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Strategic materials selection in the automobile body: Economic opportunities for polymer composite design

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Abstract

Previous studies on materials choice in automotive bodies have looked at both composite and aluminum alternatives, but have always found steel to be the most cost-effective option at the production volumes found in the overwhelming majority of vehicle models. This study finds composites to have significant economic potential when considering emerging advances in the polymer composite body-in-white design against the mild-grade steel body currently on the road. With the significant implications of a polymer composite body for vehicle light-weighting and thereby improved fuel efficiency, these results come at a time when they are particularly pertinent.

The results presented in this paper are based on a consortium-developed, 25-part unibody design not available to previous studies. Also presented for the first time are data on competing alternatives in fiber composite component assembly and implications of platform sharing across vehicle models. Finally, developments in process-based cost modeling capabilities are presented for (a) fiber-reinforced composite component production, (b) component assembly, and (c) design implications of glass versus carbon reinforcement.

Keywords: A. Carbon fiber; A. Glass fiber; A. Structured composites; C. Modelling; E. Injection molding; Automobiles

1. Materials selection in automotive body-in-whites: technologies and demands

Regulatory constraints on energy consumption have influenced vehicle development for over three decades. With recent rises in oil prices due to increasing demand and unrest in the Middle East, and the increased prominence of global warming and other environmental concerns in the popular press, technological advances to improve vehicle efficiency are becoming increasingly important to competitiveness in the global automobile market [1–5].

One key technical design strategy for improving vehicle efficiency is the reduction of vehicle mass, or light-weighting. Vehicle light-weighting not only enhances fuel efficiency, but also lowers vehicle emissions and improves driving performance.[1] Light-weight subsystems such as hoods and decklids are already employed throughout the industry to achieve small weight savings. However, significant improvements in vehicle efficiency will require larger changes in mass. A primary target for this mass reduction is the body-in-white, whose standard steel version comprises 20–25% of total vehicle curb weight.

The two main strategic approaches for reducing weight in the body-in-white are architectural changes and material substitution. Among architecture alternatives, the unibody is most mass efficient and is already ubiquitous [6]. Consequently, the primary mechanism available for further reducing the weight of the body-in-white is the use of alternative materials. This study examines the potential cost-competi-

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[1] Alternatively, lighter structures can allow for additional weight in the form of electrical conveniences such as DVD players, navigation systems, and additional motorized options.

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tiveness of two alternative body materials – Carbon Fiber Reinforcement Polymer (CFRP) and Glass Fiber Reinforcement Polymer (GFRP) composites – against the ubiquitous incumbent, mild steel.

1.1. Background: current BIW materials use

Steel has been the material of choice for automobile structures since Henry Ford's introduction of mass production in 1913. In 2004, the average light vehicle produced in North America contained 2233 pounds of steel (55% of the vehicle weight) and 331 pounds (8%), of iron [7].[2,3]

The use of polymers in US automotive applications has risen dramatically from an average of 18 pounds per vehicle in 1960 [10] to well above 300 pounds per vehicle in 2004 (8% of vehicle weight)[11]. Notably, most of the plastic applications in vehicles are lower-performance commodity polymers and short-fiber composites. The use of advanced composites in *structural* vehicle body applications has been far less extensive, but there have been some notable recent applications [11].

1.2. Previous work

Most work on the competitiveness of polymer composite technology came out in the early- to mid-1990s through the Partnership for a New Generation of Vehicles (PNGV) [12–17]. It is conventional wisdom within the industry that the use of polymer matrix composites in automobile structures cannot be defended on an economic basis [12,18]. A 1995 study by IBIS Associates and the Rocky Mountain Institute, based on GM's ultra light BIW concept car, argued that concerns over economic viability may be misplaced [12]. A 1999 study by the Rocky Mountain Institute has suggested that polymer composite BIW alternatives may be well suited to platforming goals by providing a cheaper an more easily contoured solution for the customized elements not part of the shared platform [19].

The work presented in this paper differs from previous studies in several ways: (1) it is based on, up-to-date detailed data collection with resin and fiber suppliers, equipment suppliers, component producers, and Ford, General Motors, and Daimler-Chrysler; (2) it applies new component and assembly modeling techniques; (3) it evaluates the competitiveness of polymer composites against real North American car production volumes; and (4) it looks at how platform sharing changes the competitive position of polymer composites in BIW applications.

2. Methods: process-based cost modeling

Since the late 1980s, models of firms' Cost of Ownership (COO)[4] of equipment have been used widely in industry to support investment decisions [20,21]. Activity-based costing [22] and other generative cost research [23–25] have extended these methods to incorporate the implications of individual process activities for cost. COO, activity-based, and generative costing methods, however, are unable to predict the cost-implications of new materials, design architectures, or processes while those advances are still in their early stages of development. Process-based (or technical) cost modeling was developed to address just such a problem. Process-based cost modeling is a method for analyzing the economics of alternative manufacturing processes without the prohibitive economic burden of trial and error investigation [26]. Its application has been extended to analyzing the implications of alternative design specifications or process operating conditions on production costs within and across manufacturing processes [27]. In the same way that present-day mathematical models allow designers and manufacturing engineers to understand the physical consequences of their technical choices before those choices are put into action, technical cost models harness science and engineering principles to understand the economic consequences of technology choices prior to large product development and facility investments [27].

To calculate the total cost of manufacturing the composite body-in-white, this study uses two process-based cost models (PBCM) – a component PBCM and an assembly PBCM. The total manufacturing cost (C_{Tot}) is then calculated as follows:

$$C_{\mathrm{Tot}} = \sum_q C_q, \text{ s.t. } q \in \text{Components, Assembly} \tag{1}$$

where C_{Tot} = total unit cost (\$ per good body-in-white), and C_q is the total unit cost output of one model, specifically either the total per body-in-white cost of producing all of the components ($C_{\mathrm{Components}}$) or the total per body-in-white cost of assembling those components (C_{Assembly}). According to current practice within industry, the component model assumes parallel production practices and the assembly model assumes serial production practices. The mathematical architectures of each of these models are described in detail in Appendix 1. The calculations in each of these models for the relationships between part design parameters and

[2] These weight fractions assume a total material content of 4026 pounds [8].

[3] With ongoing pressures to light-weight vehicles, in March of 1998 the US Iron and Steel Industry rolled out an Ultra Light Steel Auto Body (ULSAB) concept. In comparison to today's mid-size cars which weigh about 3300 lbs, they estimate that a ULSAB-bodied car would weigh about 2960 lbs [9].

[4] Cost of Ownership (COO) originated at Intel Corporation in the 1980s as an attempt to understand the total cost of acquiring, maintaining, and operating purchased equipment for semiconductor device fabrication. Eventually adopted into the mainstream by Sematech, COO = total cost of acquiring and using a piece of equipment/total number of good parts produced over the lifetime of that piece of equipment. COO should not to be confused with the term Total Cost of Ownership (TCO), which was defined by Gartner Corporation in 1987. CTO is typically used in the automotive industry to denote the cost of owning a vehicle from its purchase, through its maintenance, and finally its sale as a used car.

Table 1
Comparison of carbon, glass, and steel unibody design details

	Design 1: carbon fiber	Design 2: glass fiber	Design 3: steel
Design parameters			
Wheelbase (cm)	274.3	274.3	261.6
Length × Width (cm)	472.4 × 180.3	472.4 × 180.3	469.9 × 170.2
Height (cm)	137.2	137.2	144.8
Components	25	25	120
Inserts	37	37	130
Material composition			
Primary material	Two-component polyurethane	Two-component polyurethane	Mild-grade steel
Brand	Bayer AG's Baydur 420	Bayer AG's Baydur 420	Varies
Price ($/kg)	$2.65	$2.65	$0.77
Reinforcement	Carbon fiber	Glass fiber	NA
Spray price ($/kg)	$20	$2.53	
Lay-up brand	Hexcel Fabric (Woven 24 K)	Owens Corning F2 Matt	
Lay-up price ($/kg)	$13.20	$3.08	
Resin: Reinforcement	65:35 vol%, 50:50 wt%	65:35 vol%, 41:59 wt%	NA
Inserts	Mild-grade steel	Mild-grade steel	Mild-grade steel
Assembly joining	Two-component adhesive	Two-component adhesive	Spot welding
Brand	SIA's Plastilock 731SI	SIA's Plastilock 731SI	NA
Price	$17.50/kg	$17.50/kg	NA

process requirements are presented in the next section. All inputs and calculations for the composite component and assembly models are based on in-depth discussions between the authors and the members of the Automotive Composites Consortium design team. The authors also worked extensively with experts from relevant material, equipment, and component suppliers, including SIA Adhesives, 3M, Lord Corporation, Bayer Corporation, Hexel, Owens Corning, Meridian Auto Systems, The Budd Company, Visteon, RPC Alliance, Venture Industries, Tee Jay Industries, Global Tooling Systems, The ABB Group, and Oak Ridge National Labs. The steel component and assembly models inputs and calculations as well as the steel vehicle design built on previous studies by several of the co-authors for this paper [28,29].

3. A three-case comparison

3.1. Product design

This study evaluates the relative competitiveness of three design alternatives – a CFRP unibody, a GFRP unibody, and a steel unibody. A detailed comparison of the three designs is provided in Table 1. Each design is briefly introduced in the sections that follow.

3.1.1. Design 1: carbon fiber-reinforced polymer composite unibody

Design and processing information for the composite vehicles is drawn from the Automotive Composite Consortium's Focal Project III, whose goal was to characterize the perspectives of industry experts on the near-term potential of composites technology.[5] The specific design goal of the Focal Project III was to produce a body-in-white with minimum mass, while maintaining structural integrity and cost-competitiveness at medium to high production volumes (20,000–250,000 body units per year).

3.1.2. Design 2: glass fiber inforced polymer composite unibody

In addition to the carbon fiber-reinforced design, a second composite option is examined – a glass-reinforced fiber composite body. Because glass fiber is less stiff, less strong, and more dense than carbon fiber, glass fiber-reinforced parts are typically thicker and heavier than comparable carbon fiber-reinforced parts. The unit price of glass fiber, however, is 5–10times less than that of carbon fiber.

The glass-reinforced design has the same general layout as the carbon-reinforced ACC vehicle. For each of the components, height and width are the same as for the carbon-reinforced BIW. The thickness of the glass-reinforced components, however, is increased. For the carbon-reinforced and glass-reinforced components to exhibit the same stiffness, their deflection under the same loading force must be equal. The required thickness (h_g) of each glass-reinforced component is calculated by approximating the component as a centrally loaded, fixed beam:

$$h_g = \sqrt[\frac{1}{3}]{\frac{E_c}{E_g}} h_c \tag{2}$$

Here, E_c is the modulus of the carbon-reinforced material, E_g is the modulus of the glass-reinforced material, and h_c is the thickness of the carbon-reinforced component. These moduli are modeled as an average of the resin and the reinforcement moduli weighted by their respective volume fraction The volume fraction of glass reinforcement is assumed to

[5] The ACC was formed in August 1988 as a collaborative effort of Ford, GM, and Chrysler (now Daimler-Chrysler).

be equal to that used in the carbon-reinforced components. Here, $E_c = 230$ GPa, $E_g = 72.4$ GPa, and $E_r = 3.5$ GPa.

The increase in thickness of the glass-reinforced parts has consequences throughout the SRIM process, affecting material quantities, pre-form spray times, molding cycle times, and line requirements. The methods by which these differences are accounted for in the process-based cost model are described in the next section of this paper on process design.

3.1.3. Design 3: mild-grade steel unibody

The third design, a steel unibody, is based on the typical steel body design currently on the market. The minor dimensional differences between the steel and composite body designs are, for the purposes of this study, insignificant.

3.2. Process design: component production and assembly

3.2.1. Structural reaction injection molding

As chosen by the ACC, the polymer composite fabrication process in this study is structural reaction injection molding (SRIM). SRIM was chosen by the ACC because of its expected advantage in minimizing fiber scrap, accommodating part complexity, and having a relatively rapid processing rate. SRIM is a four-step process: (1) pre-form making, (2) pre-form trimming, (3) reaction injection molding, and (4) final part trimming and inspection. The organization and durations of these steps is summarized in Fig. 1A.

(1) Pre-form making

Pre-form making shapes the reinforcement material into the form of the part. This study models two different pre-forming methods: (1) spraying of fibers, here forward called the "Spray Method" and (2) cutting and layering of woven fiber fabric, here forwards called the "Lay-Up Method." The type of pre-form method – "Spray Method" or "lay-up method" – most appropriate for each part was chosen by design engineers from the ACC team, and then actuated in the model. The full list of parts and pre-form method used for each part can be seen in Appendix 2. The capital equipment and material cost assumptions for the two pre-forming methods are shown in Table 1 in Appendix 3. A brief description of each pre-forming method is provided below.

(1.1) Pre-forming "Spray Method"

The "spray method" creates the perform shape by spraying chopped fibers onto a screen in the shape of the part along with a powder or string binder. The screen is held in a press. Once the spraying is completed, the press closes, and the pre-form is heated to bind the fibers in place for handling. When using the spray method for a part, the model assumes a pre-form manufacturing line with a two-robot spray station at lower production volumes, and a six station carousel at higher production volumes. The cycle time for the spray station consists of four stages. All of the stages have the same cycle time across parts except for spraying. The spray time is a function of the mass of fiber required for each pre-form and the chopper gun operating rate. The chopper gun rate is modeled as 1.6 kg/min for carbon fiber and 2.29 kg/min for glass fiber.

The cost of the screen for the spray system is estimated from a regression of actual screen costs against the weight and surface area of the part. This regression takes the form

$$C_{\text{screen}} = 8000X \cdot W + 5000\text{SA} + 73,040 \quad (3)$$

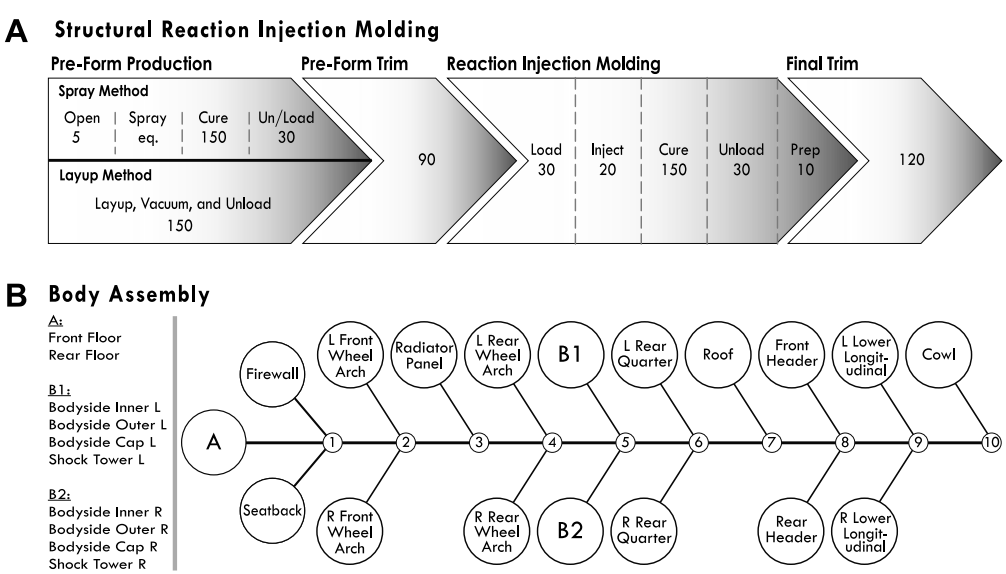


Fig. 1. (A) Process flow and duration for the steps within the Structural Reaction Injection Molding process and (B) process flow for composite body assembly.

where W is the weight of the part, SA is the surface area of the part, and X is required to take into account the difference in the density of glass-reinforced and carbon-reinforced parts. For carbon-reinforced parts $X = 1$, for glass-reinforced parts X is calculated as:

$$X = \frac{\rho_c}{\rho_g} \sqrt[-\frac{1}{3}]{\frac{E_c}{E_g}} \tag{4}$$

where component densities are derived from the volume fraction and density of the constituents (i.e., carbon fiber (ρ_c) = 1.75 g/cc, glass fiber (ρ_g) = 2.55 g/cc, and resin (ρ_r) = 0.947 g/cc) [30].

(1.2) Pre-forming "lay-up method"

The "lay-up method" uses sheets of dry-fabric reinforcement (not a pre-preg). The fabric is pulled directly from its roll onto the forming machine, where it is cut to the required pattern. The cut patterns composed of two to five sheets are then stacked directly onto the SRIM press. The number of fabric layers used depends on both the thickness and on the number of fiber orientations required to achieve the desired mechanical properties for the part. The lay-up cycle time, however, is the same for all parts. To improve the formability of the stack of fabric, blocks in the reciprocal shape of the part, called conformers, are used to press the fabric into position. A vacuum is pulled to form the sheets into the shape of the mold. Three-dimensional shaping of the pre-form occurs later in the production process when the press closes during injection molding.

(2) Pre-form trimming

During pre-form trimming, the edges of the shape are refined, removing any unwanted material. This "trimming" is estimated to remove 4% of the fiber originally sprayed and binded into form. The trimming cycle time is modeled as the same for all parts in this study due to line speed constraints; however, cycle time could be different for other parts or designs. The machine is estimated to cost $25,000 and the tooling set to cost $3500 and to last 500,000 cycles.

(3) Reaction Injection Molding

The SRIM step, as modeled in this study, consists of five stages: load, partial closing of the mold and injection of the resin, completion of the closing of the mold and cure of the resin, opening of the mold and unloading of the part, and clean and prep before the loading of the next part. To reflect current practice in industry, injection time, closing time, and mold closed time are constant, regardless of part dimensions, and the number of injection sites and dispensers are modified to accommodate the geometry of different parts. For the purposes of this study, the number of dispensers required for successful resin distribution was estimated by the ACC engineering team.[6] The model assumes that a typical two-component polyurethane thermoset resin is employed in the molding of structural automotive components. The cycle time breakdown described above is used for both the carbon- and the glass-reinforced parts in the model.

The model treats the cost of the injection molding press (C_{Press}) as a function of the maximum part length (L_{max}), maximum part width (W_{max}), and the maximum force required of the press (F_{max}). This press cost estimation was developed in a Ph.D. thesis by Paul Kang, and is independent of the component material [31]. Kang's regression is as follows:

$$C_{Press} = 49,400 + 590.0F_{max} + 94,000L_{max}W_{max} \tag{5}$$

The maximum required mold force (F_{max}) is calculated as follows:

$$F_{max} = \pi P_{injection}\left(\frac{R_{initial}^2 - R_{max}^2}{2 * \ln\left(\frac{R_{max}}{R_{initial}}\right)}\right) \tag{6}$$

Here $R_{initial}$ is the radius of the dispenser's injection port, R_{max} is the radius of the mold, and $P_{injection}$ is the number of injection ports. For a more detailed discussion see [31].

The tool cost estimate used in the model for the SRIM press was originally developed in Kang's study based on empirical production data for glass-reinforced parts. This equation, which is a function of part weight and surface area, takes the form

$$C_{tool} = 26,300 + 71,350X^{-0.67}W^{0.67} + 24,800\text{SA} \tag{7}$$

where all parameters are as defined previously.

(4) Final Part Trimming and Inspection

After being unloaded from the press, the part is ready for part trimming. Part trimming removes the resin flash that escaped beyond the mold walls. Part trimming removes 10% of the original resin material. Like in pre-form trimming, the final part trimming cycle time is modeled as the same for all parts in this study. The machine cost is estimated to be $100,000 and the tooling cost to be $20,000, where the tools last 100,000 cycles.

[6] Although not used in this analysis, the equation for fill time developed by Kang, provides a good approximation of the number of dispensers chosen by the ACC engineering team for each part. By setting the fill time (T_{fill}) constant instead of the number of injection ports ($P_{injection}$), Kang's equation to calculate fill time could be used in future studies to instead estimate the necessary number of injection ports

$$P_{injection} = \frac{\phi\mu}{2\,\mathrm{K}T_{fill}}\left(R_{initial}^2 \ln\left(\frac{R_{max}}{R_{initial}}\right) - \frac{R_{initial}^2 - R_{max}^2}{2}\right)$$

In this equation, K is the permeability of the pre-form, and ϕ is the porosity of the pre-form [31, #46].

3.2.2. Assembly

Although there are some examples of composite subassemblies, there is to date no experience in medium- to high-volume production of a composite unibody. In developing the assembly model, the authors reviewed several assembly configurations and technologies, including technologies still under development. Based on this survey of methods, the authors have selected a set of methods that they view as most effective for use in the near future. This option is described below. Fuchs [32] offers a more detailed discussion of eliminated options.

The bonding step in assembly entails positioning the first part or already-joined subassembly, laying down adhesive, and then positioning subsequent parts or subassemblies on top of the adhesive (along the join). Bonding requires pumps, a metering system, adhesive guns, a heated hose, and switch-over pumps to dispense the adhesive. The carbon and glass-composite bodies are modeled as being assembled using a heat cure epoxy. There are several advantages to a heat cure epoxy. Although heat curing requires additional equipment and time, the resulting bond has superior properties to the bond created by a room temperature epoxy. A heat cure epoxy also has the advantage of an infinite open time – the length of time between dispensing the adhesive and its curing. This infinite open time increases the number of parts that can be joined at a given station, and eliminates adhesive waste due to premature curing. This study assumes no primer and no pre-heating is necessary on the joining surfaces of the parts. Assembly join cure times within the model range between 2 and 3 min, depending on the length of the join.[7]

The authors surveyed seven different cure methods: hot blocks, hot air impingement, RS induction cure, radio frequency cure, microwave frequency cure, and oven curing. Based on the recommendations of industry experts, this study uses hot air impingement. Heaters are generally placed every 50" along the join, with each heater costing between $8 K and $12 K. The system as a whole also requires a thermocouple sensor, as well as a control panel for the thermocoupler.

In addition to bonding and curing equipment, fiber-reinforced polymer composite assembly also requires fixtures. The fixture costs used in this analysis are shown in Table 2 in Appendix 3 along with the curing systems for different sized subassemblies.

The assembly order is shown in Fig. 1B. The layout of the assembly line is dependent on this order, as well as the number of parts, the type and intensity of joining, and the production rate. As described mathematically in Appendix 1, higher production rates lead to more stations, more robots, and more automation, while smaller production runs assume fewer stations, more time at each station, and more manual labor.

[7] The cure time for a heat cured epoxy can range between 1 and 7 min depending on the magnitude of heat used for cure.

Table 2
Comparison of this study's findings with previous work on the economic competitiveness of a composite unibody

	Mascarin 1995	Kang 1998	Fuchs 2007
Steel–carbon cost parity (APV)		5000	35,000
Steel–glass cost parity (APV)		45,000	105,000
Steel–carbon/glass-mix cost parity (APV)	55,000	25,000	NA
Assumptions:			
Carbon fiber price ($/kg)	$17.50	$11	$20
Glass fiber price ($/kg)	$2.20	$2.00	$2.50
Assembly adhesive price ($/kg)	unclear[a]	$1.79	$17.50
Assembly fixture cost	unclear[a]	Small: $275 K	Small: $200–400 K
		Medium: $305 K	Medium: $600–650 K
		Large: $380 K	Large: $1.025–1.15 K
Reaction Injection Molding cycle time (min)	30 or 7[b]	on average 4.2	3.83
Cost parity w/ carbon fiber price $11/kg	~100,000	5000	45,000

[a] The only information provided by Mascarin et al. on assembly is that all joining is assumed to take 600 s. It is unclear whether this is for both steel and composite bodies, or only composites, and whether this is assumed to be per join or for the entire vehicle.

[b] Mascarin et al. assume hard tooling for some parts and soft tooling for others. 30 min is for hard tooling, and 7 min is for soft tooling.

4. Results

This section presents the model results for the three body-in-white (BIW) designs: a carbon fiber-reinforced polyurethane composite (carbon), a glass fiber-reinforced polyurethane composite (glass), and a mild-grade steel unibody (steel).

4.1. Baseline results

Fig. 2A shows the estimated unit cost of producing and assembling each of the three alternative BIW cases in the US. At annual production volumes under 105,000, the model results suggest that the glass-reinforced BIW is less costly than the steel, and at annual production volumes under 45,000, the carbon-reinforced BIW is also less costly than the steel. These steel–glass and steel–carbon cost parity points are significantly higher than previous work. Specifically, Kang estimates the steel–carbon cost parity at 5000 and the steel–glass cost parity at 35,000. Similarly, the IBIS–RMI study estimates the steel-composite cost parity at 55,000 for a BIW combining carbon and glass fiber in a vinyl-ester resin. A more complete comparison of the assumptions and subsequent results of the three studies can be seen in Table 2.

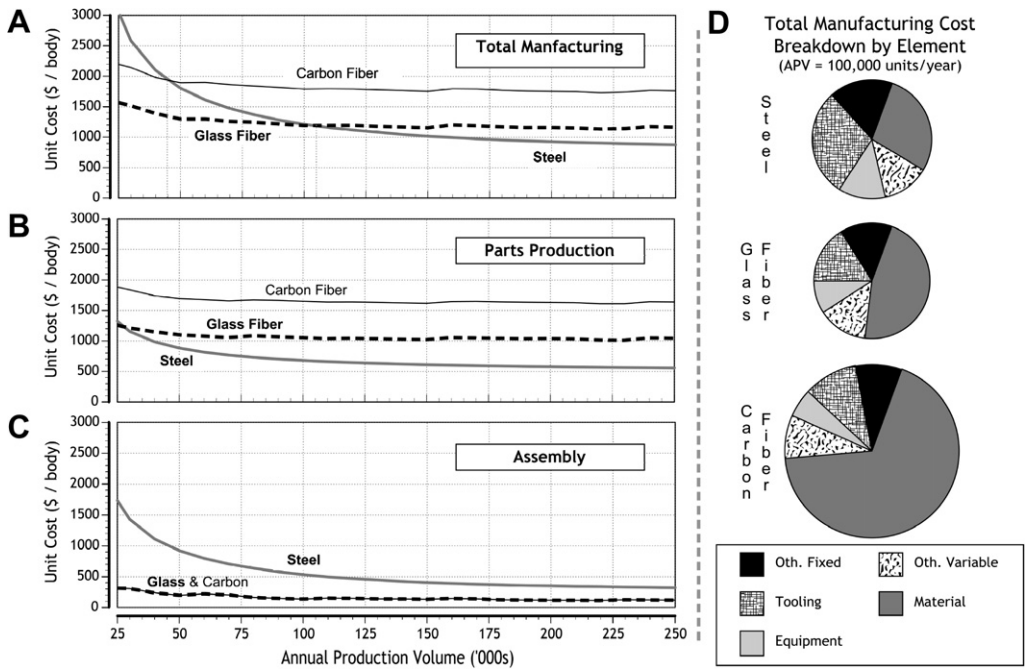


Fig. 2. US body-in-white production cost sensitivity to production volume for (A) total manufacturing cost; (B) parts production; and (C) assembly. (D) Total manufacturing unit cost breakdown at 100,000 units per year.

The steel option is the least costly alternative when modeling high production volumes, because of sheet steel's low material costs and exceptionally fast cycle times. The steel design becomes less cost-competitive than composites at lower production volumes because of the carrying costs of expensive, under-utilized steel stamping equipment and tooling. As shown in Fig. 2D, at annual production volumes (APV) of 100,000 units per year, machine, equipment, building, maintenance, and overhead – all fixed expenses – make up 59% of steel BIW costs. These fixed expenses account for only 24% of carbon, and 40% of glass BIW cost estimates.

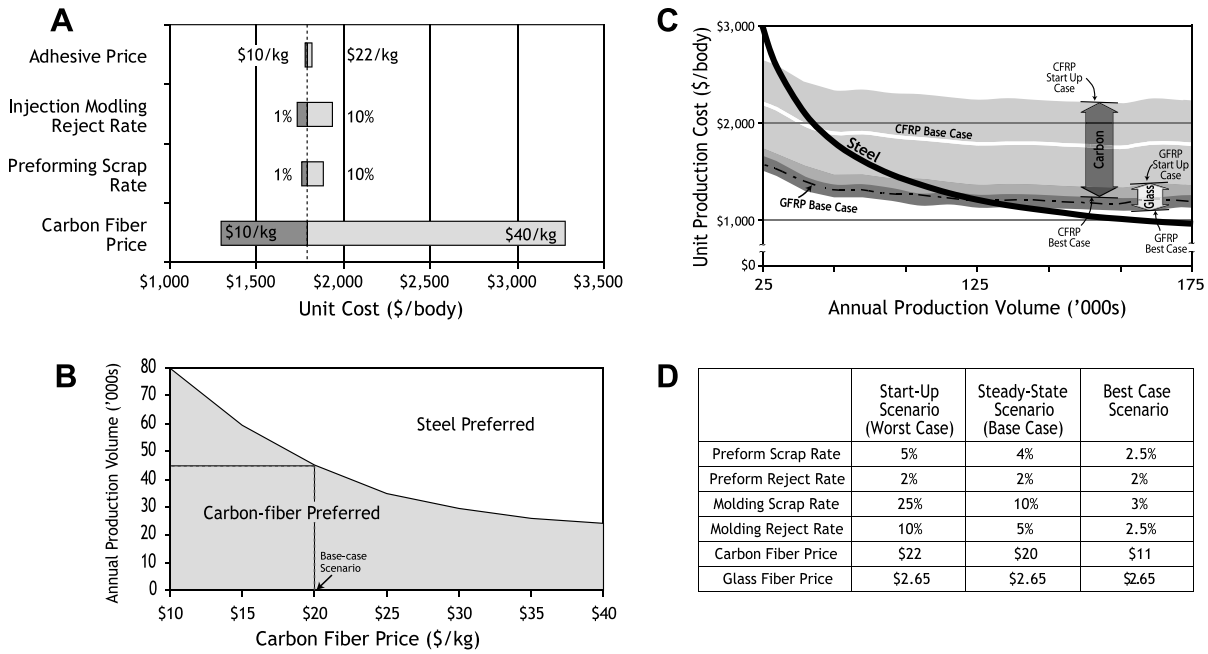
Fig. 2B and C isolates component production and assembly costs. Fig. 2B shows that, although the composite BIW has far fewer total components than steel, the sum of the modeled composite component and insert costs is significantly larger than the sum of the steel component and insert costs (so long as annual production volumes are above 30,000 for glass.) The estimated cost of assembling the composite BIW, however, is significantly cheaper than that of the steel BIW assembly, as shown in Fig. 2C.

4.2. Exploring the sensitivity of results

The results up to this point are representative of what from here forward is referred to as the "Steady State (Base Case)" results. The assumptions for this Steady State scenario represent processing characteristics expected by the ACC design team and industry experts for mature composites production in steady state (after ramping up the learning curve). Inevitably, however, the true processing characteristics of a polymer composite unibody are uncertain. This section explores the sensitivity of the Steady State cost results to changes in four variables – carbon fiber price, pre-forming scrap rate, molding reject rate, and assembly adhesive price – around which there was the greatest uncertainty and which the ACC design team and industry experts perceived as having the potential to have the largest impact on cost.

Fig. 3A and B explores the sensitivity of the Steady State cost results to isolated variations in each of the above-mentioned variables. As can be seen in Fig. 3A, isolated variation of the carbon fiber price has by far the largest impact on final cost. This results suggests that the market price of carbon fiber has a huge impact on the cost-feasibility of producing a carbon fiber-reinforced BIW. Car manufacturers claim to be willing to mass-produce carbon fiber-reinforced BIWs only when carbon fiber prices are at or below $11/kg. Carbon fiber is currently $22/kg, and can run as high as $40/kg. The impact of fiber prices on the annual production volume at which the Steady State scenario achieves steel–carbon cost parity is shown in Fig. 3B. These results suggest that, at a market price of $11/kg, the carbon composite BIW is less costly to produce than a steel BIW at annual production volumes below 75,000 units.

So far this paper has only explored the sensitivity of results when changing one or two variables. Fig. 3C presents two scenarios – a Start-up Scenario and a Best-Case Scenario – where multiple variables differ from the Steady State scenario at once. The Start-up Scenario represents processing characteristics automobile manufacturers believe would be achievable within a year of starting production. This Start-up Scenario could also serve as a proxy



	Start-Up Scenario (Worst Case)	Steady-State Scenario (Base Case)	Best Case Scenario
Preform Scrap Rate	5%	4%	2.5%
Preform Reject Rate	2%	2%	2%
Molding Scrap Rate	25%	10%	3%
Molding Reject Rate	10%	5%	2.5%
Carbon Fiber Price	$22	$20	$11
Glass Fiber Price	$2.65	$2.65	$2.65

Fig. 3. (A) US body-in-white cost sensitivity to key production factors. (B) Sensitivity of steel–carbon cost parity to fiber price. (C) US body-in-white cost sensitivity to production volume across multiple production scenarios. (D) Details of alternative production scenarios.

for a worst-case scenario for the development of composite technology. The Best-Case Scenario represents most favorable conditions suggested by the ACC design team and industry experts for composites. The inputs assigned to each of these scenarios are shown in Fig. 3D.

As can be seen in Fig. 3C, in the Start-Up Scenario, glass is cheaper than steel at annual production volumes below 70,000 and carbon is cheaper than steel at production volumes below 30,000 units. In the Best-Case Scenario, glass is cheaper than steel at production volumes below 120,000 and carbon is cheaper than steel at production volumes below 90,000 units annually.

4.3. Discussion

According to the results reported herein, composite technologies hold not only the potential to reduce vehicle mass, but also to do so in a cost-effective manner. This economic advantage, however, is strongly dependent on production volume. Typical volumes on the US market vary greatly. Fig. 4A presents the distribution of 2005 production volumes for car models produced in the US and Canada [7]. Fig. 4A shows that 68% of car models in the US and Canada in 2005 – 29% of all cars produced in 2005 – were produced in volumes under 105,000, the base case cross-over point between glass and steel. Forty-five percent of 2005 car models – 10% of all cars produced – had annual production volumes under 45,000, the carbon cross-over point.

In many vehicle models, BIW components are shared across model platforms. Conventional wisdom in the auto world suggests that such platform sharing minimizes the

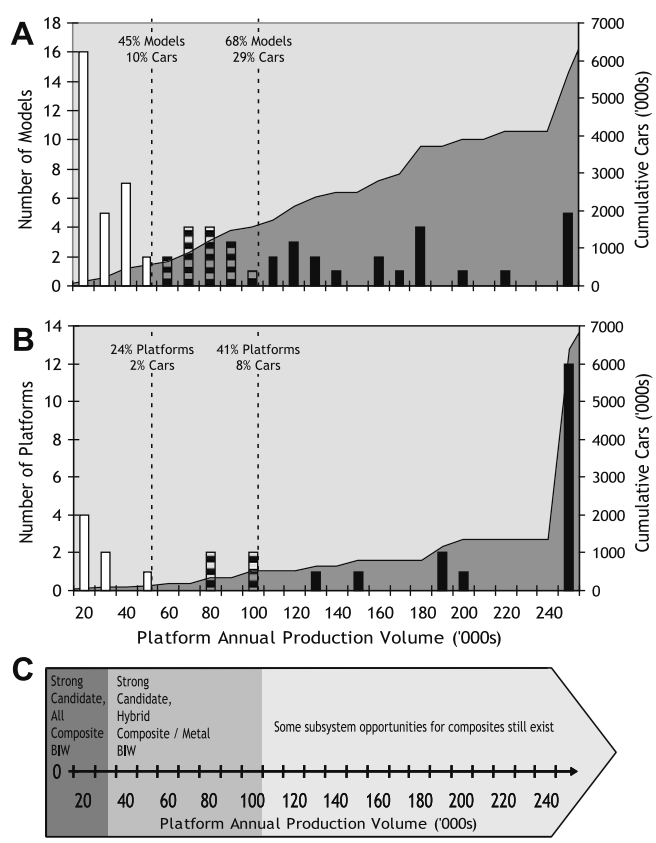


Fig. 4. (A) Car models produced in US and Canada with annual production volumes below composite–steel cost parity [8]. (B) Car platforms produced in the US and Canada with annual volumes below composite–steel cost parity [7]. (C) Synthesis of all-composite and hybrid material opportunities within the North American fleet.

competitiveness of composites. The production volumes of the car platforms produced in the US and Canada, as reported in Automotive News' 2006 Market Data Book [7], can be seen in Fig. 4B. Even accounting for this sharing, composites maintain economic advantage over a large range of platforms. Specifically, 41% of car platforms produced and 8% of all cars produced in 2005 had platforms with 2005 production volumes under the estimated glass–steel cost parity. Similarly, 24% of car platforms and 2% of all cars produced in 2005 had platforms with annual production volumes under 45,000 (the carbon–steel cost parity.) Finally, only around 50% (by mass) of a given vehicle's body is typically shared across a platform [33]. The remaining components are unique to a specific model and produced at that model's annual volume.

The results presented in this section are for a BIW constructed entirely of a single material. Although there are manufacturing and performance advantages to such a solution, the economics may favor a body using a hybrid set of materials. A more complete analysis will require exploring the economic competitiveness of composites at the subassembly level. Several insights, however, can be drawn from the present results. As can be seen in Fig. 2B, glass-reinforced composite components prior to assembly are only cheaper than steel components at annual production volumes below 30,000 units. (Notably, Fig. 2B shows the aggregate cost of all components in the body prior to assembly. The Figure's steel–glass cost parity thus represents an average steel–glass cost parity for all components. The actual steel–glass cost parity varies by component.) Thus, at annual production volumes of 30,000 or less direct substitutions of glass-reinforced composites for steel components in a body-in-white are likely to reduce costs. At higher production volumes, composites are only likely to gain cost-advantage at the subassembly level, where the fewer number of parts required for the composite unibody can yield cost savings through reduced assembly requirements. This advantage does not exist within all subassemblies. Drawing on this difference between glass-composite component's cost parity on their own, versus after including assembly considerations, an initial schematic of how to think about glass-composite competitiveness is provided in Fig. 4C. As shown in Fig. 4C, car models with annual production volumes below the 30,000 steel–glass cost parity for components (shown in Fig. 2b) should be considered a strong candidate for an all-composite body-in-white. Also shown in Fig. 4C, car models with annual production volumes between 30,000 and 105,000 (the steel–glass cost parity for a full composite body-in-white including assembly considerations as shown in Fig. 2A) should be considered a strong candidate for a hybrid glass-composite/metal body-in-white, since for some glass-composite subassemblies will likely have advantages over their steel equivalents while others will not. Finally, based on 2005 vehicle production in the US and Canada [Ward's, 2006 #262], 68% of current car models (29% of all cars) could be strong candidates for composite–steel hybrid body-in-whites, and 32% of car models (5% of all cars) could be strong candidates for entirely composite bodies-in-white. Industry trends toward build-to-order and customization may mean a further increase in the economic competitiveness of composite components over time.

In addition to hybrid body analyses, three other scenarios would be of interest for future work. The first is the competitiveness of the composites against other light-weighting body materials, in particular, aluminum and high-strength steel. The second would be the cost-feasibility of composites in a setting with greenfield investment opportunities (i.e. where both the incumbent and the new technologies require a full set of capital to be purchased, instead of only the new technology requiring a new set of capital), such as a developing country. The third would be to explore the relevance of this analysis and what additional considerations would be necessary to understand the cost-competitiveness of composites for both light- and heavy-duty trucks.

Finally, while this paper demonstrates that composite technology is an economically viable alternative from the perspective of composite BIW production economics, there are many additional issues that may impede the widescale adoption of composites. Such issues include cost of ownership concerns such as repair costs, environmental concerns such as recyclability, and safety concerns including the public perception that composites (or plastic vehicles) are less safe. Future work including a more sophisticated analysis on actual and public perceptions of safety, on cost-of-ownership and using life cycle analysis will be instrumental in shedding light on these areas.

5. Conclusions

Automobiles today are over 63% iron and steel by weight [8]. With rising energy and environmental concerns, as well as increases in electronics and other on-board vehicle systems, vehicle light-weighting continues to be a prominent concern for vehicle manufacturers. Fiber-reinforced polymer composite technologies offer a way of light-weighting the vehicle, both to increase fuel economy and to allow for the addition of other vehicle systems (and, thus, features). Previous studies have suggested that polymer composite unibodies could potentially have economic viability at low production volumes; however, these studies are no longer up-to-date on the latest design and process technology, and fail to include platforming considerations. Since these studies, several advances have occurred in fiber-reinforced polymer composite body-in-white design, component processing, and assembly technology. Drawing on these latest developments, this study uses process-based cost modeling to gain insights into the cost-feasibility of a new fiber-reinforced composite body-in-white against the existing steel design. The results show that the potential for fiber-reinforced composite bodies-in-white to be competitive against steel is greater than it has been in the past (as shown in Table 1). Moreover, platforming (included for the first time here, and not in previous studies) reduces, but

does not eliminate, the potential cost-competitiveness of composites. Considering platforming, the model results suggest that approximately 41% of car models and 8% of the cars produced in the US and Canada in 2005 could have been cheaper if produced with a glass fiber-reinforced composite rather with than a steel unibody. For another 21% of vehicles, glass fiber may be more competitive for the parts of the unibody not included in the platform (again, typically only 50% of the body is shared across a platform). In the end, any such materials substitution would need to be evaluated individually and against other light-weight materials options. These modeling results indicate that the polymer composite industry's developments in process and design have, from a production perspective, maintained composites technology as an economically credible alternative for vehicle body applications.

Appendix 1

A.1. General model architecture

Eqs. (A1)–(A33) below develop the general architecture of the process-based cost model used to forecast production costs from design specifications. For the complete body-in-white, aggregate costs are calculated as follows:

$$C_{\text{Tot}} = \sum_q C_q, \text{ s.t. } q \in \{\text{Components}, \text{Assembly}\} \tag{A.1}$$

where C_{Tot} = total unit cost (\$ per good body-in-white), and C_q is the total unit cost output of one model, specifically either the total per body-in-white cost of producing all of the components ($C_{\text{Components}}$) or the total per body-in-white cost of assembling those components (C_{Assembly}). The architectures of each of these models are described in detail below.

A.1.1. Component model

In the case of the components model, $C_{\text{Components}}$ is the sum of the unit costs of all of the components for a single body-in-white, prior to the assembly of those components. Thus,

$$C_{\text{Components}} = \sum_c \sum_{\text{El}} C_{\text{c,El}} \tag{A.2}$$

and

$$C_{\text{c,El}} = \frac{\text{AC}_{\text{c,El}}}{\text{PV}} \tag{A.3}$$

where AC_{c} = annual cost (\$ per year) for each good component c, PV = good devices per year, El = cost elements (materials, labor, energy, equipment, tooling, maintenance, overhead), and c = component type, where c ε {body side inner, body side outer, dash panel, front floor, front header, front lower longitudinal rail, shock towers, front wheel arch, upper dash panel, radiator panel, rear floor, rear header, rear quarter, roof, parcel shelf, bodyside cap, rear wheel arch}.

A.1.1.1. Variable costs. In the component model, material costs are directly driven by the effective production volume for each step in the model (effPV_i), defined as the gross number of units processed at step i to achieve the desired number of good units (PV) after the final step n_q. The calculations for effective production volume and material costs are shown below:

$$\text{effPV}_{n_q} = \text{PV}/Y_{n_q} \tag{A.4}$$

$$\text{effPV}_i = \text{effPV}_{i+1}/Y_i \quad \forall i \in [1, \ldots, n_q - 1] \tag{A.5}$$

$$\text{AC}_{\text{c,Material}} = \sum_{i,m} U^m_{\text{c},i} \cdot \text{effPV}_i \cdot P^m \tag{A.6}$$

where i = process step number, n = total number process steps, Y_{i} = yield at step i, m = material type, AU = annual usage of material m in step i, P^m = unit price of material m, U^m_i = unit usage of material m at step i.

Energy costs are based on user-specified energy consumption rates for each machine. Energy consumption values are estimated for each process according to equipment requirements, leading to annual energy costs calculated as

$$\text{AC}_{\text{Energy}} = \sum_i \text{reqLT}_i \cdot \text{EI}_i \, P^{(e)} \tag{A.7}$$

where EI_i = energy intensity of step i in kiloWatts (kW) $P^{(e)}$ (\$/kWhr) and reqLT_i = the line time required to produce effPV_i. The annual cost of these laborers is computed as described below:

$$\text{AC}_{\text{Labor}} = \sum_i \text{APT}_i \cdot P^{\text{l}} \tag{A.8}$$

where APT_i = annual paid labor time for step i, and P^{l} = direct labor wages in US dollars per hour including benefits.

A.1.1.2. Fixed costs. A key element of any cost forecast is the method used to allocate non-uniform cash flows to appropriate activities, here the production cost of a specific component. In both the component and assembly models, costs are assumed to be distributed evenly in time over the usable lifetime of a resource for those cash flows with periodicity longer than one year (e.g., equipment investments). The opportunity cost associated with tying up these funds in this long-term investment is incorporated using a standard capital recovery factor (see Eq. (A.9)) [22]

$$R_{\text{El}} = I_{\text{El}} \frac{[d(1+d)^{s_{\text{El}}}]}{[(1+d)^{s_{\text{El}}} - 1]} \quad \forall \text{El} \in \mathbb{Z} \tag{A.9}$$

where $\mathbb{Z}$ = {Tool, Equipment, Building}, R = the allocated cost for a defined period (here, one year), I = the non-periodic investment to be allocated, d = the periodic discount rate (here, $d = 10\%$), s = the number of periods over which is investment is distributed (here, $s_{\text{Tool}} = 3$, $s_{\text{Equipment}} = 10$, and $s_{\text{Building}} = 25$).

Along with each machine's direct cost, in the case of the component model, an input is provided to establish whether

the machine is (a) dedicated to the production of the product being analyzed or (b) shared across other products. In the latter case, following the approach of time-based allocation, investment expense is apportioned according to the fraction of equipment available time which is dedicated to the manufacture of the component of interest. In the component model, capital costs are calculated for each element as follows:

$$\mathrm{AC_{El}} = \mathrm{AC_{El,ded}} + \mathrm{AC_{El,nonded}} \quad \forall \mathrm{El} \in \mathbb{Z} \tag{A.10}$$

For the purposes of this study, all equipment not used by the current product is assumed to be shared with other products. Annual capital costs for this non-dedicated equipment are calculated as follow:

$$\mathrm{AC_{El,nonded}} = \sum_i (R_{\mathrm{El},i} * \mathrm{LR}_i) \quad \forall i \in \{\text{non-dedicated}\} \tag{A.11}$$

where {non-dedicated} = the set of all steps which have non-dedicated processes, {dedicated} = the set of all steps which have dedicated processes, and LR_i is the ratio of required operating time to effective available operating time at step i, as shown in the next section.

A.1.1.3. Operating time. The time required for a given process step is a key determinant of many process costs, including labor, energy, and capital requirements. Three quantities of time are tracked within any process-based cost model: (1) the amount of time that a particular resource (machine, labor, etc.) is required – *required line time*, (2) the amount of time that a unit of that resource is available in a given year – *available line time* and (3) the amount of time that a laborer would be paid for a full year, *annual paid labor time*. Annual paid labor time ($\mathrm{APT}_i^{\mathrm{l}}$), lines required ($\mathrm{LR}_i$), required line time ($\mathrm{reqLT}_i$), and available line time (availLT) are calculated as follows:

$$\mathrm{APT}_i^{\mathrm{l}} = \mathrm{DPY} \cdot (24 - \mathrm{NS} - \mathrm{UB}) \cdot \mathrm{WPL}_i^{\mathrm{l}} \cdot \mathrm{LR}_i \tag{A.12}$$

$$\mathrm{LR}_i = \frac{\mathrm{reqLT}_i}{\mathrm{availLT}} \tag{A.13}$$

$$\mathrm{reqLT}_i = \mathrm{cycT}_i + \mathrm{suT}_i \tag{A.14}$$

$$\mathrm{availLT} = \mathrm{DPY} \cdot (24 - \mathrm{NS} - \mathrm{UB} - \mathrm{PB} - \mathrm{UD}) \tag{A.15}$$

where DPY = operating days per year, NS = no operations (h/day the plant is closed), UB = unpaid breaks (h/day), $\mathrm{WPL}_i^{\mathrm{l}}$ = fractional labor assigned to step i, cycT_i = operating cycle time of i per part, suT_i = setup time of process i per part, PB = paid breaks (h/day), and UD = unplanned downtime (h/day).

A.1.2. Assembly model

In the assembly model, the 17 components produced in the components model are assembled into the body-in-white. Thus, in the case of the assembly model, $c \in$ {body-in-white}, and the total unit cost per body-in-white can be calculated as follows:

$$C_{\mathrm{Assembly}} = \sum_{\mathrm{El}} C_{\mathrm{Assembly,El}} \tag{A.16}$$

$$C_{\mathrm{Assembly,El}} = \frac{\mathrm{AC_{Assembly,El}}}{\mathrm{PV}} \tag{A.17}$$

Process-based cost modeling of assembly processes follows the same basic principles as process-based cost model of components, with a several important exceptions. First, unlike parts production, assembly involves the combination of several dissimilar activities to generate an end product. The order, combination, and intensity of these assembly activities may vary completely from one design to another. For example, one vehicle body design may be assembled using rivets and adhesive; a second may use spot and continuous welding; a third design might require all four. Second, standard practice in automotive assembly plants is to accommodate higher production volumes through in-series (rather than in-parallel) distribution of work. As an example, consider the assembly of several components. This assembly requires 2 min of welding, and occurs in a facility with output rate targets of one assembly per minute. To achieve this target, current practice in an auto assembly plant is to place two work stations in-series, each conducting approximately one minute's worth of welding. This approach is in contrast to the approach more common in component production, in which two stations would be placed in-parallel each executing the full two-minute weld. Finally, a particularly challenging characteristic of assembly are the utilization inefficiencies which arise due to the precedence requirements of assembling a complex physical object. For example, while an operator may have enough time to complete additional welds, actual welds executed at a work station may be limited by the number of components which can be accessibly fixtured at that stage of assembly. The consequences of these differences for the architecture of the assembly model are described in the following equations.

One of the most important variables in the assembly model is the rate (Rate) of the line. This rate is calculated by taking the desired annual production volume (PV) and dividing it by the available line time (availLT)

$$\mathrm{Rate} = \mathrm{PV}/\mathrm{availLT} \tag{A.18}$$

Here, the available line time is calculated the same way as described in Section A.1.1.3 on component modeling. The input for the annual production volume is the same as in the component model. The inputs for operating days per year (DPY), hours per day the plant is closed (NS), unpaid breaks (UB), paid breaks (PB), and Unplanned downtime (UD) are specific to the assembly model. The rate is calculated in units of body-in-whites per hour. The time available for work at each station (ST) is then simply the inverse of the rate. Units for this value are usually converted into seconds.

$$ST = \mathrm{Rate}^{-1} \tag{A.19}$$

In the assembly model, equipment required to produce at a particular rate are calculated as a function of the station time (ST) and the required join time for a particular subassembly ($\mathrm{reqJT}_{\mathrm{sa},b}$). The amount of equipment and the number of stations required for each subassembly – E_{sa} and S_{sa}, respectively – are calculated as follows:

$$E_{\mathrm{sa}} = \sum_b \mathrm{reqE}_{\mathrm{sa},b} \tag{A.20}$$

$$\mathrm{reqE}_{\mathrm{sa},b} = \begin{cases} \mathrm{reqJT}_{\mathrm{sa},b}/ST, & b \in \{\mathrm{soft}\} \\ \frac{\mathrm{Joins}_{\mathrm{sa},b}}{\mathrm{Joins}_{\mathrm{max},b}}, & b \in \{\mathrm{hard}\} \end{cases} \tag{A.21}$$

$$S_{\mathrm{sa}} = \sum_b s_{\mathrm{sa},b} \tag{A.22}$$

$$s_{\mathrm{sa},b} = \mathrm{reqE}_{\mathrm{sa},b}/\max E_{\mathrm{station},b} \tag{A.23}$$

Here, b represents the method, $s_{\mathrm{sa},b}$ represents the number of stations required by a particular method for a particular subassembly, and $\mathrm{reqE}_{\mathrm{sa},b}$ represents the amount of equipment required by a particular method to complete a particular subassembly. There are two different types of methods. 'Soft' methods, like hand welding, can be split up into any number of stations, depending on what is most suited for the available station time. 'Hard' methods use a single piece of equipment that is only able to do a set number of attachments or joins. Although a 'hard' method piece of equipment can be under-utilized at a given station, its capabilities can not be split across stations. Thus, in the above equations, $\mathrm{reqJT}_{\mathrm{sa},b}$ represents the join time required of a particular soft method for a particular subassembly, $\mathrm{Joins}_{\mathrm{sa},b}$ represents the number of joins required of a particular hard method for a particular subassembly.

As a consequence of these differences in model architecture, there are several key differences in the calculation of annual costs.

A.1.2.1. Variable costs. This section discussed the calculation of the variable cost elements in the assembly model. Similar to the component model, material costs are based on material usage rates. In the case of the assembly model, these material usage rates are calculated for each method in each subassembly based on part geometries. The annual cost of materials in the assembly model is calculated as follows:

$$\mathrm{AC}_{\mathrm{Assembly,Material}} = \sum_m \sum_b \sum_{\mathrm{sa}} U^m_{b,\mathrm{sa}} \cdot PV \cdot P^m \tag{A.24}$$

where b = method, sa = subassembly, m = material type, P^m = unit price of material m, and $U^m_{b,\mathrm{sa}}$ = unit usage of material m for a method b in subassembly sa.

Similar to the components model, energy costs in the assembly model are based on user-specified energy consumption rates for each machine (EI_E). Energy consumption values are estimated for each process according to equipment requirements, leading to annual energy costs calculated as

$$\mathrm{AC}_{\mathrm{Energy}} = \sum_b \sum_{\mathrm{sa}} \mathrm{reqE}_{\mathrm{sa},b} \cdot \mathrm{EI}_E \tag{A.25}$$

where EI_i = energy intensity of step i in kiloWatts (kW).

The annual cost of labor is computed as described below:

$$\mathrm{AC}_{\mathrm{Labor}} = \mathrm{APT}^{\mathrm{dl}}_i \cdot P^{\mathrm{dl}} + \mathrm{APT}^{\mathrm{il}}_i \cdot P^{\mathrm{il}} \tag{A.26}$$

where $\mathrm{APT}^{\mathrm{dl}}$ = annual paid direct labor time, $\mathrm{APT}^{\mathrm{dl}}$ = annual paid indirect labor time, and P^{l} = direct labor wages in US dollars per hour including benefits. Here, the annual paid labor time for each station is calculated differently than in the component model. In the assembly model, annual paid labor time is calculated as follows:

$$\mathrm{APT}^{\mathrm{dl}} = \mathrm{DPY} \cdot (24 - \mathrm{NS} - \mathrm{UB}) \cdot \sum_b \sum_{\mathrm{sa}} (\mathrm{dl}_b * s_{sa,b}) \tag{A.27}$$

$$\mathrm{APT}^{\mathrm{il}} = \mathrm{DPY} \cdot (24 - \mathrm{NS} - \mathrm{UB}) \cdot \sum_b \sum_{\mathrm{sa}} (\mathrm{il}_b * s_{\mathrm{sa},b}) \tag{A.28}$$

where dl_b = fractional labor required per station for method b, il_b = fractional indirect labor required per station for method b, $\mathrm{s}_{\mathrm{sa},b}$ represents the number of stations required by a particular method for a particular subassembly, DPY is operating days per year, NS is 'no operations' (h/day the plant is closed), and UB is unpaid breaks (h/day).

A.1.2.2. Fixed costs. A detailed discussion of how the assembly model calculates equipment requirements is described in the beginning of Section A.1.2. Building on these equipment requirements, capital costs are calculated for each fixed cost element as follows:

$$I_{\mathrm{Equipment}} = \sum_{\mathrm{sa}} E_{\mathrm{sa}} \tag{A.29}$$

$$I_{\mathrm{Tool}} = \sum_{\mathrm{sa}} \sum_b (\mathrm{reqE}^*_{\mathrm{sa},b} T_b) \tag{A.30}$$

$$I_{\mathrm{Building}} = \sum_{\mathrm{sa}} \sum_b (s^*_{\mathrm{sa},b} B_b) \tag{A.31}$$

Annual costs for each element in the assembly model are then calculated according to the following equation:

$$\mathrm{AC}_{\mathrm{El}} = R_{\mathrm{El}} \quad \forall \mathrm{El} \in \mathbb{Z} \tag{A.32}$$

Additional details on the architecture of the assembly model can be found in two unpublished masters theses by Harsha Marti and Anil Jain (reference).

Appendix 2

	1 Body side Inner	2 Body side Outer	3 Dash Panel & Firewall	4 Front floor	5 Front header	6 Front lower rail	7 Shock towers	8 Front wheel arch	9 UDP	10 Radiator panel	11 Rear floor	12 Rear header	13 Rear quarter	14 Roof	15 Parcel shelf, seat back	16 BCA	18 RWA
GENERAL																	
Part Count	2	2	1	1	1	2	2	2	1	1	1	1	2	1	1	2	2
Max Part Length (m)	3.30	3.30	1.40	1.54	1.19	1.23	0.16	1.09	1.54	0.96	1.08	1.18	1.29	1.40	1.07	2.11	0.0135
Max Part Width (m)	1.20	1.20	0.66	1.40	0.12	0.10	0.23	0.52	0.52	0.42	1.40	0.14	0.90	1.22	1.67	0.27	0.37
Carbon Reinf. Average Thickness (m)	0.0035	0.0032	0.0023	0.0025	0.0019	0.0027	0.0021	0.0032	0.0052	0.0018	0.0019	0.0018	0.0004	0.0010	0.0018	0.0012	0.0032
Glass Reinf. Average Thickness (m)	0.0050	0.0046	0.0034	0.0036	0.0028	0.0038	0.0031	0.0046	0.0075	0.0026	0.0027	0.0026	0.0006	0.0015	0.0026	0.0018	0.0046
Surface Area (m^2)	1.42	2.23	1.48	2.52	0.20	0.34	0.18	0.56	0.28	0.49	3.00	0.25	3.29	3.29	1.84	0.32	0.69
Projected Area (m^2)	1.28	2.00	0.74	2.27	0.18	0.24	0.09	0.39	0.14	0.34	2.10	0.18	1.65	2.96	0.92	0.22	0.49
Carbon Reinf. Total Weight (kg)	6.03	8.80	4.26	7.73	0.48	1.13	0.48	2.19	1.76	1.07	6.87	0.56	1.60	4.09	4.07	0.48	2.702
Glass Reinf Total Weight (kg)	10.55	15.40	7.45	13.54	0.84	1.97	0.84	3.83	3.09	1.86	12.02	0.98	2.79	7.16	7.12	0.84	4.73
Chopped (1=yes, 0=no)	1	1	1	0	1	0	1	1	1	1	0	1	1	0	1	1	1
Fabric (1=yes, 0=no)	0	0	0	1	0	1	0	0	0	0	1	0	0	1	0	0	0
Perimeter (m)	7.19	7.17	4.65	9.13	2.72	0.25	0.59	1.59	4.11	2.95	6.13	2.80	3.29	6.16	7.17	4.41	
PREFORM																	
P4 Process (Y/N)	Y	Y															
# Preforms	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Preform Weight (kg)	6.20	9.06	4.38	7.96	0.49	1.16	0.49	2.25	1.81	1.10	7.07	0.58	1.64	4.21	4.19	0.49	2.78
Max Preform Length (m)	3.30	3.30	1.40	1.54	1.19	1.23	0.00	1.09	1.54	0.96	1.08	1.18	0.00	1.40	1.07	2.11	0.01
Max Preform Width (m)	1.20	1.20	0.66	1.40	0.12	0.10	0.00	0.52	0.52	0.42	1.40	0.14	0.00	1.22	1.67	0.27	0.37
Avg Preform Thickness (m)	0.0050	0.0046	0.0034	0.0036	0.0028	0.0038	0.0031	0.0046	0.0075	0.0026	0.0027	0.0026	0.0006	0.0015	0.0026	0.0018	0.0046
Core (Y=1, N=0)	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0
Core Thickness (m)	0	0	0	0.005	0	0	0	0	0	0	0.005	0	0	0.003	0	0	0
Surface Area (w/o cutout) (m^2)	1.42	2.23	1.48	2.52	0.20	0.34	0.18	0.56	0.28	0.49	3.00	0.25	3.29	3.29	1.84	0.32	0.69
Projected Area (m^2)	1.28	2.00	0.74	2.27	0.18	0.24	0.09	0.39	0.14	0.34	2.10	0.18	1.65	2.96	0.92	0.22	0.49
# of Plies	1	1	1	5	1	5	1	1	1	1	4	1	1	2	1	1	1
Mix Head Injection Pressure (psi/MPa)	1100 / 7.6																
Injection Stage Pressure (psi / MPa)	200 / 1.4																
Compression Stage Pressure (psi/Mpa)	650 / 4.5																
MATERIAL																	
Resin Type	Bayer Chemical Company's Baydur 420 IMR. 2-component urethane system composed of Part A based on diphenylmethane diisocyanate and Part B, a polyol																
Resin Catalysts	Isocyanate-polyol																
PROCESS: # dispensers	4	4	2	2	1	1	1	1	1	1	4	1	1	1	2	1	1

Abbreviated Parts: UDP = Unified Upper Dash Panel, Plenum, and Cowl Panel; RWA = Unified Rear Wheel Arch and Rear Lower Longitude; BCA = Unified Bodyside Cap and A-Pillar Closeout

Appendix 3

See Tables A.1 and A.2.

Table A.1
Alternate pre-form making systems

	Spray system: two-robot	Spray system: Carousel	Lay-up system
Equipment	$1.6 M; two robots, two molds, automated robot inputs from cad, molds stationary, robot moves	$1.6 M; robot, six molds, automated robot inputs from cad, automated shuttling	Cutting table (wheel cutter, computer, and vacuum system): $150 K
Tools	$80–150 K, $78 K for i. & o. pillar	$80–150 K	"Conformers": $500 ea., last 5000 cycles
Labor	0, 1, or 2 workers depending on part size & on automation	0, 1, or 2 workers depending on part size & on automation	2 workers
Cycle time	3 min 5 s + (pre-form weight/chopper gun rate)	3 min 5 sec + (pre-form weight/chopper gun rate)	2 1/2 min

Table A.2
Fixture and equipment investments, based on final modeled assembly order (Fig. 1B)

Scale	Curing system Cost	Fixture cost	Total cost
Small	$100–200 K	$100–250 K	$200–$450 K
Medium	$200–250 K	$400 K	$600–650 K
Large	$250–275 K	$750–$900 K	$1.025–$1.15 M

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