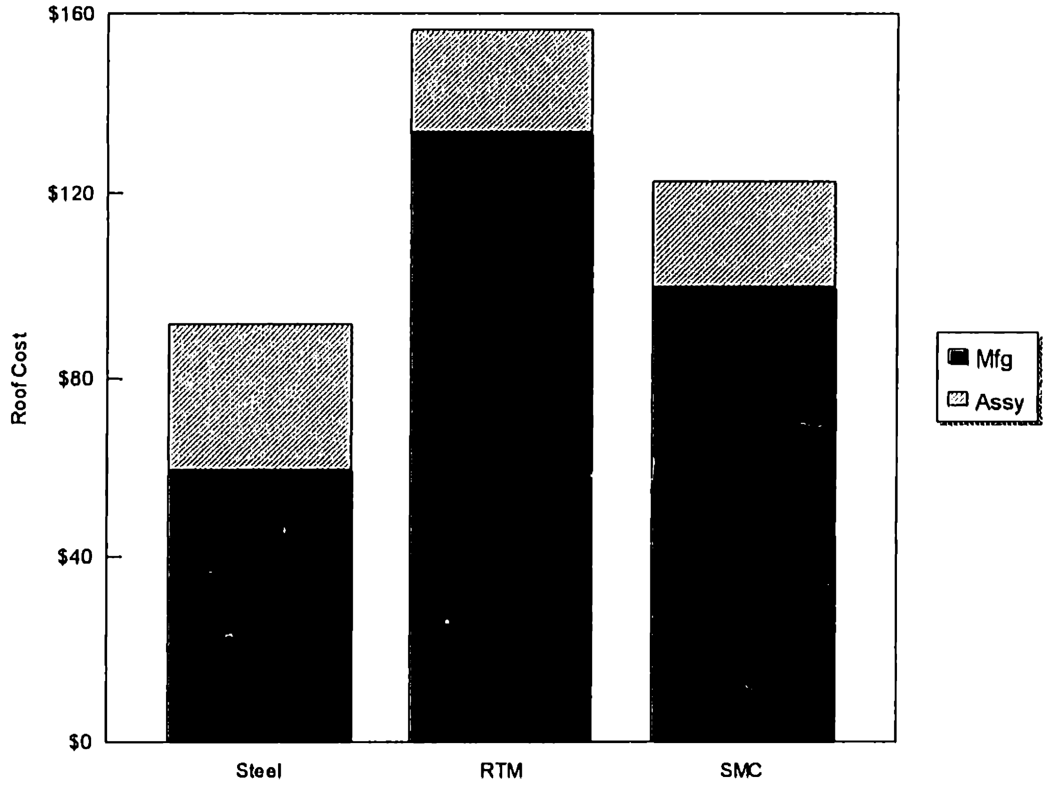

Figure 28: Roof Cost Breakdown by Process at 35,000 Parts per Year

In addition to low assembly costs, the cost breakdown by process (Figure 29) highlights the other source of advantage for the steel in the roof application. The roof is not only a simple design to assemble, but also a very simple design to manufacture. The main component of the roof subsystem is a large flat panel with no forming complexities (it is classified as a simple panel). In addition, the roof's reinforcing rails are also simple shapes that are easily formed. Therefore, tooling costs are kept low, only slightly greater than the composite roof designs. As a result, even at low volumes, there are no advantages in assembly or tooling costs that the composite designs can utilize to overcome its high material cost. The roof is a clear example of a subsystem where steel will continue to remain the dominant material.

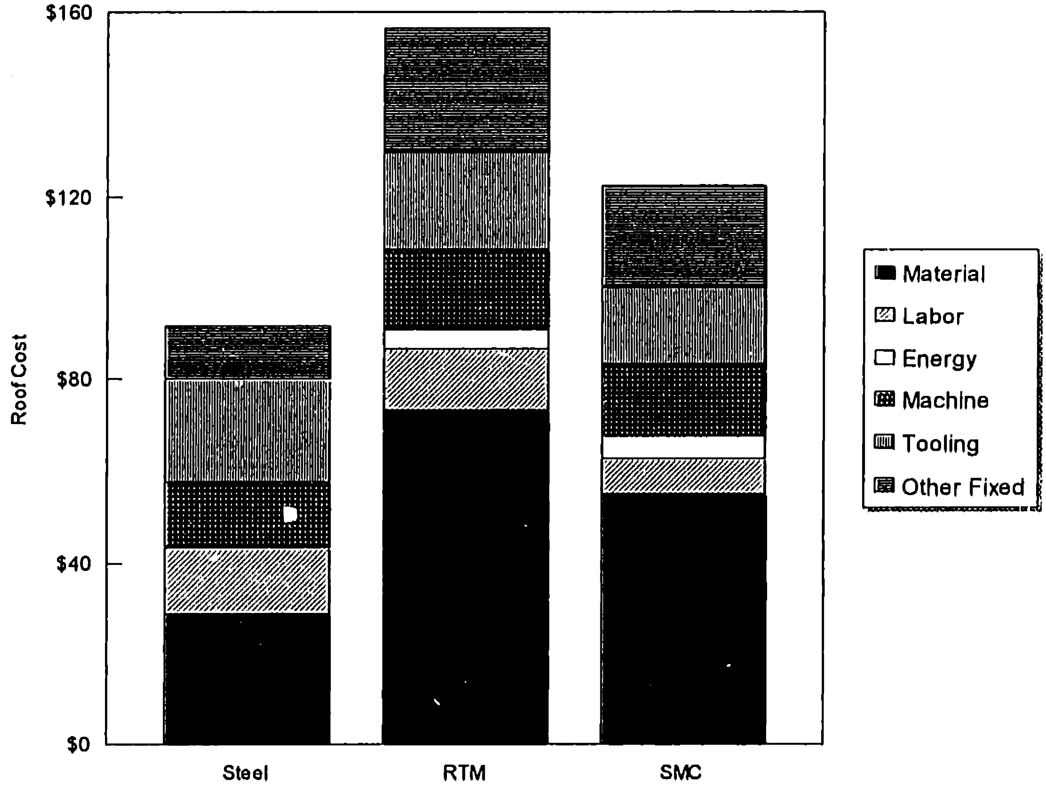

Figure 29: Roof Cost Breakdown at 35,000 Parts per Year

Bodyside case study

Compared to the roof case study, the bodyside provides more opportunities for composite materials. The steel bodyside (for both halves) is composed of 37 parts, the RTM design is composed of 2 pieces and 12 inserts and the SMC design includes 4 parts and 12 inserts. From the part count alone, it is evident that the bodyside represents a much more complex part to manufacture using steel compared to the roof case. Figure 30 shows the results of the cost analysis for the bodyside.

What is immediately evident is that there are differences in the performance of the RTM and SMC designs. The RTM bodyside exhibits a break-even point with the steel design at a volume between 20,000 and 25,000 parts per year. However, the cost of the SMC (5% scrap rate) bodyside is nearly identical to the steel design over the production volume range displayed in the figure. The SMC part is only $30 more expensive than the steel design at high volumes. Even the worst case scrap rate scenario for the SMC design (30% scrap rate) significantly outperforms the RTM bodyside.

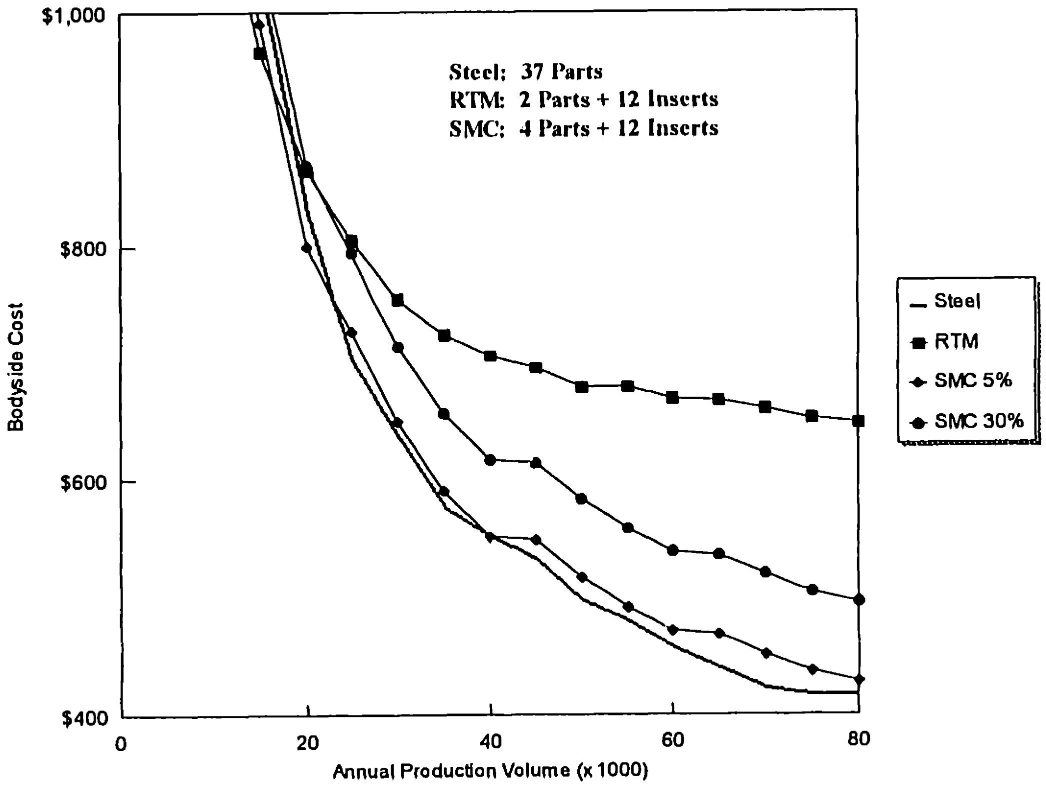

Figure 30: Bodyside Cost

Further insight can be gained from the cost breakdown by process. (Figure 31) The RTM bodyside enjoys a distinct advantage in assembly costs over the steel and SMC designs; however, its manufacturing cost outweighs its advantageous assembly cost position. The differential between the steel and the RTM assembly cost is obviously due to the benefits of parts consolidation for the composite design. The SMC assembly cost is high because of the need to join halves together to form the bodyside. The bodyside is a large piece with a long join length; as a result, joining halves together is a costly task.

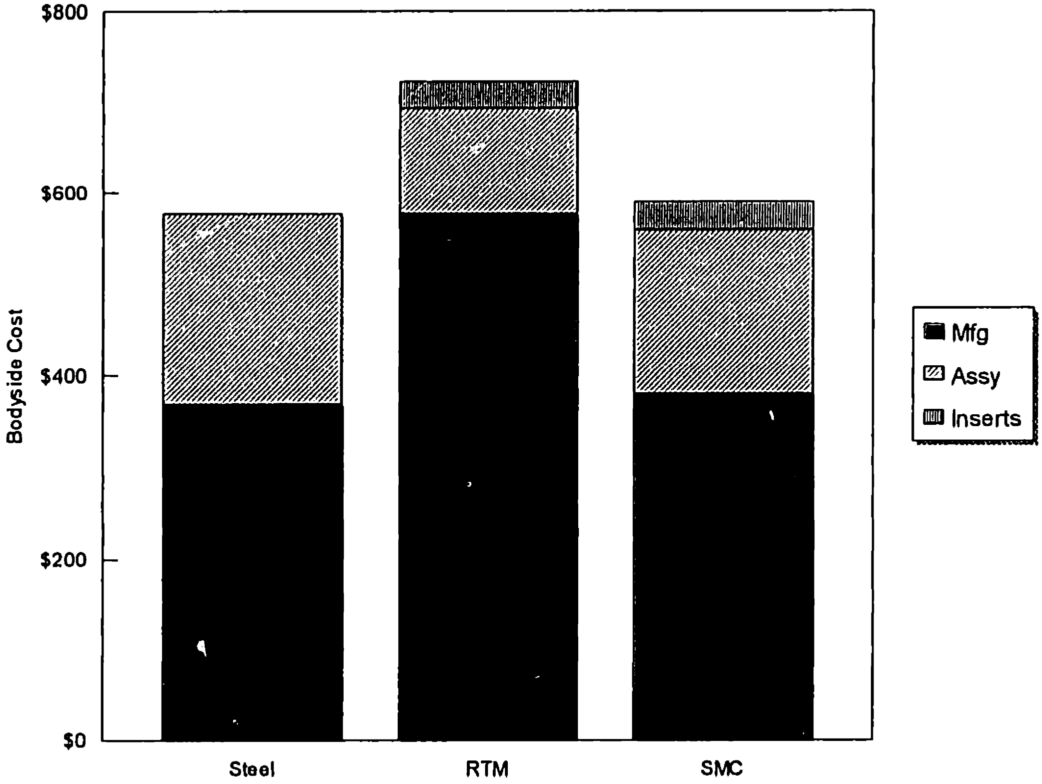

Figure 31: Bodyside Cost Breakdown by Process at 35,000 Parts per Year

The breakdown of costs shown in figure 32 explains the cost performance difference between the RTM and SMC bodysides. Both designs take advantage of their lower tooling costs (compared to the steel bodyside). The steel bodyside is a complex design composed of many parts; tooling for each of these parts is very costly at lower production volumes. Conversely, the RTM and SMC designs are composed of few parts and can gain an advantage in fixed costs. The fixed costs for the SMC design are higher than those of the RTM because the need to mold halves results in more tooling and equipment investments.

However, the distinguishing factor between the SMC and RTM designs lies in the variable costs. The material cost for the RTM design is notable because it is so much greater than for the steel or the SMC part. The large expenditure of the RTM design for materials is explained by high scrap rates for the bodyside in the preforming step. The bodyside is a large part with significant cutout areas reserved for the door and window openings. As a result of these cutouts (which are non-recyclable), the RTM part incurs large scrap losses, driving up the cost of materials. Conversely, the SMC design avoids the scrap losses in the cutout areas by shaping the charge in a pattern minimizing waste. Therefore, while the cost of materials for the SMC part is higher than its steel comparator, the disadvantage is mitigated by labor and fixed cost savings. As a result, the SMC remains cost competitive with the steel design even at high volumes.

The bodyside demonstrates the effect of materials cost on the competitiveness of the composite designs. Although there were opportunities for the RTM bodyside due to parts consolidation and complexity of the steel design, its high material costs prevented it from capitalizing on these advantages. This case clearly demonstrates the importance of scrap losses into the design of a part. Engineers should anticipate and minimize the amount of material loss in the design exercise.

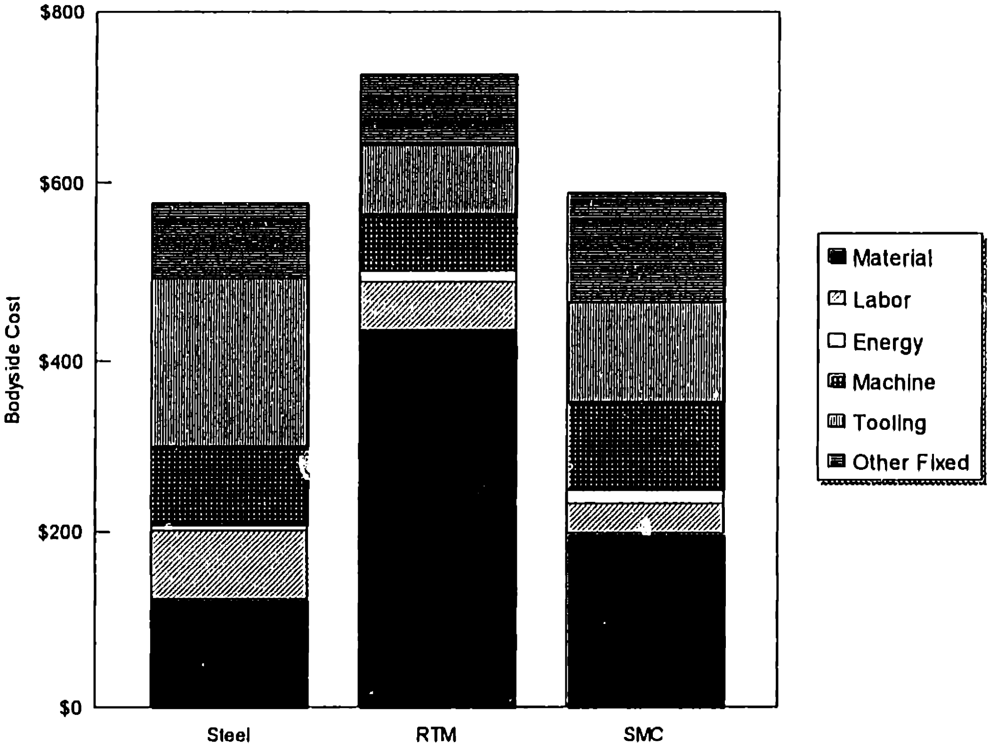

Figure 32: Bodyside Cost Breakdown at 35,000 Parts per Year

Underbody case study

The underbody, consisting of the floorpan and cross member is the most complex subsystem in the steel body-in-white. There are 57 parts included in the steel underbody, compared to 2 parts plus 20 inserts for the RTM underbody and 9 parts plus 20 inserts for the SMC underbody. However, unlike the bodyside, the underbody has no large cutouts which drive up material costs; much improved cost performance is the result. The RTM underbody breaks even with the steel underbody at volumes between 55,000 to 70,000 parts per year. (Figure 33)

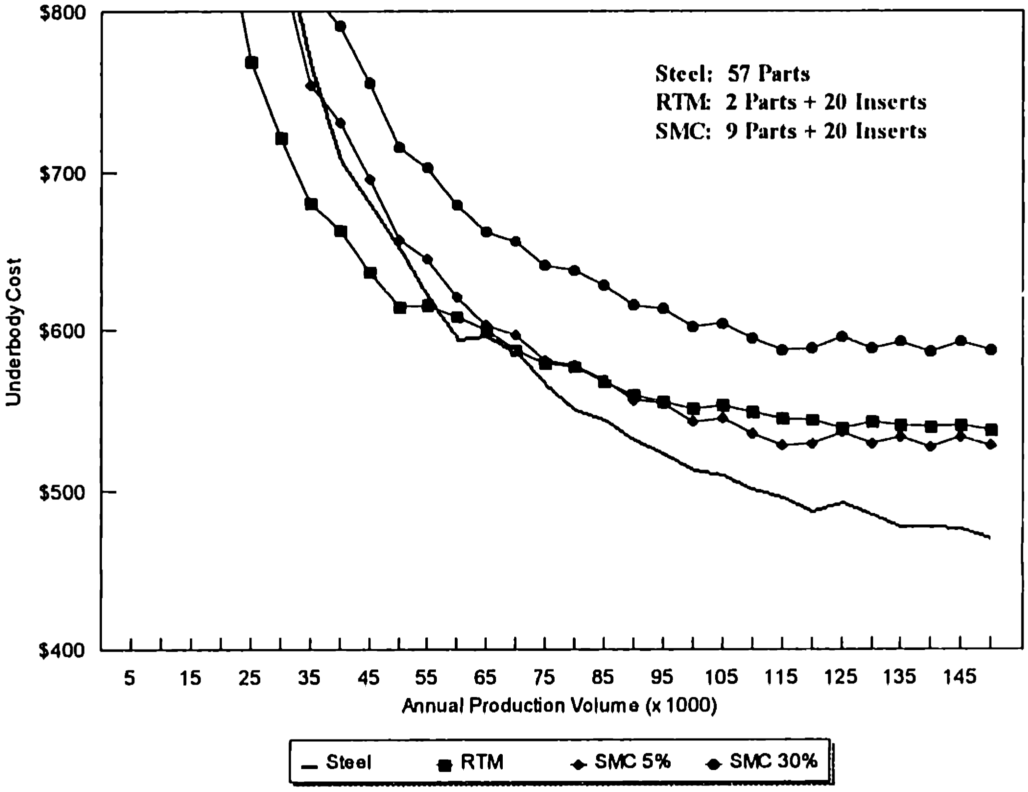

Figure 33: Underbody Cost

One of the factors that allows the RTM underbody to be competitive with the steel design is that the RTM floorpan's assembly costs are significantly reduced relative to the steel, shown in figure 34. The assembly process required to join the 57 parts comprising the steel underbody is complex and expensive. Equipment and labor costs contribute the largest portion of total assembly cost. The second, more important explanation that can be given is that the manufacturing cost for the RTM underbody is lower than its steel counterpart, even given the large disparity in material factor prices.

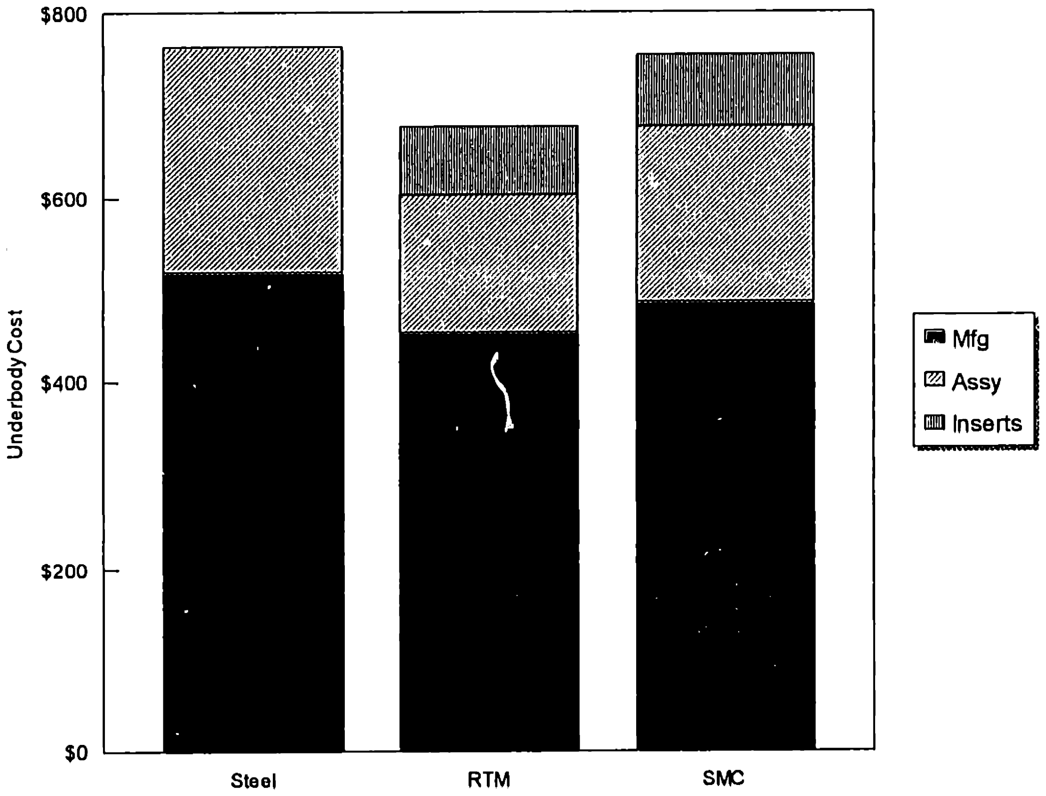

Figure 34: Underbody Cost Breakdown by Process at 35,000 Parts per Year

The breakdown of the cost components for the three designs is shown in figure 35. The most noticeable difference between the steel and RTM designs occurs in the cost of tooling. The tooling cost for the RTM process is only 40% that of the steel. The steel floorpan is composed of 57 parts and the cost of steel tooling for each of these parts is a large capital expenditure, magnified at lower production volumes when tooling costs cannot be distributed over many parts. As a result, the RTM design eliminates the design complexity of the steel floorpan in assembly and tooling to remain competitive up to a relatively high production volume. In addition, the scrap losses incurred in the RTM underbody are not as great as those in the bodyside. Although material costs are significantly higher for the RTM underbody, advantages in assembly and tooling allow the total cost to remain competitive at higher production volumes.

The SMC design, on the other hand, does not perform as well compared to the bodyside case. There is one major difference between the SMC bodyside and underbody designs. In the floorpan, the SMC design incorporated foam cores for crush resistance (whereas no foam cores were assumed in the bodyside design). The addition of foam cores results in two cost penalties. The cost of polyurethane to mold the foam cores is expensive and adds to the material cost. In addition, the cycle times for the foam core molding and post curing process are lengthy (approximately 20 minutes for both steps), increasing labor costs in addition to requiring more tooling and equipment to satisfy the production requirement. While at lower production volumes, the effect is negligible, the effect of the foam cores becomes more apparent as production volumes are increased.

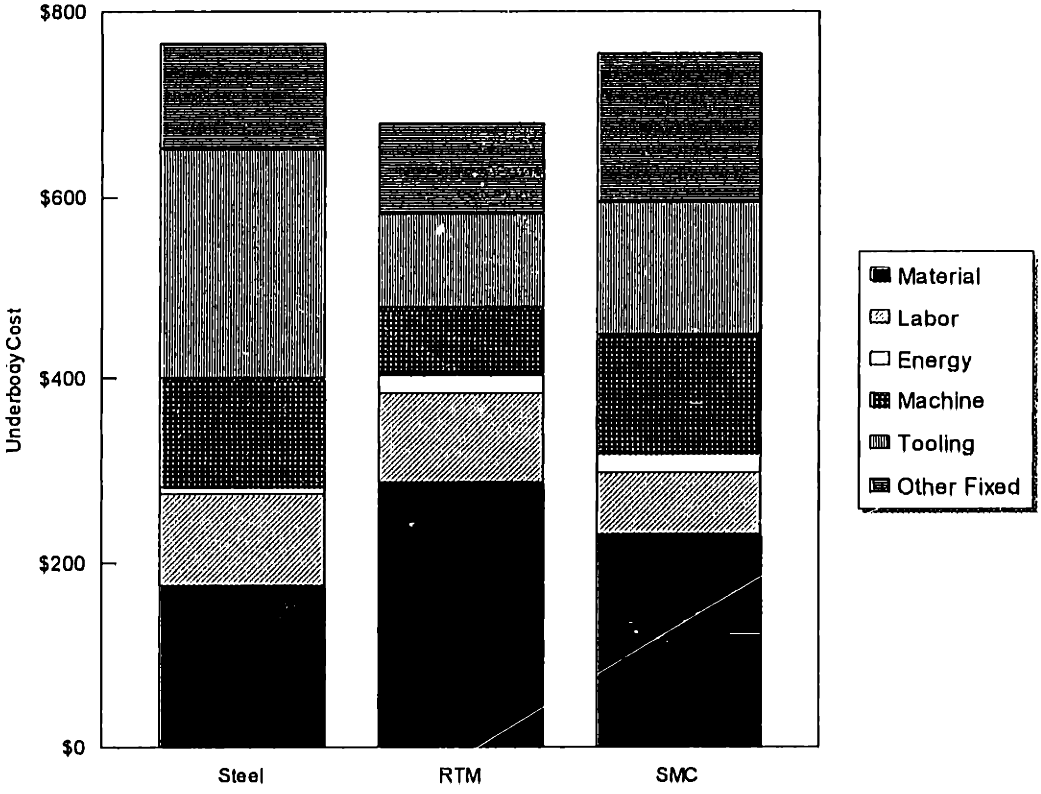

Figure 35: Underbody Cost Breakdown at 35,000 Parts per Year

Front end case study

The front end results are similar to that of the underbody. The steel part is relatively complex, composed of 38 parts. The RTM front end is composed of two halves and the SMC design is composed of 4 pieces. In modeling the total costs of the front end, an assumption had to be made regarding the assembly cost for the composite parts. The two front end pieces are joined to the rest of the body-in-white at the final assembly step. However, there are also other BIW subsystems that are attached at this step. As a result, the cost of only assembling the front end is difficult to separate out from the rest of joining steps. In order to account for the front end assembly, an assumption was made to attribute 40% of the cost from the final assembly step to the front end. The results of the total front end cost is shown in figure 36.

The break-even point of the RTM and steel front end is between 75,000 to 80,000 parts per year. The break-even point of the SMC (5% scrap rate) and the steel front end is between 35,000 to 40,000 parts per year.

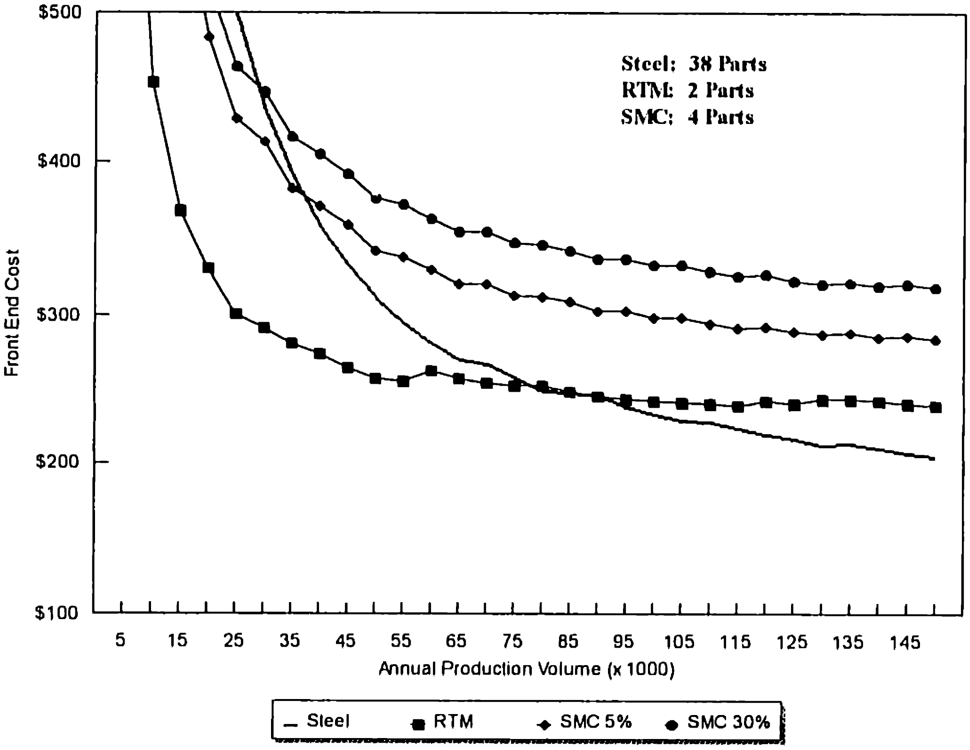

Figure 36: Front End Cost

The explanation behind the performance of the RTM front end is similar to the reasons given in the underbody analysis. From the breakdown of costs by process, figure 37 shows a significant advantage for the RTM front end in assembly costs relative to the steel design. Although this result may be an artifact of the assembly cost calculation assumption, it exhibits evidence of the benefits of parts consolidation to the assembly cost. The simpler design results in much improved assembly cost performance. While the SMC also enjoys some advantages in assembly cost relative to steel, its assembly is more complex (compared to the RTM design) because of the need to join two halves to complete a right or left hand front end piece. The assembly cost results shown in figure 37 exhibit the costs of extra assembly steps.

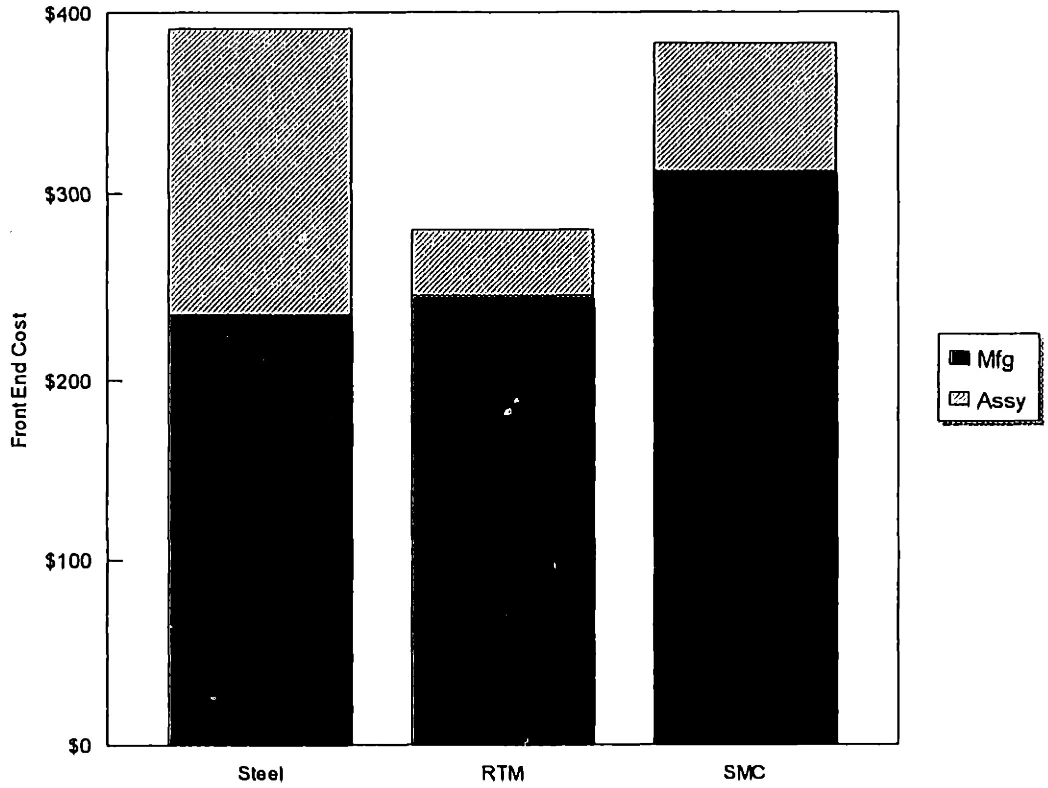

Figure 37: Front End Cost Breakdown by Process at 35,000 Parts per Year

Figure 38 shows the results of the breakdown of the front end designs according to their cost components. Similar to the findings from the underbody, the composite designs do show the benefits of parts consolidation through lower tooling costs (and fixed costs in general). As a result of fixed cost advantages, the front end can overcome the material cost penalty incurred from the use of more expensive composite materials.

The lower crossover volumes of the SMC can also be explained through the breakdown in cost. The material costs for the RTM and SMC designs are nearly identical, even though SMC raw material is cheaper than the reinforcement/resin material used for the RTM process and the scrap rate is lower. Although more SMC material is used, the other subsystems exhibited lower material costs for the SMC relative to the RTM design (implying that lower material price and scrap rate benefits outweighed the disadvantage of greater material use).

Similar to the findings from the underbody, this result can be attributed to the use of foam cores in the SMC front end. The front end core, with its high material costs and long cycle times, add to the total cost.

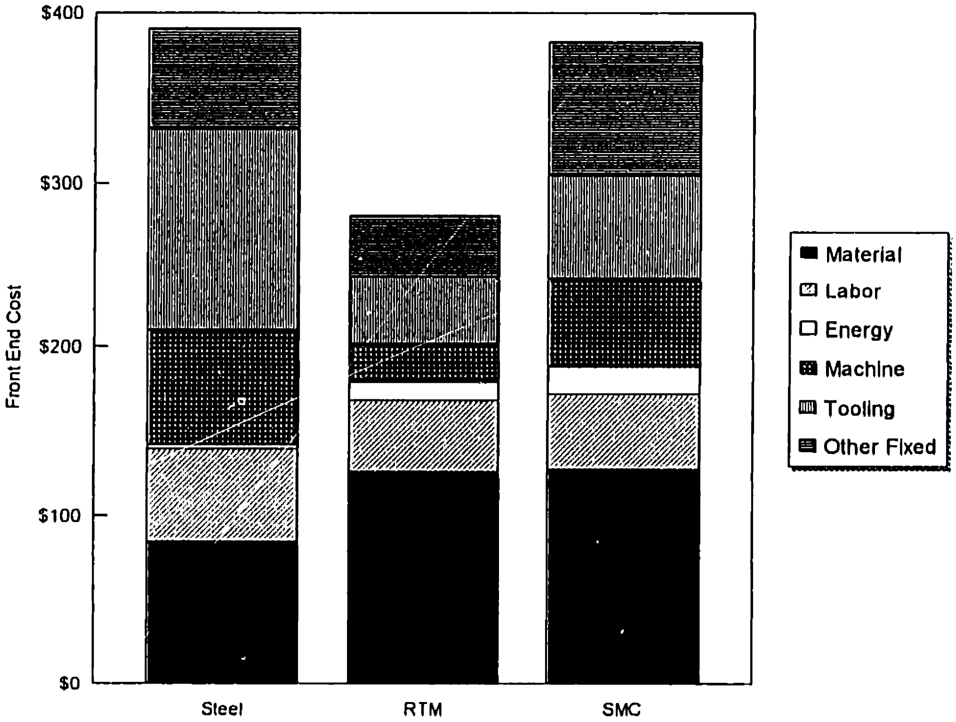

Figure 38: Front End Cost Breakdown at 35,000 Parts per Year

HYBRID VEHICLE SCENARIO

One key finding from the case study analyses is that each subsystem within the body-in-white has unique requirements which can give certain material technologies advantages over others. This result naturally lends itself then to the notion of a hybrid vehicle, a design that utilizes the most appropriate material for each subsystem, rather than homogenous material designs that have been considered up to this point.

Several assumptions were made in order to develop a preliminary analysis of the performance of a potential hybrid vehicle. First, it was assumed that no changes in the current design were required to construct a hybrid vehicle. Therefore, seamless swapping between the three material technologies could occur for all subsystems without regard to any redesign concerns. Second, it was assumed that the hybrid vehicle would require no changes in the assembly process for the individual subsystems. For instance, for a hybrid vehicle consisting entirely of composites with the exception of a steel bodyside, the bodyside would be welded together, then adhesively joined to the rest of the BIW. Third, no regard was given to the potential factory layout of the hybrid. The question of the feasibility of housing steel stamping, SMC molding and RTM processes (in addition to the various assembly processes) under one roof was not considered an issue.

The assumptions made vastly simplifies the analysis of a potential hybrid vehicle design. While the simplifying assumptions made will present serious issues in any future effort to design hybrid vehicles, a preliminary inquiry into the potential benefits of hybrid vehicle design should be a valuable exercise to guide future research efforts.

The hybrid vehicle design chosen for this analysis was configured to maximize the use of composite materials wherever possible. Therefore, the roof was the only subsystem using steel. The reasons for selecting steel for this subsystem are obvious from the analysis of the roof case in the previous section. The roof is a clear instance where the demands of the subsystem overwhelmingly favor steel over composites. SMC was chosen for the bodyside application. The subsystem analysis clearly indicated that SMC was more competitive than the RTM design because of the high material costs incurred in the RTM design. The underbody and front end applications were constructed using RTM parts. The results of the cost analysis for the hybrid vehicle are shown in figure 39.

Depending on the scrap rate assumption used for the SMC bodyside, the hybrid vehicle break-even point ranges from 50,000 to 75,000 vehicles per year (compared to mid-30,000's for the RTM and SMC designs). Although much more research is required to prove out the feasibility of a hybrid design, the results are promising for the future application of composite materials in automotive body-in-white applications. While there are subsystems which do not favor the use of composites, other applications do have the requirements necessary to take full advantage of the benefits of composite materials. As a result, although entire composite BIW designs may be infeasible, there are opportunities for significant composite utilization in specific areas of the BIW.

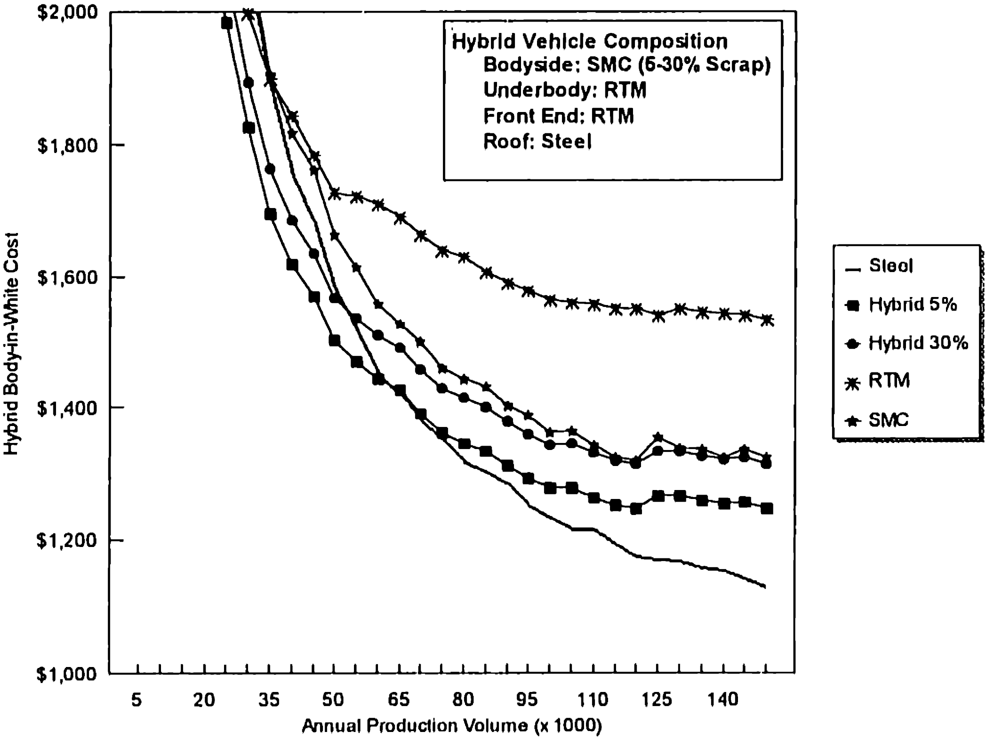

Figure 39: Total Cost for Hybrid Vehicle Design

The analysis determining the cost per kilogram saved is shown in figure 40. As opportunities for weight savings become increasingly valuable to automotive designers, there may be a willingness to pay for weight savings. While the analysis presented here shows only one (although extremely important) metric in which to evaluate materials selection decisions, other benefits of composites may justify a slight cost premium. The analysis shows that for the hybrid vehicle design (5% bodyside scrap rate), the additional cost per kilogram in weight savings is below $1/kg up to a production volume of 150,000 vehicles per year. Therefore, if automobile manufacturers are willing to sacrifice some cost for lighter body-in-white designs, the hybrid vehicle is the most cost-efficient approach and, depending on the willingness to pay, can merit serious consideration for high volume applications.

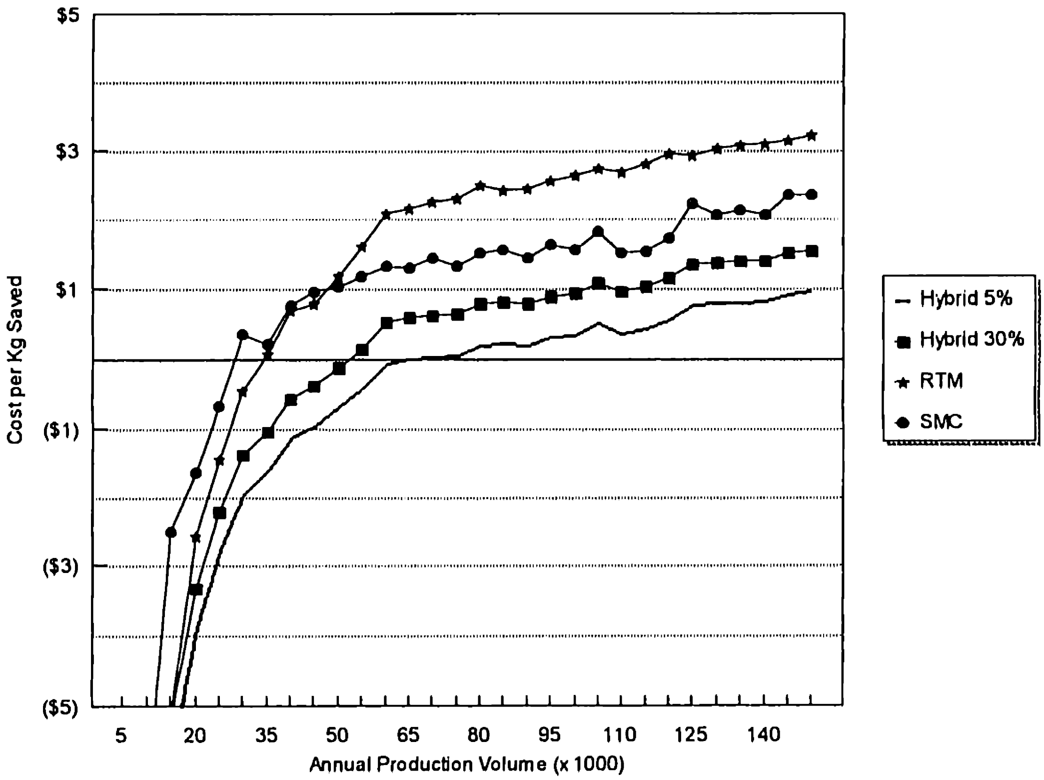

Figure 40: Cost per Kilogram Saved for Hybrid Vehicle

Chapter 13: Policy Analysis

The economic analysis has shown that a body-in-white made entirely of composite materials is cost-competitive with the steel base case at low to medium production volumes. In addition, there are certain subsystems in which composite materials can fully utilize key design advantages and become economically viable at higher production volumes. However, an automotive manufacturers' materials technology strategy is not only based on the economics (although cost is the most important decision driver), but on a number of other factors.

Up to this point, the main theme has been to analyze the cost implications of manufacturing both composite and steel body-in-white structures. However, there are also business and governmental policy issues to consider in developing a complete analysis of the competitive position of composite materials. This section will discuss some of the other variables and decision categories that must be evaluated in order to formulate a more conclusive view on the feasibility of composite materials. The first section will address other automotive manufacturer concerns that arise from the use of composite materials. Specifically, there are issues of displacing a traditional material technology and customer acceptance of the new technology that must be considered. The next section will discuss the regulatory environment and its impact on the materials selection decision. An increase in the CAFE standards is one foreseeable scenario and a change in the recycling regulations can have a negative impact on the use of polymer composites. The final section will analyze alternative markets in which composite materials may become a strong candidate to displace steel.

NON-ECONOMIC ISSUES FOR COMPOSITE MATERIALS

A survey taken from manufacturers in the automotive industry has defined the main obstacles that composite materials face when competing against steel. (Figure 41) Not surprisingly, the issue of cost was deemed the most significant barrier to entry for composites. The majority of the analysis that has been presented in the preceding sections has centered on the economics of composite materials, since cost issues are the most important driver in any materials selection decision in the automotive industry.

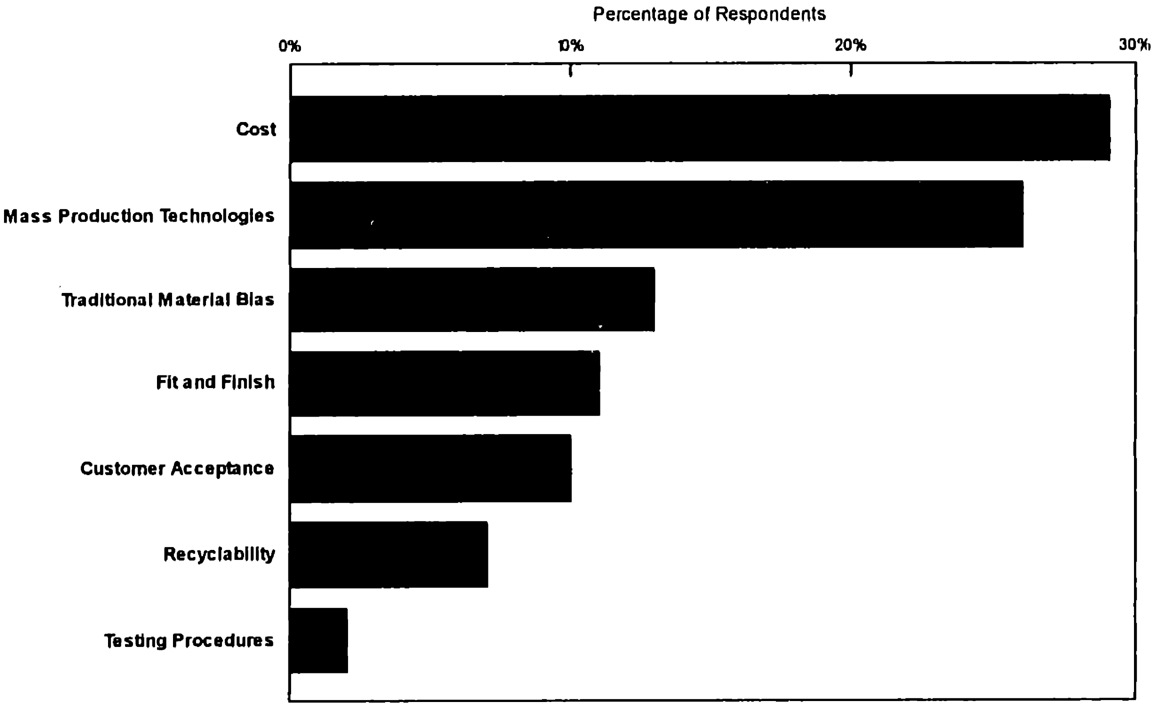

Figure 41: Obstacles to Using Composites[6]

Among the other factors, the issues of mass production technologies and fit and finish are related to the economics of composite materials. The cost analysis of the composite intensive vehicle has been developed assuming that the most current manufacturing technologies and processes are utilized in the manufacture of composite materials. Innovations in the production technology of composites will benefit the cost of composite parts. As the cost analysis has indicated, most improvements will not change the central conclusion that composite vehicles are applicable at low to medium production volumes. However, because materials are the most significant contributor to total cost, technologies

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[6] Source: Ward's Auto World; May, 1990; p. 56

which have a significant effect in decreasing the materials component will have a substantial impact on the composites' break-even volume with steel.

Fit and finish is another technical issue which merits additional research. The cost analysis has assumed a fit and finish that is comparable to the steel part. However, since there are no mass-produced structural composite applications, fit and finish concerns must be adequately addressed before the composite vehicle becomes a reality.

Traditional Material Bias

Aside from the technical and economic issues, there are also issues of traditional material bias and customer acceptance that must be considered in the materials selection decision. (The recyclability issue will be dealt with in the regulation section) The traditional material bias that exists in the automotive industry relates to its process of introducing innovations. Several steps must be accomplished before a new technology is put into a production vehicle.

First, a working prototype of the technology must be developed. This prototype must assure the design engineers that the technology works and provides benefits over the existing system. Since the body-in-white is such an integral part of the vehicle, this process of proving out the prototype will be even more rigorous. The BIW must be evaluated not in isolation but in its interaction with the other vehicle systems, since the BIW is the structure to which many systems are attached. The prototyping process may be the most time-consuming step in realizing the feasibility of composite materials because of the enormous amount of testing required.

Once the prototype has been built and is ready for production, the design engineers must work with the production staff to incorporate the new technology into the manufacture of the vehicle. Tooling and equipment needs must be designed, built and installed. The manufacturing process must be redesigned to incorporate the new technology. Finally, some pre-production runs must be carried out to gauge the effects of this new introduction and to fine-tune the process, ironing out the inconsistencies.

The process of introducing new technologies into a production vehicle is long and involved. It becomes clear that there is an enormous bias for traditional steel manufacturing technologies. The costs of developing the prototype and then building the production system to accommodate the new technology are significant. Because of the great risks involved, automakers are predictably risk-averse in dealing with radical new technologies such as composite materials.

Therefore, it can be concluded that the process of introducing composite materials into body-in-white applications will be time-intensive. The process of proving out the design will take many years of development work in order to sort through the issues that the new material presents. Automakers will probably introduce composite materials in structural applications gradually in order to mitigate the risks. By incrementally introducing composite parts into the vehicle, the manufacturer can better anticipate the interactions between the new part with the rest of the vehicle. Additionally, the manufacturer can study the effects of the new part and make a more informed decision on subsequent investments in composites manufacturing processes.

Customer Acceptance

Another important concern is the degree to which customers will accept the new technology. Automobile manufacturers must analyze the potential customers to which composite materials can be effectively marketed. Customers can be divided into four segments: utilitarian, performance-minded, economy-minded and luxury. [Altshuler, 1984]

1. Utilitarian customers value new functions (for example, four wheel drive).
2. Performance-minded customers place a premium on performance enhancing technologies, such as turbocharged engines.
3. Economy-minded customers seek to minimize the total cost of ownership of their vehicle.
4. Luxury customers are willing to pay large price premiums for convenience and comfort enhancing technologies, such as navigation systems.

Given this segmentation of the market, automakers must decide which segment to target and then orient the composite BIW design in a way which maximizes the values of the customer segment.

Two segments which may value the composite body-in-white are the performance and economy-oriented customers. Because of the weight reduction in the BIW, engineers may be able to design better performing vehicles without significant improvements in engine technology. For instance, a weight reduction will improve acceleration performance without any other modifications. Weight reduction may also be effectively marketed to the economy-minded consumers. While a cost premium is paid up front for the composite vehicle, the savings in gas costs over its life cycle may overtake the initial premium. With gas prices under $2.00/gallon in the U.S., decreased fuel costs may not be an attractive proposition; however, in Europe, fuel costs are a bigger concern and therefore customers may place a great value on high gas mileage performance.

REGULATORY EFFECTS

Changes in CAFE Regulation

Due to the oil shock in 1973, regulatory and consumer forces have acted to increase the new car fuel economy from 14 miles per gallon (mpg) to 28 mpg today. [U.S. Congress, 1991] However, in recent years, there have not been great incentives to continue increases in fuel economy. Instead, an abundant and continuous oil supply has allowed consumers to purchase bigger cars and trucks with specialized features that reduce fuel economy. Four wheel drive is one example of such a feature.

While there seems to be no immediate threat resulting from this recent trend, policy makers realize the danger in an increasing demand for gasoline. Increased dependence on foreign oil may lead to U.S. participation in wars to guarantee a continuous supply. In addition, there are economic dangers that result from this dependence. A disruption in the supply of oil can have debilitating effects on the U.S. economy. Even without a disruption, paying for foreign oil increases the U.S. trade deficit. Finally, the emissions produced from gas-powered vehicles result in negative environmental effects.

For these reasons, U.S. policy makers may increase the standards for the Corporate Average Fuel Economy (CAFE) of the various automobile manufacturers. The current standard requires a minimum average fuel economy for an automaker's vehicle fleet of 27.5 mpg. If the CAFE requirement increases, the lightweighting opportunities presented by composite vehicles may be valued more highly. Figure 42 depicts the relationship between fuel economy and body-in-white weight. Numerous studies have been carried out that positively correlate reductions in body-in-white weight with increases in fuel economy. Although the significance of the weight reduction has not been definitely answered, an upper and lower bound captures the range of expected outcomes. A manufacturer may be willing to pay a cost premium for a composite BIW design which allows the manufacturer to meet the CAFE requirements and avoid a potential cost penalty.

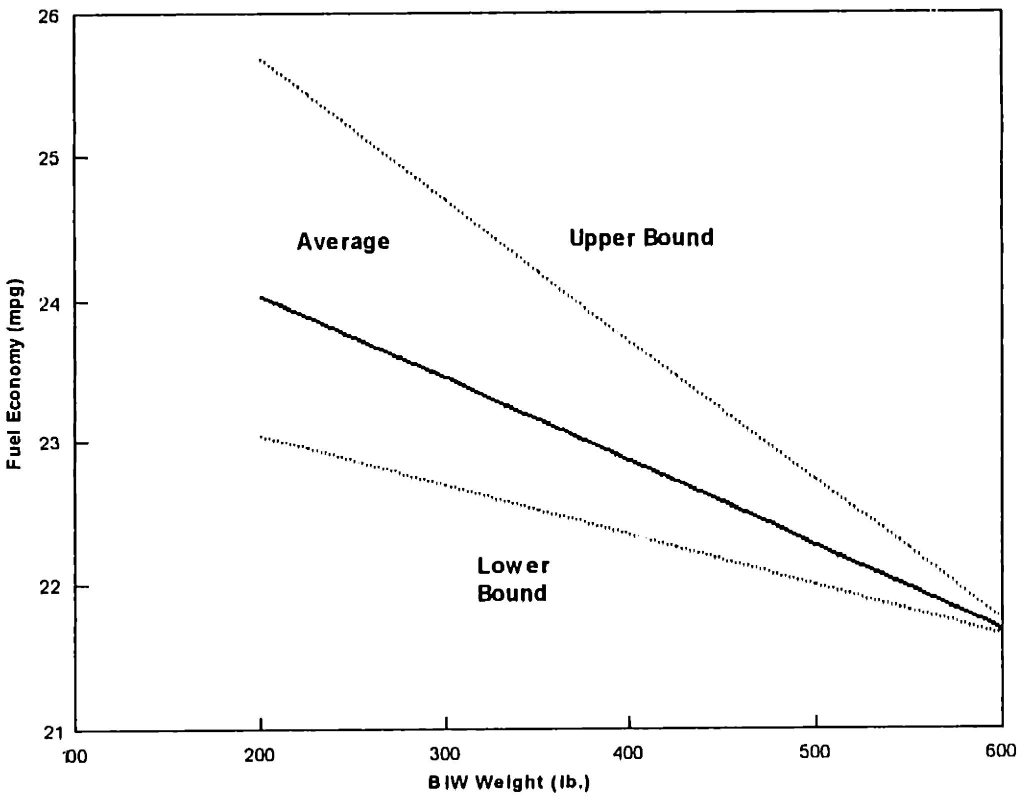

Figure 42: Fuel Economy Dependence on BIW Weight[7]

Recyclability

When considering the use of plastics, recyclability issues are a primary source of concern. Some argue that the issue of recyclability is a minor one, since automotive plastics comprise only 1.2% (by weight) of the municipal solid waste stream. [Chen, 1995] However, others contend that although automotive plastics are currently a minor portion of the waste stream, increased use of plastics in the future may have two detrimental effects. First is the obvious increase in landfill requirements from increased plastics use. Secondly, increased plastics use may result in the collapse of the existing vehicle recycling infrastructure by making it unprofitable to recycle used autobodies.

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[7] Source: Politis, 1995, p. 77.

Without delving into an analysis of the merits of the pro and con arguments for plastics, the fact remains that recycling is a major obstacle to its use in the automotive industry. Therefore, two issues will be addressed in this section of the analysis. First, the methods of recycling plastics will be discussed to give potential alternatives to the current practice of landfilling. Second, the implications of increasing polymer content on the vehicle recycling infrastructure will be analyzed.

Polymer composite material is a compound composed of polymeric resin and reinforcement material; the resin acts as a matrix for the reinforcement material. The resin itself has many additives such as catalysts, dyes and fillers. Because there are multiple materials conglomerated into a polymer composite, they are notoriously difficult to recycle by separating the compound into its original elements for reuse. In addition, the polymer resin used in composite applications is typically a thermoset resin. Thermosets cannot be melted and reformed like thermoplastics and are harder to recycle as a consequence. Despite these difficulties, recycling options exist for thermoset polymers.

There are four categories of recycling opportunities available to polymers. Primary recycling refers to reusing the material in the same application from which it came. Although thermoplastic scrap can be remelted and reused in this fashion, primary recycling is not an option available to thermoset polymers due to the permanence of its chemical structure.

Secondary recycling refers to the use of the material in less demanding applications. Thermoset materials can be reground into filler for use in new polymer formulations. However, there is a limit in the amount of filler that can be added without degrading the material's physical properties, processing performance and surface appearance.

Tertiary recycling alters the polymer's chemical structure so that the material can be reused to produce a petrochemical resin precursor in the form of monomers, basic chemicals or fuel. Pyrolysis, the heating of material to convert waste into a useful form, is the primary method for the tertiary recycling of thermosets. While the method is still in an experimental stage, pyrolysis seems promising for thermosets because of its high tolerance for contaminants and heterogeneous mixtures.

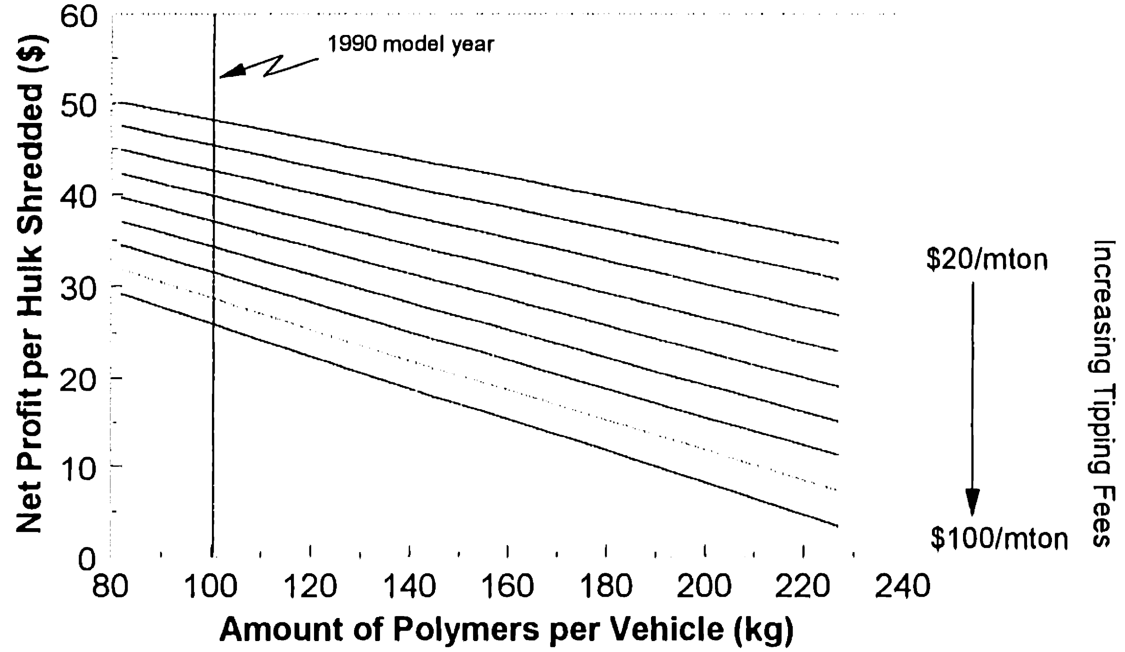
Finally, quaternary recycling refers to the incineration of plastics to capture the heat of combustion. While this approach is applicable to thermosets, there are obvious environmental concerns that arise from the prospect of large scale incineration plants. Therefore, quaternary recycling will probably not be a viable option for the reuse of plastics due to the anticipated negative public reaction.

In addition to the concerns about the potential landfilling of plastics, there is some debate as to the stability of the vehicle recycling infrastructure should the use of plastics in automobiles increase. Since the recycling of metallics constitute revenue generation in this industry (while the disposal of plastics is a cost), there are concerns that increasing plastics use would result in an increase in costs such that vehicle recycling would become unprofitable. This section will address the profitability implications of plastics use, considering the current practice of landfilling plastics.

The afterlife of an old car begins when a dismantler purchases the car from the last owner. The dismantler removes the reusable components and valuable materials. In addition, components such as tires and fluids are removed to be landfilled. The remains of the automobile (consisting mainly of the body and chassis), called the hulk, are then sold to the shredder.

The shredder segregates the hulk into three main components: ferrous and nonferrous metallics and nonmetallic materials. The ferrous material can be sold as scrap to a mini-mill and nonferrous metallics, such as aluminum, can be sold in the secondary material market. The metallics generate revenue for the shredder. The nonmetallic material, called automotive shredder residue (ASR), is sent to the landfill. The shredder pays for the use of landfill space; the average landfill cost is $33 per ton of ASR.

Studies have shown that given the current materials content in the automobile, the shredder realizes a net profit of over $44 per processed hulk. [Chen, 1995]. In addition, while the increasing polymer content does decrease profitability, shredders can still make a significant profit (approximately $30 per hulk) from an automobile with a composite intensive body structure. If landfill prices increase to $100 per ton, the profitability per hulk would decrease from $44 per hulk to under $10 per hulk. (Figure 43) Despite issues of the profitability of the shredder industry resulting from increased plastics content, it should be noted that the cost analysis of the CIV has predicted a low to medium volume market potential. In addition, significant composite part substitution has been shown to be viable for certain components only and therefore is likely to represent a slight cost increase to the shredders.



Ferrous Scrap Price: $110/mton
Nonferrous Scrap Price: $880/mton

Figure 43: Effect of Polymer Content & Landfill Tipping Fee on Profit per Hulk[8]

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[8] Source: Chen, 1995, p.56.

While profitability and the viability of the recycling infrastructure are not likely to be threatened by a composite intensive body-in-white, there are environmental concerns about the prospect of increased landfilling. There are recycling options available that can decrease the amount of landfill caused by the ASR. For thermosets, regrinding and pyrolysis are the two most promising options. However, the costs of recycling outweigh the benefits of extracting value from the used material, since the separation of recyclable material is an expensive undertaking. The filler material produced from reground thermoset is not particularly valuable and faces a limited market. Pyrolysis faces several technical challenges in addition to the high cost of equipment and materials that are required for the process. As a result, shredders have no economic motivation to consider other options besides landfilling.

From this analysis, some conclusions about the recycling implications of automotive plastics use can be reached. First, concerns about the vehicle recycling infrastructure are largely unfounded; only radical increases (greater than 300%) in landfill costs will likely effect the recycling of old automobiles. Increased landfill use can then be concluded as the primary objection regarding the use of polymer composites in vehicles. Ignoring the fact that the cost analysis has shown that an all composite BIW is a low to medium volume application, there are several policy alternatives that the government can take to minimize the landfilling of automotive composites.

Policies can be categorized as "push" or "pull" which seek to influence recycling on either the supply or demand side. (Figure 44) Push policies seek to compel the recycling industry to develop the technology and practices that make recycling of composites viable. Examples of push policies are forcing manufacturers to take back used cars and bans on landfilling. Pull policies seek to create a market for recycled composite materials and thus create economic incentives for shredders to recycle. An example of a pull policy is mandating a minimum recycled content in certain products. Both types of policies seek to stimulate innovation from stakeholders to create the necessary technologies and processes to make recycling of plastics more viable.

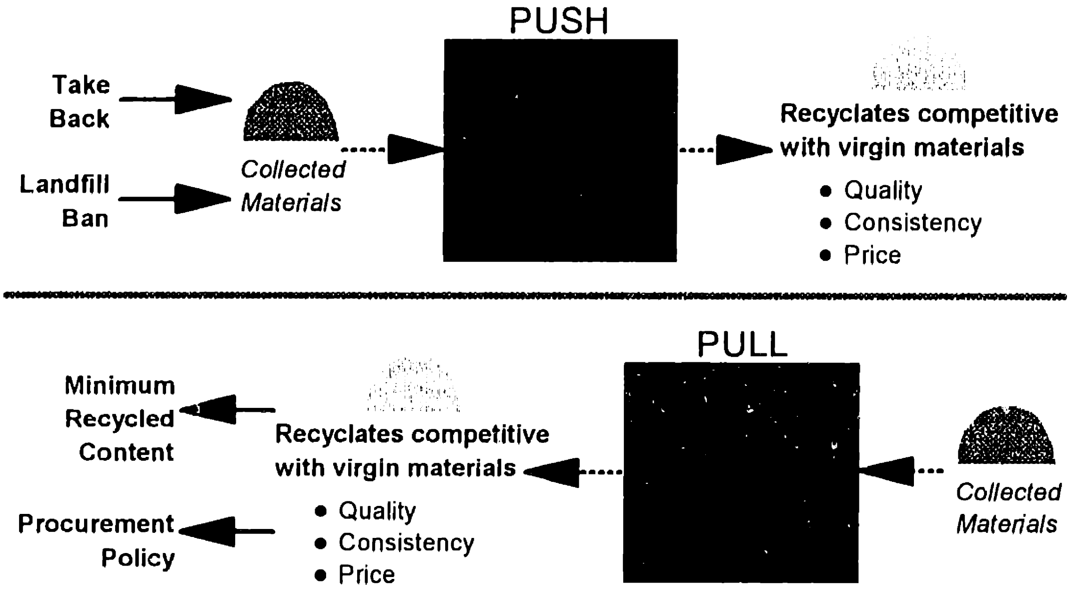

Figure 44: Schematic Representation of Common Policy Thinkings[9]

ALTERNATIVE MARKETS

The cost analysis of the composite intensive vehicle has been based on a North American or European scenario. However, all automotive manufacturers operate on a global basis and there may be other opportunities for composite materials to play a significant role in the markets of developing countries. There are several characteristics of developing nations which may allow composite materials to compete effectively with steel.

An ideal nation in which to introduce composite vehicles has two distinguishing characteristics. First, the country must have high tariffs, import/export restrictions and/or high transportation costs. These restrictions will prevent a manufacturer from shipping steel vehicles manufactured elsewhere and will force the manufacturer to invest in plants in the developing nation. Second, the country must initially have a small customer base (although the potential market is large enough to be attractive to the manufacturer).

Given the first restriction, the manufacturer will be forced to invest in plants in the developing nation. As a result, the lower investment costs in tooling and equipment will favor

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[9] Source: Chen, 1995, p. 29.

the use of composite material technologies. However, even if the manufacturer were forced to invest, steel may still be favored because a large customer base may allow it to take advantage of economies of scale.

Given these two characteristics, the cost performance of the composite and steel vehicle can be compared. The analysis is similar to the one presented in the prior sections. However, there are two differences in the economic assumptions used. First, because the manufacturer will have to invest in a greenfield plant for a limited customer base, the steel stamping presses may not have full capacity utilization as in a developed market. Second, because the composites and steel manufacturing will require similar types of workers, wages can be assumed to be the same for both processes. Given these two assumptions, an anticipated cost performance can be analyzed. (Figure 45)

The solid and dotted lines represent the best and worst case scenarios for steel manufacturing in developing markets. The worst case represents a machine utilization of only 25% that of the best case scenario. A manufacturer projecting lower utilization rates than the worst case would alter the manufacturing setup or consider performing non-automotive stamping for other manufacturers in order to increase the use of the stamping presses. Given a worst case manufacturing scenario, the initial cost curve would probably be located nearer to the top steel curve, given the investment conditions. (Note that this curve is an absolute worst case; it is plotted to give a sense of the bounds of the cost curve in a developing market.) However, as the consumer market grows (and if export restrictions are relaxed), the cost curve would migrate toward the lower dotted line. Therefore, the best and worst case lines capture the range of expected costs for manufacturing in developing nations.

The results indicate that composite vehicles can be cost competitive with steel at volumes ranging from 30,000 vehicles per year (vpy) to almost 100,000 vpy, depending on the utilization of the stamping plant. This type of market may force automakers to seriously consider the use of composite materials for structural applications in developing nations.

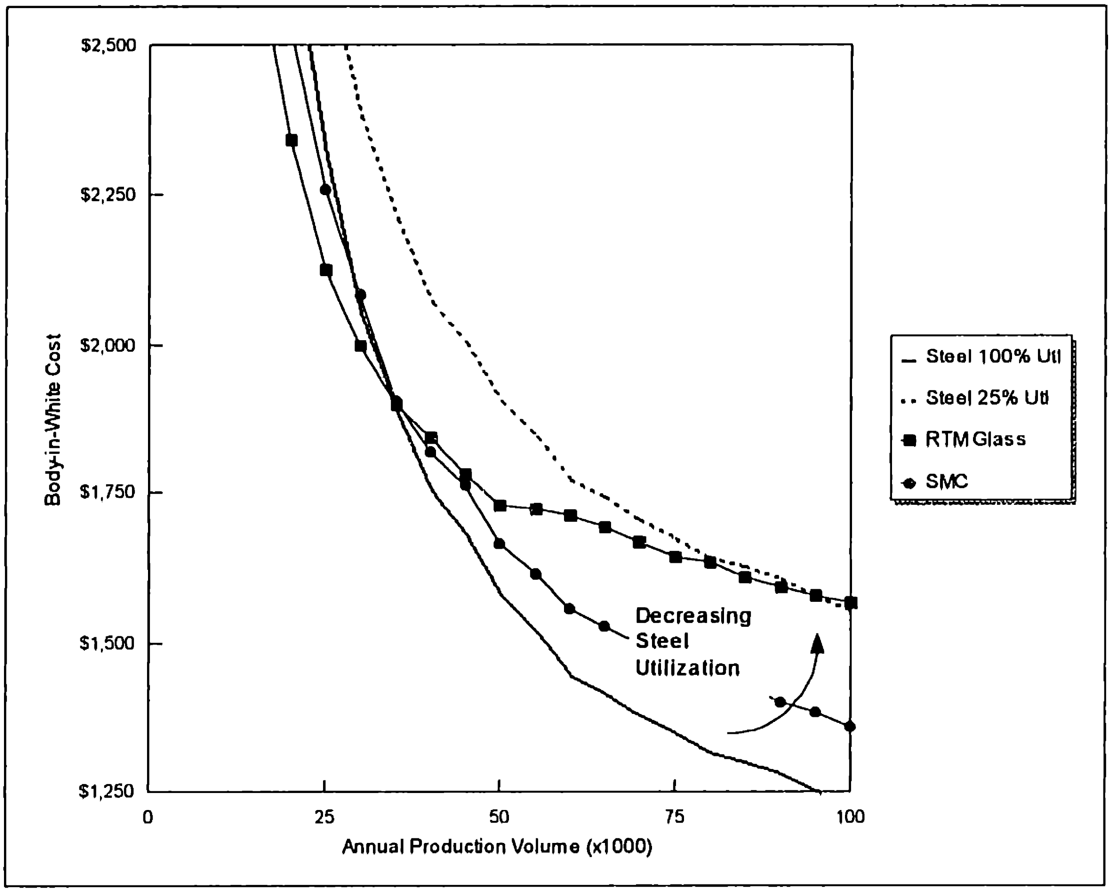


Figure 45: Total Cost Curve in Alternative Markets

Chapter 14: Summary and Conclusions

The forces of industry competition, governmental legislation and consumer preference have given a continual motivation for automotive manufacturers to offer product innovations. New materials technologies play an important role in product strategy, since the material plays a critical role in ability of the manufacturer to decrease the weight of the automobile.

Plastic products have found their way into many applications in the automobile, ranging from dashboards to fenders. A natural evolution of the use of plastics may result in its use in structural parts, specifically in the body-in-white. The thesis presented an analysis of the competitive position of polymer composite materials in relation to the current industry standard material in body-in-white applications.

In analyzing the competitive position of new materials, cost becomes the major factor in automotive materials selection decisions. Polymer composites have made significant inroads into applications for the aerospace industry, which is more likely to be willing to pay a premium for increased performance. Composites have not enjoyed similar penetration into the automotive industry mainly due to cost reasons. However, past applications of composite materials have involved a one-to-one part substitution strategy, mainly to replace a steel part. Replacing a part designed to be manufactured in steel with an identical composite part does not capitalize on the advantages of composite materials. Therefore, a more equitable analysis should focus on applications designed specifically for composite materials and compare its performance to a steel equivalent.

METHODOLOGY

Two body-in-white designs were used in the analysis. The Composite Intensive Vehicle is a body-in-white designed by Ford Motor Company that takes advantage of the unique properties inherent in composite materials. Three composite designs were evaluated: resin transfer molded parts with glass fiber reinforcement, resin transfer molded parts with carbon fiber reinforcements and parts utilizing sheet molding compound. Although the CIV design had no identical steel comparator, the Honda Odyssey, a currently manufactured minivan, was chosen as a likely potential competitor with similar physical dimensions.

To analyze costs, the technical cost modeling methodology was used. Three previously developed models were employed to model the manufacturing and assembly costs for the steel stamping process, the SMC process and several assembly processes. A resin transfer molding model was developed to evaluate the cost of the RTM process. Information gathered about the various parts constituting the steel and composite BIW designs were used as inputs to the cost models.

SUMMARY OF COST ANALYSIS

Use of the cost models allowed an analysis of the economics of the competing material technologies. When comparing the steel and composite BIW designs, the break-even point was determined to be between 15,000 vehicles per year (for the carbon fiber reinforced BIW) and 35,000 (for the glass reinforced and SMC BIW's). There are several reasons to explain the performance. First, the composite designs are less capital intensive than their steel counterparts, resulting in a cost advantage at lower production volumes. However, the cost of materials is high for composite materials and negates the fixed cost advantage as production volume increases.

The carbon fiber reinforced designs proved to be infeasible for use in automotive applications because of the high cost of carbon fiber reinforcement material. The extraordinary physical properties of carbon fiber allows less material to be used in the BIW, resulting in the lightest BIW design of those studied. However, the price/performance tradeoff proved to be unreasonable for significant use of carbon fiber in future automotive structural applications.

In addition to investigating the entire body-in-white, the individual subsystems were analyzed. The body-in-white was divided into four subsystems: roof, bodyside, underbody and front end. Several important guidelines for the use of composite materials emerged from the subsystem analysis. First, composite materials have no advantage in simple applications such as the roof. Composite materials allow the designer to take a multi-part steel design and convert it into a composite design with one or two parts. Parts consolidation then allows tooling cost and assembly savings. Simple applications do not allow for significant parts consolidation opportunities.

However, even complex applications may not favor the use of composite materials if material waste becomes a significant factor. Since material cost is a primary driver in the total part cost, large amounts of material waste results in a sharp increase in materials cost. The bodyside application is an example where large cutouts for windows and door openings are required in the RTM design, necessitating material waste.

In complex applications where material waste is not significant, composite parts have been able to capitalize on the savings resulting from parts consolidation and become competitive with steel at higher production volumes. The underbody and front end are two applications where multiple part steel subsystems were consolidated into one or two parts using composite materials.

In predicting the materials content of future automobiles, one may not be limited to single material options for BIW designs. Material hybrids are the more logical answer, since each material has unique benefits and disadvantages that make it desirable for use in some subsystems but not others. Therefore, a purely hypothetical hybrid was concocted from the current BIW designs used in the cost analysis. The hybrid consisted of a steel roof, SMC bodyside and RTM (glass fiber reinforced) underbody and front end. The cost analysis indicated encouraging results. Break-even points ranged from 50,000 to 75,000 vehicles per year. This preliminary analysis should be more rigorously pursued in future studies.

POLICY CONSIDERATIONS

Finally, other decision factors besides cost should also be considered in analyzing the materials selection decision in automotive body-in-white applications. In addition to the economic barrier, composite materials must overcome the traditional material bias of the automotive manufacturers. Because of significant risks, radical changes in the composition of future body-in-white designs are unlikely. More foreseeable is the gradual implementation of composite materials into the BIW. On the consumer side, composites must also make a favorable impact on the buying public, delivering benefits which have marketable value.

Governmental legislation will also influence the materials selection decision. Two notable areas are in CAFE regulation and recycling. By increasing the CAFE standards and requiring more fuel-efficient vehicles, policy decisions can have a significant impact on the value placed on weight savings by the automotive industry. As a result, manufacturers may be willing to pay a premium for lightweight materials such as composites.

Recycling is an issue that may impede the acceptance of composite materials. The two main concerns are the anticipated increase in landfill use and a dissolution of the vehicle recycling infrastructure due to increasing use of composite materials in the automobile. However, upon closer examination of these two concerns, neither seem so serious as to significantly diminish the future prospects for composite materials. While landfilling should increase with increased composites use, public policies can be used to reduce landfill use significantly. Policy should provide recyclers with the economic incentives required to drive technical improvements for non-landfilling options.

Finally, in regard to business strategy, composite materials look favorable for use in certain developing markets where import restrictions, local content regulation and other conditions make it likely that a local plant is necessary. In these markets, a steel manufacturing plant may not be fully utilized and thus give a significant advantage for composite materials due to high capital costs required for a steel plant.

Appendix A: Steel Stamping Model

ULSAB Stamping Model — **Part Number: FLRPAN**

(Part # MUST Be Entered as Label, e.g., '006/007)

PART/MATERIAL DATA		
Stamping Weight (R&L)	22.02	kg
Maximum Stamping Length (R&L)	1397	mm
Maximum Stamping Width (R&L)	1372	mm
Stamping Surface Area (R&L)	2.00	sqm
Projected Surface Area (R&L)	1.96	sqm
Annual Production Volume	100000	parts/yr
Number Req'd Per Vehicle	1	parts/vehicle
EXOGENOUS DATA		
Days per Year	250	
Downtimes:		
Planned, workers unpaid	10.00	hr/day
Planned, workers paid	1.00	hr/day
Wage (including benefits)	$44.00	$/hr
Energy Unit Cost	$0.10	$/kWhr
Capital Recovery Rate	10%	
Capital Recovery Period	20	yr
Add'l Workers/Direct Workers	0.25	
Add'l Workers/Machine	1.00	
Building Costs	$1,500	$/sqm
Product Life	5	yrs
Building Life	25	yrs
Idle Percent	50%	
Working Capital Period	2	months
PROCESS DATA		
BLANKING		
Purchased Blank Cost (0=in house)	$0.00	
Number of Blanks Per Part	1	
Blanking Unplanned Downtime	2.00	hr/day
Blanking Reject Rate	0.0%	
Blanking Material Loss Percent	5%	
Average Die Change Time	0.50	hr
Average Blanking Lot Size	3000	
Blanking Energy Consumption Rate	150	kW
Blanking Press Installation %	25%	
Blanking Auxiliary Eqiupment %	25%	
Blanking Maintenance %	10%	
Blanking Space Requirement	100	sqm
Workers per Blanking Line	1	
Clean Running Rate (parts/hr)	1200	

	Blank #1	Blank #2	Blank #3	Blank #4	Blank #5
Blank Width (mm)	1530	0	0	0	0
Blank Length (mm)	1503	0	0	0	0
Blank Thickness (mm)	1.40	0.00	0.00	0.00	0.00
Blanks Shaped (1) or Sheared (0)	0	0	0	0	0
Material Density (g/cc)	7.85	0.00	0.00	0.00	0.00
Material Price ($/kg)	$0.77	$0.00	$0.00	$0.00	$0.00
Scrap Price ($/kg)	$0.10	$0.00	$0.00	$0.00	$0.00

WELDING

After Weld Reject Rate	0.0%	
Precision Shear Required? (1=yes,0	0	
Use Filler Metal? (1=yes,0=no)	0	
Total Weld Length	0	mm
Number of Welds	0	
Parts Welded Simultaneously (#)	0	
Filler Metal Application Rate	0	mm/sec
Wire Diameter	0.00	mm
Wire Density	0.00	g/cc
Wire Material Cost	$0.00	$/kg
Laser Power	0	kW
Weld Line Base Cost	$0	$
Precision Shear Cost	$0	$
Unit Fixturing Station Cost	$0	$
Robot Cost	$0	$
Workers per Weld Line	0	
Number of Fixturing Stations	0	
Number of Load/Unload Robots	0	
Blank Load/Unload Time	0	sec
Fixture Load/Unload Time	0	sec
Weld Rate	0	mm/sec
Time Between Welds	0	sec
Welding Unplanned Downtime	0.00	hr/day
Weld Line Installation Percent	0%	
Weld Line Maintenance Percent	0%	
Weld Line Space Requirement	0	sqm

PRESSING

Stamping Reject Rate	1.0%	
Stamping Unplanned Downtime	5.00	hr
Average Die Change Time	0.50	hr
Average Lot Size	1500	parts
Clean Running Rate	450	parts/hr
Workers per Press Line	4	
Forming Requirements:		
Number of Deep Draws	0	
Number of Additional Forming Hits	1	
Number of Flange Hits	1	
Number of Trim Hits	1	
Energy Consumption Rate/Press	150	kW
Press Line Installation %	25%	
Press Line Auxiliary Equipment %	25%	
Press Line Maintenance %	10%	
Press Space Requirement	50	sqm

OPTIONAL INPUTS

BLANKING:	Blank #1	Blank #2	Blank #3	Blank #4	Blank #5
Minimum Bed Width	0	0	0	0	0
Minimum Bed Length	0	0	0	0	0
Req'd Blanking Press Tonnage	0	0	0	0	0
Blanking Press Cost	$0	$0	$0	$0	$0
Blanking Die Cost	$0	$0	$0	$0	$0

STAMPING:		
Minimum Bed Width	0	mm
Minimum Bed Length	0	mm
Single Action Press Tonnage	0	tons
Double Action Add'l Tonnage	0	tons
Double Action Press Unit Cost	$0	
Single Action Press Unit Cost	$0	
TOTAL PRESS COST	$0	
Number of Presses in the Line	0	

BLANKING

VARIABLE COSTS	per piece	per year	percent
Material Cost	$20.55	$2,055,461	98.03%
Labor Cost	$0.06	$5,666	0.27%
Energy Cost	$0.01	$1,263	0.06%
Total Variable Cost	$20.62	$2,062,390	98.36%

FIXED COSTS	per piece	per year	percent	investment
Main Machine Cost	$0.05	$5,493	0.26%	$46,766
Tooling Cost	$0.13	$13,190	0.63%	$50,000
Overhead Labor Cost	$0.07	$7,082	0.34%	
Building Cost	$0.01	$912	0.04%	$8,278
Maintenance Cost	$0.02	$1,959	0.09%	
Working Capital Cost	$0.06	$5,754	0.27%	
Total Fixed Cost	$0.34	$34,391	1.64%	$105,044

Total Fabrication Cost	$20.97	$2,096,780	100.00%

EFFECTIVE MACHINE RATE (For MSL assumptions ONLY, see cell A130 for details)	$278 per hour

RELATED VARIABLES

	Blank #1	Blank #2	Blank #3	Blank #4	Blank #5
Blanking Press & Die Requirements:					
Shaped (1)/Sheared (0)?	0				
Predicted Bed Width (mm)	1829				
Predicted Bed Length (mm)	1524				
Predicted Press Tonnage	1000				
Predicted Blanking Press Cost	$813,512				
Predicted Blanking Die Cost	$50,000				
Bed Width Used (mm)	1829				
Bed Length Used (mm)	1524				
Press Tonnage Used	1000				
Blanking Press Cost Used	$813,512				
Blanking Die Cost Used	$50,000				
Average Blanking Press Cost	$813,512				
Total Cost of Blanking Dies	$50,000				
Material Requirements:					
Blank Weight (kg)	25.27				
Blank Width (mm)	1530.337				
Blank Length (mm)	1502.512				
Blank Thickness (mm)	1.4				
Material Density (g/cc)	7.85				
Input Steel (kg)	2686877				
Recovered Scrap (kg)	134344				
Material Price ($/kg)	$0.77				
Scrap Price ($/kg)	$0.10				
Total Weight of Blanks (kg)	25.27				
Total Input Steel (kg)	2686877				
Blanking Scrap Recovered (kg)	134344				
Average Material Price ($/kg)	$0.77				
Average Scrap Price ($/kg)	$0.10				

Volumes, Times & Workers:

Effective Prod Vol.	101011
Clean Rate (parts/hr)	1200
Blanking Reject Rate	0%
Blanking Material Loss %	5%
Number of Lots Per Year	34
Annual Prod. Time (hr)	84
Die Change Time (hr)	17
Line Time Req'd (hr)	101
Line Time Available (hr)	2750
Percent of the Line Req'd	4%
Annual Paid Time (hr)	3500
Direct Workers/Line	1
Add'l Workers/Direct Workers	0.25
Add'l Workers/Machine	1
# of Indirect Workers	0.05

Other Factors:

Energy Consumed (kWhr)	12626
Installation Percent	25%
Aux. Eqiupment Percent	25%
Maintenance Percent	10%
Space Req'd/Press (sqm)	150
Working Capital	$345,239
Interest on Working Capital	$5,754

Tooling Requirements:

Predicted Cost of Draw Dies	$0
Predicted Cost of Other Forming Dies	$357,470
Predicted Cost of Flange Dies	$357,470
Predicted Cost of Trim Dies	$268,102
PREDICTED TOTAL TOOLING COST	$983,041
Cost of Draw Dies Used	$0
Cost of Other Forming Dies Used	$357,470
Cost of Flange Dies Used	$357,470
Cost of Trim Dies Used	$268,102
TOTAL TOOLING COST USED	$983,041

Material Requirements:

Part Weight	22.02	kg
Recovered Scrap	353859	kg
Scrap Price	$0.10	$/kg

Other Factors:

Press Line Energy Consumption	101011	kWhr
Press Line Installation Percent	25%	
Press Line Auxiliary Eqiupment Perce	25%	
Press Line Maintenance Percent	10%	
Press Line Space Requirement	225	sqm
Working Capital	$20,986	
Interest on Working Capital	$350	

STAMPING

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	($0,35)	($35,386)	-7,97%
Labor Cost	$0,80	$79,608	17,92%
Energy Cost	$0,10	$10,101	2,27%
Total Variable Cost	$0,54	$54,324	12,23%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0,54	$53,735	12,10%	$457,478
Tooling Cost	$2,59	$259,324	58,39%	$983,041
Overhead Labor Cost	$0,40	$39,804	8,96%	
Building Cost	$0,05	$4,805	1,08%	$43,617
Maintenance Cost	$0,32	$31,786	7,16%	
Working Capital Cost	$0,00	$350	0,08%	
Total Fixed Cost	$3.90	$389,806	87,77%	$1,484,136

Total Fabrication Cost	$4,44	$444,120	100,00%

EFFECTIVE MACHINE RATE (For MSL assumptions ONLY, see cell A130 for details)	$852 per hour

RELATED VARIABLES

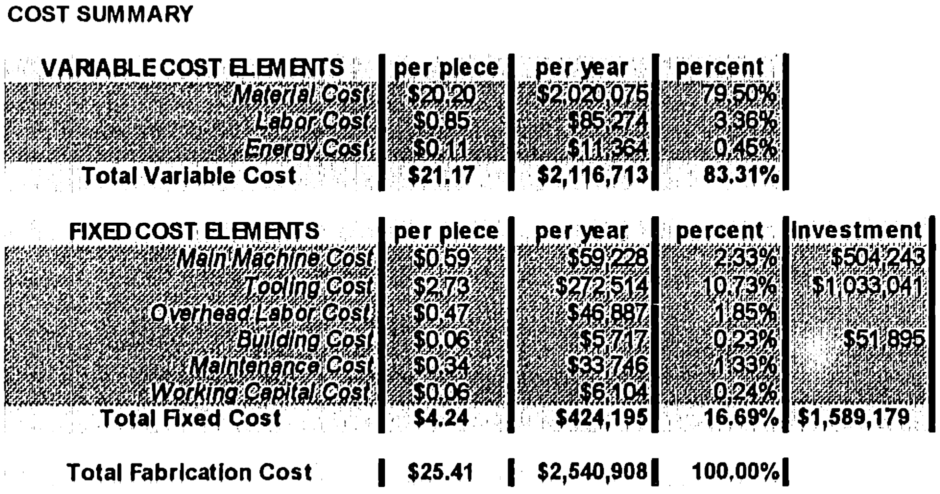
Volumes, Times & Workers:

Effective Stamping Production Volume	101011 parts/yr
Number of Lots Per Year	68
Annual Stamping Production Time	224 hr/yr
Annual Stamping Die Change Time	34 hr/yr
Total Press Line Time Required	258 hr
Total Press Line Time Available	2000 hr
Percent of the Line Required	13%
Annual Paid Working Time	3500 hr
Workers per Press Line	4
Overhead Workers/Direct Workers	0.25
Overhead Workers/Machine	1
Total Number of Indirect Workers	0.26
Total Number of Hits	3
Total Number of Presses	3

Stamping Press Requirements:

Predicted Bed Width	1524 mm
Predicted Bed Length	1372 mm
Predicted Stamping Press Tonnage	1000 tons
Predicted Double Action Tonnage	0 tons
Predicted Double Action Press Unit Cc	$0
Predicted Single Action Press Unit Co:	$755,180
PREDICTED TOTAL PRESS COST	$2,265,539

Bed Width Used	1524 mm
Bed Length Used	1372 mm
Stamping Press Tonnage Used	1000 tons
Double Action Tonnage Used	0 tons
Double Action Press Unit Cost Used	$0
Single Action Press Unit Cost Used	$755,180
TOTAL PRESS COST USED	$2,265,539



COST SUMMARY

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$20.20	$2,020,075	79.50%
Labor Cost	$0.85	$85,274	3.36%
Energy Cost	$0.11	$11,364	0.45%
Total Variable Cost	**$21.17**	**$2,116,713**	**83.31%**

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.59	$59,228	2.33%	$504,243
Tooling Cost	$2.73	$272,514	10.73%	$1,033,041
Overhead Labor Cost	$0.47	$46,887	1.85%	
Building Cost	$0.06	$5,717	0.23%	$51,895
Maintenance Cost	$0.34	$33,746	1.33%	
Working Capital Cost	$0.06	$6,104	0.24%	
Total Fixed Cost	**$4.24**	**$424,195**	**16.69%**	**$1,589,179**

Total Fabrication Cost	**$25.41**	**$2,540,908**	**100,00%**

Appendix B: SMC Model

Overall Machine Usage
Large SMC Parts

SMC Molding

Dedicated?	1
Machine Cost Coefficient	$8,621
Machine Cost Scaling Exp.	0,650
Maximum Machine Tonnage	4089,24
Machine Cost	$1,919,222,54
Total Runtime for all Machines	1,74
Total Number of Parallel Streams	2
Number of Machines (RHBDY1)	0,33
Number of Machines (RHBDY2)	0,33
Number of Machines (LHBDY1)	0,33
Number of Machines (LHBDY2)	0,33
Number of Machines (FLR5)	0,33
Number of Machines (ROOF1)	0,33

Trimming and Drilling

Total Runtime for all Machines	0,83
Total Number of Parallel Streams	1,00
Number of Machines (RHBDY1)	0,17
Number of Machines (RHBDY2)	0,17
Number of Machines (LHBDY1)	0,17
Number of Machines (LHBDY2)	0,17
Number of Machines (FLR5)	0,17
Number of Machines (ROOF1)	0,17

EXOGENOUS COST FACTORS

Annual Production Volume	35	(000)/yr
Product Lifetime	5	yrs
Dedicated Equipment	1	(1=Y,0=N)
Process Rejection Rate	5,0%	
Direct Wages (w/benefits)	$25,00	/hr
Working Days/Yr	250	
Working Hours/Day	20	
Capital Recovery Rate	10,0%	
Capital Recovery Period	20	yrs
Working Capital Period	2	months
Price of Building Space	$139,35	/sq ft
Building Recovery Life	25	yrs
Price of Electricity	$0,100	/KWh
Fixed Overhead	35,0%	
Auxiliary Equipment Cost	25,0%	
Maintenance Cost	10,0%	
Installation Cost	25,0%	

Overall Machine Usage
Small SMC Parts

SMC Molding

Dedicated?	1	
Machine Cost Coefficient	$8,621	/press
Machine Cost Scaling Exp.	0.650	
Maximum Machine Tonnage	636.1384615	
Machine Cost	$572,619.61	
Total Runtime for all Machines	2.69	
Total Number of Parallel Streams	3	
Number of Machines (FLR1)	0.24	
Number of Machines (FLR2)	0.24	
Number of Machines (RHFLR3)	0.24	
Number of Machines (LHFLR3)	0.24	
Number of Machines (RHFLR4)	0.24	
Number of Machines (LHFLR4)	0.24	
Number of Machines (XMBR1)	0.32	
Number of Machines (XMBR2)	0.24	
Number of Machines (RHFRT1)	0.24	
Number of Machines (RHFRT2)	0.24	
Number of Machines (LHFRT1)	0.24	
Number of Machines (LHFRT2)	0.24	

Trimming and Drilling

Total Runtime for all Machines	1.66
Total Number of Parallel Streams	2.00
Number of Machines (FLR1)	0.17
Number of Machines (FLR2)	0.17
Number of Machines (RHFLR3)	0.17
Number of Machines (LHFLR3)	0.17
Number of Machines (RHFLR4)	0.17
Number of Machines (LHFLR4)	0.17
Number of Machines (XMBR1)	0.17
Number of Machines (XMBR2)	0.17
Number of Machines (RHFRT1)	0.17
Number of Machines (RHFRT2)	0.17
Number of Machines (LHFRT1)	0.17
Number of Machines (LHFRT2)	0.17

SMC MOLDING MODEL
Materials Systems Laboratory MIT

Revision Date : 09/03/91

COMPONENT SPECIFICATIONS			
Part Name:	Bodyside 1		
Formulation Number	5		MAT
Weight	48.96	lbs	WGT
Maximum Wall Thickness	0.197	in	THKM
Total External Surface Area	3,503	sq in	SAREA
Projected Area	2,463	sq in	PAREA
Number of Cavities	1		CAV
Number of Actions in Tool	1		ACT
Backup Mold	1	(1=Y;0=N)	BACK
Molding Cy. Time <optional>	120	sec	CYC
Tool Cost/Set <optional>		($000/set)	MOLD
Press Tonnage <optional>		tons	TONS

EXOGENOUS COST FACTORS			
Annual Production Volume	35	(000)/yr	NUM
Product Lifetime	5	yrs	PLIFE
Dedicated Equipment	1	(1=Y;0=N)	DED
Process Rejection Rate	5.0%		PREJ
Direct Wages (w/ benefits)	$25.00	/hr	WAGE
Working Days/Yr	250		DAYS
Working Hours/Day	20		HRS
Capital Recovery Rate	10.0%		CRR
Capital Recovery Period	20	yrs	CRP
Working Capital Period	2	months	WCP
Price of Building Space	$139.35	/sq ft	PBLD
Building Recovery Life	25	yrs	BLIFE
Price of Electricity	$0.100	/KWh	ELEC
Fixed Overhead	35.0%		OVHD
Auxiliary Equipment Cost	25.0%		AUX
Maintenance Cost	10.0%		MNT

PROCESS RELATED FACTORS

Average Downtime	15.0%		DOWN
Material Scrap Rate	5.00%		SCR
Molding Cycle Time Intercept	50	sec	CYC1
Molding Cycle Time Factor	250	sec/in	CYC2
Machine Cost Coefficient	$8,621		MCH1
Machine Cost Scaling Exp.	0.650		MCH2
Direct Laborers Per Machine	2		NLAB
Installation Cost	25.0%		INST
Internal Molding Pressure	1,000	psi	PRES1
Press Tonnage Safety Factor	20.0%		PRES2
Mold Cost Coefficient	$48,280		MOL1
Complexity Deformation Exp.	1.08		MOL2
Complexity Actions Exponent	0.4		MOL3
Weight Factor Exponent	0.6		MOL4
Baseline Physical Mold Life	1,000,000	cycles	MOLLI
Electrical Heat	0.50	kWh/lb	POW1
Electrical Mechanical Energy	0.08	kW/press ton	POW2
Floor Space Coefficient	251	sq ft	FLR1
Floor Space Scaling Exponent	0.71		FLR2

In-Mold Coating Paramters

Coating in Use	0	(1=Y;0=N)	COAT
Additional Capital Invest.	$60,000	/press	
Added Cycle Time	30	sec	
Coating Thickness	0.005	in	
Sides Coated (1 or 2)	1		
Coating Material Price	$20.00	/gal	
Coating Transfer Efficiency	95.0%		

Trimming & Drilling Parameters

Process in use	1	(1=Y;0=N)	CUT
Machine Cost	$400,000		CMACH
Toolind & Fixture Cost	$50,000		CDIE
Tool Lifetime	150,000	cycles	CDLIFE
Process Rejection Rate	0.5%		TREJ
Number of Additional Laborers	1		ADDLAB
Trimming & Drilling Cy. Time	60	sec	CUTIME
Simulataneous Trimming	1	parts	SIMTRIM

| SMC MOLDING & COATING: COST ESTIMATE |

Cumulative Piece Cost	$87.22		Bodyside 1	
	$/piece	$/year	percent	
VARIABLE COST ELEMENTS				
Material Cost	$46.83	$1,639,013	53.7%	
Direct Labor Cost	$2.07	$72,602	2.4%	
Energy Cost	$3.00	$104,942	3.4%	
TOTAL VARIABLE COST ===>	$51.90	$1,816,557	59.5%	
	$/piece	$/year	percent	investment
FIXED COST ELEMENTS				
Equipment Cost	$6.03	$210,953	6.9%	$799,676
Tooling Cost	$14.51	$507,701	16.6%	$1,924,586
Fixed Overhead Cost	$9.16	$320,504	10.5%	
Building Cost	$1.75	$61,087	2.0%	$554,491
Auxiliary Equipment Cost	$1.51	$52,738	1.7%	$199,919
Maintenance Cost	$2.38	$83,248	2.7%	
TOTAL FIXED COST ===>	$35.32	$1,236,231	40.5%	
TOTAL OPERATION COST ===>	$87.22	$3,052,788	100.0%	

ADDITIONAL INFORMATION

Sheet Price	$0.86	/lb	PRICE
Material Scrap Rate	5.0%		SCRAP
Cumulative Rejection Rate	5.5%		REJ
Effective Production Volume	37,027	/yr	ENUM
Press Tonnage	1,478	tons	FORCE
Press Cycle Time	120.0	sec	CTIME
Run-Time for One Machine	29.0%		RTIME
Number of Parallel Streams	1.00		#PL
Productive Mold Life	5.00	yrs	TLIFE
Number of Tools (incl backup)	2	/line	#TOOL
In-Mold Coating Use	0.000	gal/pc	IMC
Building Space Requirement	3,979	sq ft/line	SPACE
Approximate Machine Rent	$776.64	/hr	RENT
Total Capital Investment	$3,478,672	(all streams)	

CAPITAL COST	CRP yrs	CRF	$/yr
Equipment	20.00	0.0620	$326,718
Tooling	5.00	0.0514	$130,545
Building	25.00	0.0650	$99,269
Working Capital	0.17	0.0478	$17,019
		Total ===>	$573,550

SMC TRIMMING & DRILLING: COST ESTIMATE

Cumulative Piece Cost	$91.16		Bodyside 1

VARIABLE COST ELEMENTS	$/piece	$/year	percent
Material Cost	$0.00	$0	0.0%
Direct Labor Cost	$0.49	$17,243	12.5%
Energy Cost	$0.75	$26,236	19.0%
TOTAL VARIABLE COST ===>	$1.24	$43,479	31.5%

FIXED COST ELEMENTS	$/piece	$/year	percent	investment
Equipment Cost	$0.50	$17,586	12.7%	$66,667
Tooling Cost	$0.75	$26,380	19.1%	$100,000
Fixed Overhead Cost	$0.70	$24,499	17.8%	
Building Cost	$0.44	$15,272	11.1%	$138,623
Auxiliary Equipment Cost	$0.13	$4,397	3.2%	$16,667
Maintenance Cost	$0.18	$6,363	4.6%	
TOTAL FIXED COST ===>	$2.70	$94,497	68.5%	

TOTAL OPERATION COST ===>	$3.94	$137,976	100.0%

ADDITIONAL INFORMATION

Cumulative Rejection Rate	0.5%		REJ
Effective Production Volume	35,176	/yr	ENUM
Cycle Time	60.0	sec	CTIME
Run-Time for One Machine	13.8%		RTIME
Number of Parallel Streams	1.00		#CL
Productive Tool Life	4.26	yrs	CLIFE
# Cutting Tools	2	/line	#CTOOL
Building Space Requirement	995	sq ft/line	SPACE
Approximate Machine Rent	$191.31	/hr	
Total Capital Investment	$321,956	(all streams)	

CAPITAL COST	CRP yrs	CRF	$/yr
Equipment	20.00	0.0620	$27,238
Tooling	5.00	0.0514	$6,783
Building	25.00	0.0650	$24,817
Working Capital	0.17	0.0478	$541
		Total ===>	$59,379

SMC MOLDING & TRIMMING: COST SUMMARY

Cumulative Piece Cost	$91.16	Bodyside 1

VARIABLE COST ELEMENTS	$/piece	$/year	percent
Material Cost	$46.83	$1,639,013	51.4%
Direct Labor Cost	$2.57	$89,846	2.8%
Energy Cost	$3.75	$131,178	4.1%
TOTAL VARIABLE COST ===>	$53.14	$1,860,036	58.3%

FIXED COST ELEMENTS	$/piece	$/year	percent	investment
Equipment Cost	$6.53	$228,539	7.2%	$866,343
Tooling Cost	$15.26	$534,081	16.7%	$2,024,586
Fixed Overhead Cost	$9.86	$345,004	10.8%	
Building Cost	$2.18	$76,359	2.4%	$693,114
Auxiliary Equipment Cost	$1.63	$57,135	1.8%	$216,586
Maintenance Cost	$2.56	$89,611	2.8%	
TOTAL FIXED COST ===>	$38.02	$1,330,729	41.7%	

TOTAL OPERATION COST ===>	$91.16	$3,190,765	100.0%

ADDITIONAL INFORMATION

Total Building Space	4,974 sq ft/line
Eff. Production Volume	37,027 /yr

EQUIPMENT REQUIREMENTS <minimum>	# of Lines	Cost	Total Investment
Molding Press	1.00	$799,676	$799,676
Trimming & Drilling Eq.	1	$166,667	$166,667
Mold & Fixtures	1	$1,924,586	$1,924,586
		TOTAL ===>	$2,890,929

Appendix C: RTM Cost Model

MATERIALS SYSTEMS LABORATORY
RESIN TRANSFER MOLDING COST MODEL
January 1997

MANUFACTURING SPECIFICATIONS

Annual Production Volume	50,000 /yr
Product Lifetime	5 yrs.
Working Days per Year	250 days/yr.
Working Hours per Day	20 hrs/day
Average Downtime	15.00%

MATERIAL SPECIFICATIONS

<u>Material Components</u>

	Menu Selection	Weight %
Resin	17	35.00%
Filler	1	9.50%
Reinforcement	21	40.00%
Catalyst	1	0.50%
Foam Core	2	15.00%
		100.00%

<u>Selected Material Characteristics (from menu)</u>

Resin:

Component Name	Generic	
Density		1000 kg/m^3
Viscosity		0.425 Pa*sec
Price		$2.60 /kg

Filler:

Component Name	Calcium Carbonate (fine)	
Density		2700 kg/m^3
Price		$0.13 /kg

Reinforcement:

Component Name	Glass Mat 1.5 oz	
Density		550 kg/m^3
Fiber Diameter		0.000054 m
Price		$2.00 /kg

Foam Core:

Component Name	Mobay Bayflex 110-80 IMR	
Isocyanate Price		$2.54 /kg
Polyol Price		$2.54 /kg
Density		96.15 kg/m^3

Catalyst:

Component Name	Akzo Cadox M 50	
Density		1200 kg/m^3
Price		$3.24 /kg

Kinetic Data (Resin)

Polymer System	VINYL ESTER	
Rate Coefficient		8.00E+07 /sec
Activation Energy		7.66E+04 J/mol

Kinetic Data (Foam Core)

Polymer System	POLYURETHANE	
Rate Coefficient		1.27E+05 /sec.
Activation Energy		3.89E+04 J/mol

MOLDED PART

Maximum Part Length	6.00	m
Maximum Part Width	3.556	m
Average Part Thickness	3.46E-02	m
Surface Area	13.414	m^2
Perimeter	25.364	m
Total Volume	4.641E-01	m^3
Total Weight	55	kg
No. of Inserts	0	
Insert Weight	0	kg
Insert Volume	0	m^3
Average Insert Price	$100	/insert
Volume Fraction of Reinforcement	0.0509	
Permeability	5.34E-08	m^2

EXOGENOUS COST FACTORS

Direct Wages	$25.00	/hr
Capital Recovery Rate	10%	
Capital Recovery Period	20	yrs
Electricity Price	$0.10	/KWh
Auxiliary Equipment Cost	25%	
Installation Cost	25%	
Overhead Burden	35%	
Maintenance Cost	10%	
Price of Building Space	$1,500.00	/m^2
Building Recovery Life	25	yrs

CONSTANTS, CONVERSION FACTORS

Universal Gas Constant	8.314	J/mol*K
Pascals to tons/m^2	1.11E-04	Pa/(ton/m^2)
N to tons	1.12E-04	ton/N

MATERIALS SYSTEMS LABORATORY
RESIN TRANSFER MOLDING COST MODEL
January 1997

RESIN TRANSFER MOLDING

SUB-ASSEMBLY OPERATION

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.00	$0	0.00%
Labor Cost	$0.66	$33,203	0.20%
Energy Cost	$0.04	$1,992	0.01%
Total Variable Cost	$0.70	$35,195	0.21%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.15	$7,341	0.04%	$62,500
Tooling Cost	$0.00	$0	0.00%	$0
Fixed Overhead Cost	$0.09	$4,487	0.03%	
Building Cost	$0.05	$2,479	0.01%	$22,500
Auxiliary Equipment Cost	$0.04	$1,835	0.01%	$15,625
Maintenance Cost	$0.02	$1,166	0.01%	
Total Fixed Cost	$0.35	$17,308	0.10%	$100,625

RTM

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$84.59	$4,229,292	25.25%
Labor Cost	$50.21	$2,510,281	14.99%
Energy Cost	$3.01	$150,617	0.90%
Total Variable Cost	$137.80	$6,890,190	41.14%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$81.09	$4,054,601	23.14%	$34,519,107
Tooling Cost	$88.94	$4,446,802	25.38%	$16,856,878
Fixed Overhead Cost	$73.92	$3,695,775	21.09%	
Building Cost	$1.69	$84,363	0.48%	$765,764
Auxiliary Equipment Cost	$20.27	$1,013,650	5.78%	$8,629,777
Maintenance Cost	$19.20	$959,942	5.48%	
Total Fixed Cost	$285.10	$14,255,133	81.35%	$60,771,525

TRIMMING/INSPECTION

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.00	$0	0.00%
Labor Cost	$0.57	$28,345	0.17%
Energy Cost	$0.03	$1,701	0.01%
Total Variable Cost	$0.60	$30,045	0.18%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.03	$1,468	0.01%	$12,500
Tooling Cost	$0.08	$3,957	0.02%	$15,000
Fixed Overhead Cost	$0.06	$3,184	0.02%	
Building Cost	$0.05	$2,479	0.01%	$22,500
Auxiliary Equipment Cost	$0.01	$367	0.00%	$3,125
Maintenance Cost	$0.02	$827	0.00%	
Total Fixed Cost	$0.25	$12,283	0.07%	$53,125

RESIN TRANSFER MOLDING

Sub-Assembly Operation

Input Volume	53,124 /yr
Output Volume	52,062 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	1 /station
Electricity Usage	15 KW
Cycle Time	90.00 sec
Scrap Rate	1.00%
Rejection Rate	2.00%
Machine Cost	$50,000
Run Time for One Machine	31.25%
Number of Parallel Streams	1.00
Floorspace Requirement	15 m^2

RTM

Input Volume	52,062 /yr
Output Volume	51,020 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	2 /station
Electricity Usage	30 KW

	Usage (unit/m^2)	Price ($/unit)
Mold Cleaning Material Usage, Price (gal)	0.50	$20.00
Mold Release Agent Material Usage, Price (l)	0.50	$20.00
Gel Coating Material Usage, Price (kg)	0.27	$4.00

	Rate (sec/m^2)	Frequency (parts/op)
Mold Cleaning Rate, Frequency	20.00	20
Mold Release Agent Coating Rate, Frequency	40.00	20
Gel Coating Rate, Frequency	20.00	1

Preform/Foam Core/Insert Placement Time	30 sec
Open/Close Mold Time	30 sec
Demold Time	20 sec
Rectilinear or Radial Flow?	1 0=Rect, 1=Rad
Radial Source or Sink?	0 0=Source, 1=Sink
Constant Flow Rate or Constant Pressure Filling?	0 0=Flow, 1=Pressure
Mold Temperature	100 oC
Minimum Conversion for Demold	80%
Flow Rate	0.00004 m^3/s
Injection Pressure (Initial)	5.00E+05 Pa
Injection Pressure (Final)	9.03E+02 Pa
Mold Force	3.35E+06 N
Mold Radius	6 m
Mold Radius Override	m
Injection Port Radius	3.24 m
Number of Injectors per Cavity	1
Fill Time	456.73 sec
Cure Time	2626.41 sec
Overall Cycle Time	3471.66 sec
Scrap Rate	1.00%
Rejection Rate	2.00%

Select Tooling Technology (from Tool Menu)	1	
Results of Selection:		
Tool Cost Intercept	$26,300	
Tool Weight Coefficient	71350.00	/kg
Tool Weight Exponent	0.67	
Tool Area Coefficient	24800.05	/m^2
Tooling Life	1,000 000	cycles
Tool Cost	$1,404,740	/toolset
Number of Tool Sets per Line	12.00	/line
Mold Shuttle System?	0	0=No, 1=Yes
Mold Shuttle Cost	$150,000	/shuttle
Press Cost Coefficient 1	$257.79	$/ton
Press Cost Coefficient 2	$93,959.31	$/m^2
Press Cost Intercept	$49,378.56	$
Calculated Press Cost	$2,151,274	/press
Dispensing Unit Cost	$150,000	$/unit
Run Time for One Machine	1181.31%	
Number of Parallel Streams	12.00	
Floorspace Coefficient	0.02	m^2/ton
Floorspace Intercept	2.85	m^2
Floorspace Requirement	42.54	m^2

Trimming/Inspection

Input Volume	51,020	/yr
Output Volume	50,000	/yr
Choose Operation	1	0=NO, 1=YES
Dedicated Capital Equipment?	1	0=NO, 1=YES
Number of Laborers	1	/station
Electricity Usage	15	KWh/part
Cycle Time	80	sec
Scrap Rate	2.00%	
Rejection Rate	2.00%	
Tooling Cost	$5,000	/toolset
Tooling Life	100 000	cycles
Number of Tool Sets per Line	3.00	/line
Machine Cost	$10,000	/machine
Run Time for One Machine	26.68%	
Number of Parallel Streams	100	
Floorspace Requirement	15	m^2

MATERIALS SYSTEMS LABORATORY
RESIN TRANSFER MOLDING COST MODEL
January 1997

PREFORMING SUB-OPERATION

FIBER CUTTING COSTS

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$9.26	$462,842	2.76%
Labor Cost	$0.06	$2,910	0.02%
Energy Cost	$0.00	$116	0.00%
Total Variable Cost	$9.32	$465,868	2.78%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.01	$553	0.00%	$4,707
Tooling Cost	$0.24	$11,871	0.07%	$45,000
Fixed Overhead Cost	$0.10	$5,220	0.03%	
Building Cost	$0.02	$996	0.01%	$9,037
Auxiliary Equipment Cost	$0.00	$138	0.00%	$1,177
Maintenance Cost	$0.03	$1,356	0.01%	
Total Fixed Cost	$0.40	$20,133	0.11%	$59,920

PREFORMING COSTS

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.00	$0	0.00%
Labor Cost	$0.82	$40,877	0.24%
Energy Cost	$0.25	$12,263	0.07%
Total Variable Cost	$1.06	$53,140	0.32%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.50	$25,170	0.14%	$214,286
Tooling Cost	$0.60	$29,805	0.17%	$112,984
Fixed Overhead Cost	$0.49	$24,270	0.14%	
Building Cost	$0.04	$1,771	0.01%	$16,071
Auxiliary Equipment Cost	$0.13	$6,292	0.04%	$53,571
Maintenance Cost	$0.13	$6,304	0.04%	
Total Fixed Cost	$1.87	$93,611	0.53%	$396,912

PREFORM TRIMMING

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.00	$0	0.00%
Labor Cost	$0.10	$5,195	0.03%
Energy Cost	$0.00	$104	0.00%
Total Variable Cost	$0.11	$5,299	0.03%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.05	$2,409	0.01%	$20,507
Tooling Cost	$0.26	$13,190	0.08%	$50,000
Fixed Overhead Cost	$0.13	$6,446	0.04%	
Building Cost	$0.01	$542	0.00%	$4,922
Auxiliary Equipment Cost	$0.01	$602	0.00%	$5,127
Maintenance Cost	$0.03	$1,674	0.01%	
Total Fixed Cost	$0.50	$24,863	0.14%	$80,555

Preform Characteristics

Maximum Length	2.050 m
Maximum Width	0.200 m
Maximum Height	0.150 m
Average Ply Thickness	0.0012 m
Surface Area (w/o cutout)	0.21762 m^2
Cutout Area	0 m^2
Perimeter	4.6 m
Cutout Perimeter	0 m
Number of Plies	5
Weight	121 kg
Number per Part	1

PREFORMING SUB-OPERATION

Fiber Cutting

Input Volume	55,873 /yr
Output Volume	54,756 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	1 /station
Electricity Usage	10 KW
Number of Plies Cut Concurrently	6
Cutting Rate	2.00 sec/m
Cycle Time (1)	7.500 sec
Scrap Rate	1.00%
Rejection Rate	2.00%
Tooling Cost	$ 15,000 /toolset
Tooling Life	100 000 cycles
Number of Tooling Sets per Line	3.00 /line
Machine Cost	$ 25,000
Run Time for One Machine	2.74%
Number of Parallel Streams	1000
Number of Machines Required	0.151
Floorspace Requirement	40 m^2

Preforming

Thermoforming

Input Volume	54,756 /yr
Output Volume	54,208 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Carousel Thermoformer? Single Station?	1 0=C, 1=SS
Number of Laborers	1 /station
Electricity Usage	75 KW
Thermoform Temperature	100 oC
Room Temperature	25 oC
Heating Rate	0.50 sec/oC
Load/Unload Time (unnecessary for carousel)	10.00 sec
Thermoform Time	60 sec
Cycle Time	107.50 sec
Scrap Rate	0.00%
Rejection Rate	1.00%

Select Tooling Technology (from Tool Menu)	1
Results of Selection	
Tool Cost Intercept	$ 26,300
Tool Weight Coefficient	71350.00 /kg
Tool Weight Exponent	0.67
Tool Area Coefficient	24800.05 /m^2
Tooling Life	1000 000 cycles
Tooling Cost (1)	$ 112,984 /toolset
Number of Tool Sets per Line (for Override)	100 /line
Machine Cost	$ 400,000 /machine
Run Time for Machine	38.47%
Number of Parallel Streams	100
Number of Machines Required	0.43
Floorspace Requirement	25 m^2

Alternative Preforming Technology

Input Volume	54,208 /yr
Output Volume	54,208 /yr
Choose Operation	0 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	/station
Electricity Usage	KW
Direct Material Usage	
Direct Material Cost	
Indirect Material Usage	
Indirect Material Cost	
Cycle Time	0 sec
Scrap Rate	
Rejection Rate	
Tooling Cost	
Tooling Life	1000 000 cycles
Number of Tool Sets per Line	0
Machine Cost	
Run Time for One Machine	0
Number of Parallel Streams	0
Number of Machines Required	0.000
Floorspace Requirement	m^2

<u>Preform Trimming</u>

Input Volume	54,208 /yr
Output Volume	53,124 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	1 /station
Electricity Usage	5 KW
Number of Plies Cut Concurrently	1
Cutting Rate	3.00 sec/m
Cycle Time (1)	13.80 sec
Scrap Rate (1)	69.67%
Rejection Rate	2.00%
Tooling Cost	$ 50,000 /toolset
Tooling Life	1000 000 cycles
Number of Tool Sets per Line	100 /line
Machine Cost	$ 75,000
Run Time for One Machine	4.89%
Number of Parallel Streams	100
Number of Machines Required	0.219
Floorspace Requirement	15 m^2

FOAM CORE SUB-OPERATION

FOAM CORE MOLDING

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$6.02	$301,159.07	1.80%
Labor Cost	$8.02	$401,175.95	2.40%
Energy Cost	$0.80	$40,117.60	0.24%
Total Variable Cost	$14.85	$742,452.62	4.43%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$2.30	$115,246.40	0.66%	$981,157.53
Tooling Cost	$3.06	$152,894.99	0.87%	$579,592.32
Fixed Overhead Cost	$2.41	$120,569.23	0.69%	
Building Cost	$0.32	$16,213.84	0.09%	$147,173.63
Auxiliary Equipment Cost	$0.58	$28,811.60	0.16%	$245,289.38
Maintenance Cost	$0.63	$31,316.68	0.18%	
Total Fixed Cost	$9.30	$465,052.73	2.65%	$1,953,212.86

FOAM CORE POST-CURE

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.00	$0.00	0.00%
Labor Cost	$2.74	$136,889.62	0.82%
Energy Cost	$1.75	$87,609.36	0.52%
Total Variable Cost	$4.49	$224,498.98	1.34%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.58	$29,057.98	0.17%	$247,387.01
Tooling Cost	$0.32	$15,827.85	0.09%	$60,000.00
Fixed Overhead Cost	$0.57	$28,472.16	0.16%	
Building Cost	$0.44	$21,803.32	0.12%	$197,909.60
Auxiliary Equipment Cost	$0.15	$7,264.50	0.04%	$61,846.75
Maintenance Cost	$0.15	$7,395.36	0.04%	
Total Fixed Cost	$2.20	$109,821.17	0.63%	$567,143.36

FOAM CORE TRIMMING

VARIABLE COST ELEMENTS	per piece	per year	percent
Material Cost	$0.00	$0.00	0.00%
Labor Cost	$0.69	$34,568.09	0.21%
Energy Cost	$0.11	$5,530.89	0.03%
Total Variable Cost	$0.80	$40,098.98	0.24%

FIXED COST ELEMENTS	per piece	per year	percent	investment
Main Machine Cost	$0.02	$978.83	0.01%	$8,333.33
Tooling Cost	$0.08	$3,956.96	0.02%	$15,000.00
Fixed Overhead Cost	$0.06	$2,842.79	0.02%	
Building Cost	$0.04	$2,203.36	0.01%	$20,000.00
Auxiliary Equipment Cost	$0.00	$244.71	0.00%	$2,083.33
Maintenance Cost	$0.01	$738.39	0.00%	
Total Fixed Cost	$0.22	$10,965.03	0.06%	$45,416.67

Foam Core Characteristics

Maximum Length	2.05 m
Maximum Width	0.2 m
Average Thickness	0.1388 m
Surface Area	0.2 m^2
Volume	2.78E-02 m^3
Weight	2.0030 kg
Number per Part	1 /part
No. of Inserts	0
Insert Volume	0 m^3
Insert Weight	0 kg
Average Insert Price	$ 100 /insert
Iso/Poly Weight Ratio	1

FOAM CORE SUB-OPERATION

Foam Core Molding

Input Volume	55,309 /yr
Output Volume	54,756 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	1 /station
Electricity Usage	25 KW

	Usage (unit/m^2)	Price ($/unit)
Mold Cleaning Material Usage, Price (gal)	0.50	$ 20.00
Mold Release Agent Material Usage, Price (l)	0.50	$ 20.00

	Rate (sec/m^2)	Frequency (parts/op.)
Mold Cleaning Rate, Frequency	20.00	20
Mold Release Agent Coating Rate, Frequency	40.00	20

Mold Filling Rate	1000.00 sec/m^3
Setup Time	30.00 sec
Minimum Conversion for Demold	99%
Average Mold Temperature	60 oC
Cure Time	986.13 sec
Cycle Time (1)	1044.48 sec
Scrap Rate	100%
Rejection Rate	100%
Select Tooling Technology (from Tool Menu)	1
Results of Selection:	
Tool Cost Intercept	$ 26,300
Tool Weight Coefficient	71350.00 /kg
Tool Weight Exponent	0.67
Tool Area Coefficient	24800.05 /m^2
Tooling Life	1,000 000 cycles
Tooling Cost (1)	$ 144,898 /toolset
Number of Tool Sets per Line	4.00 /line
Machine Cost	$ 200,000
Run Time for One Machine (Foam Core 1)	377.58%
Number of Parallel Streams	4.00
Number of Required Machines	3.92
Floorspace Requirement	25 m^2

Foam Core Post-Cure

Input Volume	54,756 /yr
Output Volume	54,208 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	0.5 /station
Electricity Usage	80 KW
Batch or Continuous Oven?	0 Batch=0, Continuous=1
Post-Cure Temperature	100 oC
Batch Oven Capacity	10 /oven
Batch Oven Size	126.075 m^3
Batch Oven Cure Time	7200 sec
Batch Oven Cycle Time	720 sec
Batch Oven Cost	$75,000
Scrap Rate	0.00%
Rejection Rate	100%
Continuous Oven Length	20 m
Continous Oven Speed	0.50 m/min
Continuos Oven Cost	$500,000
Support Frame Tooling Cost	$1,000 /frame
Number of Support Frames per Line	60 /line
Machine Cost	$75,000
Run Time for One Machine	257.67%
Number of Parallel Streams	3.00
Number of Required Machines	2.64
Floorspace Requirement	50 m^2

Foam Core Trimming

Input Volume	54,208 /yr
Output Volume	53,124 /yr
Choose Operation	1 0=NO, 1=YES
Dedicated Capital Equipment?	1 0=NO, 1=YES
Number of Laborers	0.5 /station
Electricity Usage	20 KW
Cycle Time	180.0 sec
Scrap Rate	2.00%
Rejection Rate	2.00%
Tooling Cost	$5,000 /toolset
Tooling Life	100 000 cycles
Number of Tool Sets per Line	3.00 /line
Machine Cost	$10,000 /machine
Run Time for One Machine	63.77%
Number of Parallel Streams	100
Number of Required Machines	0.67
Floorspace Requirement	20 m^2

Appendix D: Symbol Notation

A (in Darcy's Law) = Cross-sectional Area

A (in Cure Model) = Frequency constant

C_{cr} = Critical conversion percentage

d_p = Diameter of fibrous media

E_a = Activation energy

F_m = Maximum mold force

k, k_1, k_2 = Arrhenius rate constants

K = Reinforcement permeability

L_{max} = Maximum mold length

n = Order of reaction

N_{inj} = Number of injection ports

P_{inj} = Injection pressure

P_{max} = Maximum pressure

P_{surf} = Part surface area

∇P = Pressure gradient

Q = Flow rate

R = Universal gas constant

R_i = Mold radius

R_m = Mold radius

R_o = Gate radius

R_s = Injection port radius

t = Part thickness

T = Temperature (°K)

T_{fill} = Fill Time

v_f = Reinforcement volume fraction

W = Mold width

X = Degree of cure

X_m = Mold Radius

μ = Fluid viscosity

ϕ = Porosity

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