Plastic Cars in China? The Significance of Production Location over Markets for Technology Competitiveness

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Plastic Cars in China? The Significance of Production Location over Markets for Technology Competitiveness

This paper provides insights into (1) the impact of production location on design competitiveness and (2) the tension between product customization for regional production and for product customization for regional markets. The results show that as production and demand for automobiles shifts to emerging economies, and in particular to China, there may be a shift in the technologies that are competitive. Specifically, contrary to conventional wisdom, innovative new polymer composite vehicle bodies – a critical energy-savings technology – are less cost-competitive in China than in the United States. Production characteristics are different abroad, and the prevailing steel body technology is more cost-competitive in China. Further, while national differences in market characteristics improve the competitiveness of the composite design in China, this advantage is far outweighed by the above-discussed penalty from differences in production. These results suggest that in cases such as automobile bodies where markets and manufacturing location are tightly coupled, firms may need to put as much or more emphasis on understanding the impact of local production differences on technology competitiveness as in understanding local markets.

Key words: international, product development, design for manufacturing, automobile

1. Introduction: Location and Technology Competitiveness

   Today only 64% of car production occurs within developed countries, and only 9% in the U.S. While this figure steadily declines, the percentage of automobile production in developing countries continues to grow – particularly in China (Ward's, 2006a). During the 1990s alone the average annual growth in passenger car production in China was 27% (Gallagher, 2006). While the existing design literature acknowledges that there exist global differences in consumer preferences and that a global strategy must address these differences (Abdalla, 1999; Swan et al.,
2005), there is surprisingly little literature on global differences in manufacturing, and how such differences should influence technology and operations strategy. A long history of engineering and management research has explored how manufacturing considerations should be incorporated into product development through methods known as “Design for Manufacturing and Assembly” (Boothroyd et al., 2002). Precisely the variables most influential in these methods – e.g. yield, downtimes, material costs, scrap rates, etc. – are those that change when manufacturing is moved to a developing country. Further, in cases such as automobile bodies, markets and manufacturing are coupled – i.e. production occurs regionally for regional markets (Carillo, 2004). Thus, manufacturing location influences both production costs and the target market. These facts beg an answer to how production location should influence early-stage design decisions and what tensions may exist in optimizing technology to meet local production characteristics versus local markets.

This paper uses a combination of simulation modeling and empirical data to show the impact of manufacturing in the U.S. versus China on the relative competitiveness of two body designs – one emerging and one prevailing – in the automotive industry. The paper leverages detailed data on manufacturing processes from the three major U.S. automotive manufacturers and their suppliers, and how these processes differ between the U.S. and China. Using three simulation models – one of composite auto body component manufacturing, one of steel auto body component manufacturing, and one of auto body component assembly – the paper then demonstrates how these differences in processes between the U.S. and China affect the relative competitiveness of the two designs. Finally, the paper maps the results onto actual production data in each country to show the percentage of vehicles competitive with each design.

The results show that the relative competitiveness of the emerging composite design shifts
when production is performed in China instead of the United States. Specifically, while the composite design is more cost-competitive for annual model production volumes of 104,000 or less with U.S. production, the composite design is only competitive for annual model production volumes of 68,000 or less in China. While market-based differences – specifically, lower annual production volumes per car model – in China help the case for composites in China, this help is insufficient to compensate for the disadvantages incurred by national differences in production. Specifically, 29% of cars produced in the U.S. in 2006 would be cheaper if produced out of composites, while only 14% of cars produced in China during that period would be cheaper if produced out of composites. These results are contrary to conventional wisdom, which suggests that the high-labor, low-capital nature of composites should make them more competitive in the low-wage, low-production volume environments of developing countries.

2. Previous Work: Rethinking Design for Manufacturing

The idea that management practices may need to differ with regional and national contexts has a long history in the international business literature (Ricart et al., 2004), with some arguing that it is actually the focus of the field (Ghemawat, 2003). Traditional management science disciplines, however, have been slow to embrace the importance of international context. It wasn’t until 1994 that a special issue of Management Science focused on the question, “Is Management Science International?: In Search of Universal Rules” (Aharoni and Burton, 1994). The special issue editors conclude that good management practices do vary across borders and cultures (Aharoni and Burton, 1994). The literature differs, however, on how to deal with locational specificity, ranging from those who argue for adapting generalizable models (Rosenzweig, 1994; Whybark, 1997) to those who expect an entirely new approach (Starr, 1997).

Despite these conclusions emphasizing the importance of locational specificity in operations, a
review of the management science literature reveals surprisingly little research on global manufacturing practices, particularly in developing countries. A 2001 review article finds only 91 articles between 1986 to 1997 on the topic of international operations management, with only seven examining emerging economies (Prasad, 2001). A search of the literature in the ten-year period since this review reveals similarly surprising results. The existing empirical articles on production differences across countries provide an important glimpse into how operations variables can differ by region. Important examples for developed nations include the work on the Japanese Production System (Ohno 1988; Womack 1990), and three edited books based on global surveys of manufacturing practices in developed countries (Ohno, 1988; Womack et al., 1990; Whybark and Vastag, 1993; Bolisani and Scarso, 1996; Lindberg et al., 1998; Schroeder and Flynn, 2001), all of which emphasize the influence of cultural differences. The few empirical studies on production differences in developing countries provide critical insights into how design for manufacture and assembly variables differ in these contexts. For example, studies on Mexican Maquiladoras find them to have better final product quality, less scrap, lower labor costs, and increased productivity over their U.S. counterparts (Prasad et al., 1995). In Brazil, Lindberg et al. (1998) find plants to have narrower product lines, longer lead times, and higher raw material inventories than other countries globally (Lindberg et al., 1998). In Korea, Kim (1997) shows semiconductor plants to lag in development and shipment time (Kim, 1997). Finally, Terwiesch et al. provide data on yields, downtimes, and tact times experienced by a company during product transfer from the U.S. to a same-company facility in South-East Asia (Terwiesch et al., 1999). None of these studies, however, explore how these differences in production variable inputs translate into differences in the most competitive design.

The process of including manufacturing cost considerations into the design of products is well-
known in the product development literature, specifically as Design for Manufacturing and Design for Assembly (Boothroyd et al., 2002). Key variables determining the cost of manufacturing a design include labor, materials, tooling, cycle time, yields, downtime, and overhead (Ostwald and McLaren, 2004). To help simplify engineers’ calculations involving these variables, design textbooks typically provide cost tables or functions to be applied in design decision-making (Michaels and Wood, 1989; Pahl and Beitz, 1996). Research has also established rules of thumb for manufacturing costs (Ashby, 1999). Such methods have been expanded to Design for ‘X’ (DFX) strategies, where X can represent a variety of considerations such as the environment or intended markets (Gatenby, 1988; Keys, 1990; Taylor, 1992). One subset of DFX strategies, known as Design for the Existing Environment (DFEE) attempt to optimize multiple objectives, including process selection, production capacity, product mix, and market timing (Taylor, 1997). There has, however, been only a limited amount of research on how global diversity in markets and manufacturing environments should influence design. Daci and Verter present an approach for simultaneous optimization of plant location, capacity, and process technology decisions (Dasci and Verter, 2001). Likewise, Taylor et al. present a mathematical tool to identify the facility for a new product that minimizes design, inventory, logistics, and process costs (Taylor et al., 1994). Finally, a few DFX articles look at how to incorporate global market diversity into global product design decisions (Abdalla, 1999; Swan et al., 2005). However, despite the origins of the DFX literature, systemic, empirically-grounded research has been lacking on how location-specific differences in operational characteristics may change the cost-optimal design. This paper addresses this issue.

3. Industry Background

3.1. The Confluence of Two Trends in the Global Automotive Industry

Regulatory constraints on energy consumption have influenced vehicle development for over
three decades (Lee, 2007). With recent rises in oil prices and the increased prominence of global warming and other environmental concerns, technological advances to improve vehicle efficiency are becoming increasingly important to competitiveness in the global automobile market (Visnic, 2004; Fuyuno, 2005; Truett, 2005; Kelly, 2007). Globally, motor vehicles constitute one third of total oil consumption and are the number one source of air pollution (Davis, 2004). In the U.S., the impacts are far greater, with motor vehicles contributing to two thirds of oil consumption and 60% (80% in cities) of air pollution (Davis, 2004). As can be seen in Figure 1a, in addition to environmental concerns, the security implications are significant. In the past 50 years, the U.S. has gone from importing 0% to importing 70% of the oil it consumes.

At the same time as concerns about oil use are growing, the vehicle market is evolving rapidly. While vehicle ownership rates in developed countries are nearly static, individuals within transitional economies are rapidly acquiring personal transportation. Of all markets, the one with the largest growth rate and potential is China. Chinese car ownership has had an average annual growth rate of 17% over the past decade. (See Figure 1b.) Currently, with 20% of the world’s population, China only owns 1.5% of the world’s cars (Gallagher, 2006). Even though sales in China are currently small, forecasts expect Chinese annual light vehicle sales to exceed sales in

Figure 1: a) Growth in U.S. Dependency on Foreign Oil (Davis, 2004); b) Growth in Chinese Passenger Car Ownership (Source: (Ward’s, 2006c))
the U.S. by 2015 (IBM, 2005). Understanding how to design competitive automobile products for this rapidly growing market will be critical to not only to the sustainability of global car companies, but also to those regions national security, and to the global environment.

3.2. Improving Vehicle Efficiency with Polymer Composites

One key technical design strategy for improving vehicle efficiency is the reduction of vehicle mass, or light-weighting. Lightweight 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 car body-in-white. A standard body-in-white on the road today is made of steel and contributes 20-25% of the total curb weight of a car. Given the mass-efficiency of current body design architectures (Sawyer, 2003), the primary mechanism available for further reducing the weight of the body-in-white is the use of alternative materials. One option for such material substitution is fiber-reinforced polymer composites (FRPCs).

A primary advantage of FRPCs is their superior strength-to-stiffness ratio. This material property advantage can lead to a 60-65% reduction in vehicle weight, depending on whether glass-fiber or carbon-fiber reinforcement is used. This light-weighting has direct advantages for fuel economy and emissions reduction. It can also be leveraged to improve driving performance, compensate for the additional weight of advanced electronics, or compensate for the lower power or additional weight of alternative power trains. The material properties of FRPCs also provide additional design flexibility over steel – both in appearance (part shape) and performance (part functionality). Finally, the production process used by polymer composites is less capital intensive than steel, allowing for greater competitiveness at low production volumes.

There are also several disadvantages to using FRPCs in vehicle bodies. Automobile manufacturers currently lack design and production experience with FRPCs. Building a
polymer-composite body production plant would also require new capital investment. From a market perspective, the public currently has a poor perception of the crashworthiness of FRPC – aka “plastic” – vehicles. The less glossy appearance of composite body components (i.e., without additional finishing corrections), is also generally not well-received. Finally, additional difficulties may exist for the repair, replacement and recycling of composite components.

3.3. The Case for Polymer Composite Vehicles Bodies in China

Given the long-term trends in the global automotive industry, and the pros and cons of polymer composites in the U.S. market, producing a polymer composite vehicle in China for the Chinese market has repeatedly tempted automobile manufacturers as an obvious choice. Conventional wisdom suggests that low-capital high-labor intensive processes are well-suited to developing country production economics. The lower investment required for a composite production facility also reduces risk for the manufacturer. Developing country consumers may provide a more forgiving market with regard to appearance. Finally, investment greenfields, such as exist in China, can provide an interesting opportunity to experiment with new technologies.

Building on this logic, both General Motors and Daimler Chrysler have in recent years engaged in initiatives to manufacture automobiles with glass-fiber reinforced composite bodies in China for the Chinese market (see Figure 2.) After significant time and investment, however, the firms pulled out of these initiatives – Daimler Chrysler temporarily halting investment in China, and General Motors choosing to produce a standard steel body. While the composite technology was blamed, in actuality, the firms found they misjudged consumer preferences, and as a consequence developed a design with little demand. Since the initiatives were aborted before production, the firms continue not to know the cost of producing a composite body-in-white in China, and thus whether their original logic may, with a different design, be economically viable. This paper addresses whether the firms’ original logic is actually correct.
Recent advances in simulation modeling have enabled significant experimentation, and hence time savings and cost-reduction, prior to investment (Thomke, 2003). Among these modeling techniques, a spattering of papers discuss methods to aid production cost estimation during early stages of design (Ong, 1995; Ou-Yang and Lin, 1997; Rehman and Guenov, 1998; Asiedu et al., 2000; Layer et al., 2002; LaTrobe-Bateman and Wild, 2003). These efforts come primarily out of engineering disciplines, are often problem-focused, and, as a consequence, frequently do not reference one-another. This lack of cross-referencing prevents discourse on the appropriate assumptions for such work. This paper moves beyond these previous models (1) by providing a transparent description of the mathematical relationships in the underlying models, and (2) by developing and validating the models using real-world empirical data. The engineering costing method built upon in this paper is a pioneer of such engineering costing methods – process-based cost modeling (PBCM). PBCM was developed for analyzing the economics of emerging manufacturing processes (Busch and F.R., 1988). The modeling has been extended to show the implications of alternative design specifications and process operating conditions on production costs, within and across manufacturing processes (Kirchain and Field, 2000).

To forecast the total cost of manufacturing a composite body-in-white, this study uses two PBCM – a component PBCM and an assembly PBCM. The authors first developed these models...
to perform a detailed analysis of the competitiveness of a composite body-in-white assuming a U.S.-based manufacturing environment (Fuchs, 2008). This paper extends the work in (Fuchs, 2008) to address the implications of production location on the relative competitiveness of technology alternatives. To achieve this goal, the authors identified a set of factors that would lead production costs for identical technologies to differ across two regions. They mapped each factor to the set of potential model variables that would be affected. (See Table 1.) The first author then collected empirical data for both regions on all variables in the models (see Appendix 1), to observe empirically which variables (starred in Table 1) differed by region. We reproduce the full mathematical description of the models from (Fuchs, 2008) in Appendix 1.

The variable assignments in Table 1 match the variables in Appendix 1. To emphasize the impact of these region-specific variables, we mark them in bold in the Appendix.

**Table 1: Region-Specific Factor Inputs Affecting Process-Based Cost Model Variables**

<table>
<thead>
<tr>
<th>Region-Specific Factor Inputs</th>
<th>Potential Affected Model Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Labor</strong></td>
<td></td>
</tr>
<tr>
<td>Wage</td>
<td><em>Wage (P</em>)</td>
</tr>
<tr>
<td>Skill</td>
<td>*Downtime (UD), *yield (Y), scrap, *cycle time <em>(cycT+suT)</em></td>
</tr>
<tr>
<td>Experience</td>
<td>Initial investment, labor availability</td>
</tr>
<tr>
<td>Absenteeism</td>
<td>Fixed versus variable labor costs, “buffer labor” factor = number of laborers multiplied by (1 - absentee rate)</td>
</tr>
<tr>
<td><strong>Raw Materials</strong></td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td><em>Buying price (P</em>), cost of transport, tariffs/fees</td>
</tr>
<tr>
<td>Quality</td>
<td>*Yield (Y), scrap, line rate, design change requirements (thicker, etc.)</td>
</tr>
<tr>
<td>Reliability</td>
<td>Inventory, back-up supplier, *yield (Y)</td>
</tr>
<tr>
<td><strong>Electricity</strong></td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td><em>Price per kWhr (P</em>)</td>
</tr>
<tr>
<td>Reliability/availability</td>
<td>*Downtime (UD), capital (industrial boiler, etc.)</td>
</tr>
<tr>
<td><strong>Real Estate</strong></td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>*Price per sq. m (R_{Building})</td>
</tr>
<tr>
<td><strong>Components (Source)</strong></td>
<td></td>
</tr>
<tr>
<td>Imported from supplier</td>
<td>Transportation cost</td>
</tr>
<tr>
<td>Imported from OEM’s production Facilities</td>
<td>Transportation cost</td>
</tr>
<tr>
<td>Produced by local firm w/ OEM oversight (or) Produced locally by an OEM.</td>
<td>Transportation cost, investment for oversight functions, *yield (Y), scrap, line rate</td>
</tr>
<tr>
<td><strong>Capital (Source)</strong></td>
<td></td>
</tr>
<tr>
<td>Discount rate</td>
<td>*Discount rate (d)</td>
</tr>
<tr>
<td>Imported from supplier</td>
<td>Transportation costs</td>
</tr>
<tr>
<td>Produced by local firm w/ OEM Oversight</td>
<td>Transportation costs, investment for oversight functions, *yield (Y), scrap, *downtime (PD+UD)</td>
</tr>
</tbody>
</table>
3.4.1. Design Selection: The Automotive Composite Consortium Focal Project III

This study compares the economic viability of two automobile body designs – a glass fiber reinforced composite unibody (the “emerging design”) and a steel unibody (the “prevailing design”). The glass-fiber reinforced design is a derivative of the Automotive Composites Consortium’s (ACC) Focal Project III. The ACC was formed in August 1988 as a collaborative effort of Ford, General Motors and Chrysler. The goal of the Focal Project III was to design a structurally-sound, cost-competitive body-in-white with minimum mass for medium to high production volumes. Although the original ACC design uses carbon-fiber reinforcement, the authors’ previous U.S.-focused study, however, showed a glass-fiber reinforced version to be economically superior (Fuchs, 2008). The glass-fiber reinforced design also has the same basic production cost-structure as the carbon-fiber reinforced design. This paper therefore focuses on only comparing the glass-FRPC design against steel in the U.S. versus China. A detailed comparison of the two designs is provided in Table 2.

Table 2: Comparison of Glass-Reinforced Polymer Composite vs. Steel Unibody Designs

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Emerging Design: Glass Fiber Composite</th>
<th>Prevailing Design: Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelbase (cm)</td>
<td>274.3</td>
<td>261.6</td>
</tr>
<tr>
<td>Length x Width (cm)</td>
<td>472.4 x 180.3</td>
<td>469.9 x 170.2</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>137.2</td>
<td>144.8</td>
</tr>
<tr>
<td>Components</td>
<td>25</td>
<td>120</td>
</tr>
<tr>
<td>Inserts</td>
<td>37</td>
<td>130</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Composition</th>
<th>Emerging Design: Glass Fiber Composite</th>
<th>Prevailing Design: Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary material</td>
<td>Two-component polyurethane</td>
<td>Mild-Grade Steel</td>
</tr>
<tr>
<td>Brand</td>
<td>Bayer AG’s Baydur 420</td>
<td>Varies</td>
</tr>
<tr>
<td>Price ($/kg)</td>
<td>$2.65</td>
<td>$0.77</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>Glass Fiber</td>
<td>NA</td>
</tr>
<tr>
<td>Spray Price ($/kg)</td>
<td>$2.53</td>
<td>NA</td>
</tr>
<tr>
<td>Lay-up Brand</td>
<td>Owens Corning F2 Matt</td>
<td>NA</td>
</tr>
<tr>
<td>Lay-up Price ($/kg)</td>
<td>$3.08</td>
<td>NA</td>
</tr>
<tr>
<td>Resin: Reinforcement</td>
<td>65:35 vol%, 41:59 wt%</td>
<td>NA</td>
</tr>
<tr>
<td>Inserts</td>
<td>Mild-Grade Steel</td>
<td>Mild-Grade Steel</td>
</tr>
<tr>
<td>Assembly Joining</td>
<td>Two-component adhesive</td>
<td>Spot Welding</td>
</tr>
<tr>
<td>Brand</td>
<td>SIA’s Plastilock 731Si</td>
<td>NA</td>
</tr>
<tr>
<td>Price</td>
<td>$17.50/kg</td>
<td>NA</td>
</tr>
</tbody>
</table>
3.4.2. Company Participation

The authors worked with all three of the ACC companies over the course of the project, although they had the most extensive interaction with one. The first author also collected processing data with potential material, equipment, and component suppliers. These companies included 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.

3.4.3. Process: Component Production and Assembly

Figure 3: (A) Process flow and duration for the steps within the Structural Reaction Injection Molding process; (B) Process flow for composite body assembly (Fuchs, 2008).

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 Figure 3A. The assembly steps are summarized in
Figure 3B. Additional details on these processing parameters can be found in (Fuchs, 2008).

### 3.4.4. Location-Specific Differences in Processing Characteristics

The authors obtained data on regional production differences from one of the three companies, and cross-checked this data with representatives from the other two firms. The authors focused on gathering empirical data on the production variable inputs in the two countries, and not on the underlying cause of any differences. Table 3 shows the results. The “i” in Table 3 represents the step of the component production or the station number in assembly. As shown in Figure 3, composite component production using structural reaction injection molding has four steps. The number of stations, and thus steps, in assembly varies with production volume.

**Table 3: Body-In-White Production Variable Differences in the U.S. versus China**  
Note: $R_i$, $S_i$, $K_i$, $M_i$, and $T_i$ are the average reject rate, scrap rate, machine costs, raw material costs, and tool costs, respectively. “i” represents each fabrication and assembly step for all i, {0,…,I}.  

<table>
<thead>
<tr>
<th>Body-In-White Production</th>
<th>U.S.</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Wages (w/ benefits)</td>
<td>$15.00/hr</td>
<td>$2.60/hr</td>
</tr>
<tr>
<td>Working Days / Year</td>
<td>240</td>
<td>360</td>
</tr>
<tr>
<td>Number of Shifts</td>
<td>3 x 8-hour shifts</td>
<td>2 x 12 hour shifts</td>
</tr>
<tr>
<td>Paid Breaks</td>
<td>1.2 hours / day</td>
<td>1.8 hours / day</td>
</tr>
<tr>
<td>Capital Recovery Rate</td>
<td>10%</td>
<td>16%</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>15%</td>
<td>10%</td>
</tr>
<tr>
<td>Price of Building Space</td>
<td>$1080 /m²</td>
<td>$150 /m²</td>
</tr>
<tr>
<td>Building Recovery Life</td>
<td>20 yr</td>
<td>10 yr</td>
</tr>
<tr>
<td>Average Downtime</td>
<td>20%</td>
<td>50%</td>
</tr>
<tr>
<td>Yield</td>
<td>$Y_i$</td>
<td>$Y_i + 3%$</td>
</tr>
<tr>
<td>Scrap Rate</td>
<td>$S_i$</td>
<td>$S_i + 1%$</td>
</tr>
<tr>
<td>Machine Costs</td>
<td>$K_i$</td>
<td>$K_i + 17.5%$ (shipping)</td>
</tr>
<tr>
<td>Raw Material Costs</td>
<td>$M_i$</td>
<td>$M_i - 30%$</td>
</tr>
<tr>
<td>Tool Costs (mask, fixtures)</td>
<td>$T_i$</td>
<td>$T_i - 50%$</td>
</tr>
<tr>
<td>Utilization</td>
<td>100%</td>
<td>50%</td>
</tr>
</tbody>
</table>

### 3.5. Results

#### 3.5.1. Process-Based Cost Modeling

In China, at annual production volumes below 68,000, the glass-reinforced BIW is the most cost-competitive option (see Figure 4). In the U.S., glass is the more cost-competitive alternative at production volumes under 104,000. As can be seen in Figure 4, the cost curve for production of a steel body in the U.S. is much steeper than cost curve for the steel body in the China.
Figure 4: U.S. versus P.R.C. Body-In-White Unit Cost Sensitivity to Annual Production Volume

The production cost drivers of each technology, shown in Figure 5, help explain these regional differences between the two technologies. While steel body-in-white production costs are dominated by equipment in China and by tooling in the U.S., composite body-in-white production costs are dominated by material in both China and the U.S.

Figure 5: Body-In-White P.R.C. and U.S. Production Cost Structure Breakdown at Annual Production Volumes of 100,000 Units
As can be seen in Figure 6, for both technologies, while assembly is cheaper in China than in the U.S., component production is cheaper in the U.S. than in China. Since assembly is a greater portion of overall steel production costs, steel gains greater cost advantages than composites from production in China.

![Figure 6: U.S. and P.R.C. Body-In-White Component and Insert versus Assembly Cost Sensitivity to Annual Production Volume](image)

Finally, as can be seen in Figure 7, as manufacturing capabilities in the P.R.C. improve and approach that of the U.S., if we assume wage differences for the short to immediate term remain the same, the composite design becomes competitive over an ever smaller set of annual production volumes. Here, “Current P.R.C. Conditions” represents the base case assumptions for the P.R.C. used throughout this paper. The “Conservative” and “Optimistic” assumptions
represent “what if” scenarios for more positive assumptions of processing capabilities in China, whether now or in the future.

![Figure 7: Sensitivity of P.R.C. Total Body-In-White Steel-Glass Cost Parity to Alternative Production Assumptions](image)

3.5.2. Market Results

Companies and academics commonly believe that the larger number of models produced at low-volumes in China would benefit the relative competitiveness of composite vehicles. While our results show this to be true, the difference in U.S. versus Chinese market distributions is not sufficient to outweigh the reduced production-cost competitiveness of composites in China.

Figure 8 below uses available data on 2005 North American Vehicle production and on 2004 P.R.C. vehicle production, to provide insights on how the composite versus steel production cost curves in the U.S. versus China map onto each country’s respective market. According to these results, 68% of models (29% of total cars) produced in the U.S. would have been cheaper if produced with a glass-fiber body-in-white unibody, and 42% of the models (14% of total cars) produced by multinationals in China in 2004 would have been cheaper if produced with a glass-fiber body-in-white. (See Figure 8 parts A and B, respectively.)
4. Analysis and Discussion

4.1. Design for Location: Debunking the Conventional Wisdom

There are several important take-aways from the results in the previous section. First, contrary to conventional wisdom the composite body-in-white production costs are cheaper than steel over a greater range of production volumes in the U.S. than in China. Specifically, composites
are cheaper than steel for annual production volumes of 104,000 units or less in the U.S. In contrast, composites are cheaper than steel at annual production volumes of 68,000 units or less in China. Second, true to popular belief, the larger number of low-volume production models in China does increase the viability of composites. However, this increase in the economic viability of composites due to differences in China’s market, is outweighed by the reduction in the economic viability of composites caused by differences in China’s production. As a consequence, a lower percentage of the models currently produced in China have annual production volumes such that they would be cheaper if produced out of composites. Given the annual vehicle production volume of each model, also a lower percentage of the total vehicles currently produced in China would be cheaper if produced instead out of composites. Indeed, while 29% of total vehicles produced and sold in the U.S. in 2006 would have been cheaper if produced out of composites, only 14% of total vehicles produced and sold in China during approximately the same time period would have been cheaper if produced out of composites. These results show that, contrary to conventional wisdom, emerging composites automobile unibodies are less economically competitive in China compared to in the U.S. Further, while previous research has focused on the importance of incorporating regional market differences into global product development, these results show that the impact of these regional market differences on technology viability can be outweighed by regional differences in production.

4.2. Potential for Polymer Composite Automobile Body Technology in China?

Despite these results showing composites for many annual production volumes to be less competitive when produced in China, a reasonable argument can be made for multinational automotive firms to still experiment with a polymer-composite body-in-white in China: (1) Automakers will most likely be forced to significantly improve the fuel economy of their vehicles in the upcoming few decades. (2) Although polymer composite body-in-whites are cheaper for a
smaller range of production volumes in the China than in the U.S., 42% of car models (14% of total vehicles) would still be cheaper if produced out of composites. (3) Automotive producers frequently misestimate demand by Chinese consumers for their new product. *Investment in a composite, rather than steel, production facility has the advantage of there being lower financial penalties for misjudging annual production volumes.* Specifically, the unit cost difference between the steel and composite body alternatives is large at low production volumes, but small at high production volumes. Although composites are more expensive than steel at production volumes over 68,000, at 250,000 units annually composites are only $260 more expensive per unit in China. In contrast, at annual production volumes of 20,000 units, steel is $950 per unit more expensive than composites when produced in China. Thus, with highly uncertain demand, there is less risk involved in choosing the composite than the steel investment. (4) *Given the right design, polymer composites may actually have advantages rather than disadvantages, in meeting Chinese consumer preferences.* The Chinese market is known for being prestige-oriented. The additional flexibility in design provided by polymer composites may thus be quite well suited to the fashion and status-conscious nature of the Chinese people.

4.3. **Towards a Generalizable Framework**

Automobile bodies represent a case of an emerging technology where production and market location are tightly coupled. In contrast to semiconductor or engine technologies, which are frequently manufactured in one location for the global market, automobile body components are generally produced and assembled regionally for regional markets (Carillo, 2004). Two factors contribute to this coupling of production and market location in the case of automobile bodies. First, automobile bodies and their components have high volume and mass, and, as a consequence, high transportation costs. Second, as can be seen in combining the shape of the cost curves in Figure 4 with the regional model production data in Figure 8, the minimum
efficient plant size for automobile bodies (~50,000 for composites and 100,000-200,000 for steel) is approximately the size of regional vehicle model markets. Based on these case-specific parameters, we suggest a broader framework for thinking about organizational footprint and technology decision-making in Figure 9. Here, transportation costs are all factors – including volume, weight, and shelf life – that influence the costs of transporting a good. We define the ratio of market size over minimum efficient plant size, in other words, the number of production facilities that can be supported by the market, as the “Market-Technology match.”

<table>
<thead>
<tr>
<th>Market-Technology Match</th>
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<tbody>
<tr>
<td>Low</td>
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<tr>
<td>Organizational Footprint</td>
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<tr>
<td>Technology Choice</td>
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<tr>
<td>High</td>
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<td>Organizational Footprint</td>
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<td>Technology Choice</td>
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**Figure 9:** The influence of product and process technology characteristics on organizational footprint and technology choice

5. Conclusions

Firms in the automotive industry today face two momentous trends – rising environmental and energy concerns and an enormous shift in the composition of global markets. Greatly affected by both of these trends is the design of the automobile body. Traditionally, when making global product development decisions, automotive firms have focused on how to leverage production strategies to meet differences in markets. The results of this work, however, suggest that in the case of the automobile body-in-white, differences in production between the U.S. and China have greater significance for the competitiveness of body technologies than differences in the compositions of the two countries’ markets.

This paper focuses on the case of manufacturing composite vehicle bodies in China for the
Chinese market. Conventional wisdom suggests that composites should have cost advantages over steel in low-wage high-risk environments due to their supposed higher labor and lower capital content during component production. The model results show that, contrary to conventional wisdom, composite bodies are cheaper than steel over a smaller range of production volumes in China than they are in the U.S. This difference is for three reasons. First, the consolidation of parts achieved by composites during assembly primarily reduces labor content, and is thus less significant in China than it is in the U.S. Second, although material availability may change in the future, material sourcing challenges in China create an additional cost penalty for high-material-content designs. Third, less efficient use of capital in China causes both technologies to have flatter cost curves, and with composites production curve already being relatively flat, in doing so gives greater comparative advantage to steel. True to traditional expectations, the model results confirm that the lower annual production runs per model in China give some advantage to composites. However, this advantage is insignificant compared to the cost-penalty caused by differences in production between China and the U.S. These results suggest that in cases such as automobile bodies where markets and manufacturing location are tightly coupled, firms may need to put as much or more emphasis on understanding the impact of local production differences on technology competitiveness as in understanding local markets. Future work should explore whether, given overall market trends, advantages may still exist for experimenting with emerging technologies in developing nations – for example, producing composite automobile bodies in China for the 14% of vehicles where composites are the most competitive option. Finally, future research must explore on how to incorporate local production differences into the new product development process, so that emerging technologies are more rather than less competitive in their desired location.
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Appendix 1
A.1 General Model Architecture

Equations 1-33 below develop the general architecture of the process-based cost model used to forecast production costs from design specifications. We mark inputs which differ between the U.S. and China in bold. For the complete body-in-white, we calculate aggregate costs as follows:

\[ C_{TAC} = \sum_{q} C_q , \text{ s.t. } q \in \{\text{Components, Assembly}\} \quad \text{Equation 1} \]
where $C_{\text{Tot}} = \text{total unit cost} (\$ \text{per good body-in-white})$, and $C_q$ is the total unit cost of either producing all of the components ($C_{\text{Components}}$) or assembling those components ($C_{\text{Assembly}}$).

A.1.1 Component Model

$C_{\text{Components}}$ is the sum of the unit costs, $C_{c,El}$, of all of the components, $c$, for a single body-in-white. Thus,

\[ C_{\text{Components}} = \sum_{c,El} C_{c,El} \quad \text{Equation 2} \]

and

\[ C_{c,El} = \frac{AC_c \cdot El}{PV} \quad \text{Equation 3} \]

where $AC_c = \text{annual cost} (\$ \text{per year})$ for each good component $c$, $PV = \text{good devices per year}$, $El = \text{cost elements (Materials, Labor, Energy, Equipment, Tooling, Maintenance, Overhead)}$, and $c = \text{component type}$, where $c \in \{\text{body side inner, body side outer, dash panel, front floor, front header, front lower longitudinal rail, shock towers, front wheel arch, upper dash panel, radiator panel, rear floor, rear header, rear quarter, roof, parcel shelf, bodyside cap, rear wheel arch}\}$.

A.1.1.1 Variable Costs

In the component model, material costs are driven by the effective production volume for each step ($\text{effPV}_i$), defined as the gross number of units processed at step $i$. We show the calculations for effective production volume and material costs in Equations 2 – 4 below:

\[ \text{effPV}_{i} = \frac{PV}{Y_i} \quad \text{Equation 4} \]

\[ \text{effPV}_i = \frac{\text{effPV}_{i+1}}{Y_i} \quad \forall \ i \in [1, \ldots, n_q-1] \quad \text{Equation 5} \]

\[ AC_{c,\text{Material}} = \sum_{m} U_{i,m} \cdot \text{effPV}_i \cdot P^m \quad \text{Equation 6} \]

where $i = \text{process step number}$, $n_q = \text{the final process step}$, $n = \text{total number process steps}$.

$Y_i = \text{yield at step } i$, $m = \text{material type}$, $P^m = \text{unit price of material } m$, $U_{i,m} = \text{unit usage of}$
material m at step i.

Energy costs are based on user-specified energy consumption rates for each machine, leading to annual energy costs calculated as:

$$AC_{c,\text{Energy}} = \sum_{i} \text{reqLT}_i \times EI_i \times P^e$$

Equation 7

where $EI_i$ = Energy intensity of step i in kiloWatts (kW), $P^e$ = price of electricity in kW per hour, and $\text{reqLT}_i$ = the line time required to produce effPV\textsubscript{i}. The annual cost of required labor is computed as described below in Equation 8:

$$AC_{c,\text{Labor}} = \sum_{i} APT_i \times P^l$$

Equation 8

where $APT_i$ = annual paid labor time for step i, and $P^l$ = direct labor wages (US$/hr) including benefits.

A.1.1.2. Fixed Costs

In both the component and assembly models, we assume costs are distributed evenly in time over the usable lifetime of a resource (e.g., equipment). We calculate the opportunity cost associated with tying up these funds in this long-term investment using a standard capital recovery factor (see Equation 9).

$$R_{EI} = I_{EI} \frac{\left[ d(1 + d)^{s_{EI}} \right]}{\left( (1 + d)^{s_{EI}} - 1 \right)}, \forall EI \in \{\text{Tool, Equipment, Building}\}$$

Equation 9

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

In the case of the component model, we use an input to establish whether the machine is a) dedicated to the product being analyzed or b) shared across products. If shared, we apportion investment expense according to the fraction of equipment available time used toward
manufacturing the product of interest. For this study, we assume all equipment is shared with other products. Annual capital costs for this non-dedicated equipment are calculated as follows:

\[ AC_{el, nonded} = \sum (R_{el,i} \times LR_i) \quad \text{Equation 10} \]

Where LR\(_i\) is the ratio of required operating time to effective available operating time at step \(i\).

A.1.1.3 Operating Time

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. We calculate annual paid labor time (APT\(_i\)), lines required (LR\(_i\)), required line time (reqLT\(_i\)), and available line time (availLT) as follows:

\[ APT_i = DPY \times (24 - NS - UB) \times WPL_i \times LR_i \quad \text{Equation 11} \]

\[ LR_i = \frac{\text{reqLT}_i}{\text{availLT}} \quad \text{Equation 12} \]

\[ \text{reqLT}_i = \text{effPV}_i \times (\text{cycT}_i + \text{suT}_i) \quad \text{Equation 13} \]

\[ \text{availLT} = DPY \times (24 - NS - UB - PB - UD) \quad \text{Equation 14} \]

where DPY = operating days per year, NS = no operations (hr/day the plant is closed), UB = unpaid breaks (hr/day), WPL\(_i\) = 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 (hr/day), and UD = Unplanned downtime (hr/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, \(c \in \{ \text{body-in-white} \}\), and the total unit cost per body-in-white can be calculated as follows:
Process-based cost modeling of assembly processes follows the same 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. Second, automotive assembly plants accommodate higher production volumes through in-series (rather than in-parallel) distribution of work. The consequences of these differences for the assembly model architecture are described in equations 19-33.

A critical parameter in the assembly model is the rate (Rate) of the line. We calculate this rate by dividing the desired annual production volume (PV) by the available line time (availLT):

$$Rate = PV / availLT$$

Equation 16

Here, we calculate the available line time as in Equation 15. 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 the inverse of this rate. Units for this value are usually converted into seconds.

$$ST = Rate^{-1}$$

Equation 17

We calculate equipment required to assemble at a particular rate as a function of the station time (ST) and the required join time for a particular subassembly (reqJTsa,b). We calculate the amount of equipment (Esa) and the number of stations (Ssa) for each subassembly as follows:

$$E_{sa} = \sum_p reqE_{sa,b}$$

Equation 18
\[
reqE_{sa,b} = \begin{cases} 
reqJT_{sa,b} / ST, & b \in \{\text{soft}\} \\
Joins_{sa,b} / Joins_{\text{max},b}, & b \in \{\text{hard}\} 
\end{cases}
\]  
Equation 19

\[
S_{sa} = \sum_{b} S_{sa,b}
\]  
Equation 20

\[
s_{sa,b} = reqE_{sa,b} / \max E_{\text{rate},b}
\]  
Equation 21

Here, b represents the method, \(s_{sa,b}\) represents the number of stations required by a particular method for a particular subassembly, and \(reqE_{sa,b}\) 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. ‘Hard’ methods use a single piece of equipment that is only able to do a set number of joins. For ‘hard’ methods equipment can not be split across stations. In the above equations, \(reqJT_{sa,b}\) is applicable to soft methods, \(Joins_{sa,b}\), for hard methods. 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

For the assembly model, we base material costs on material usage rates. We calculate these material usage rates for each method in each subassembly based on part geometries. We calculate the annual cost of materials in the assembly model as follows:

\[
AC_{\text{Assembly,Material}} = \sum_{m} \sum_{b} \sum_{sa} U_{b,sa}^m \cdot PV \cdot P^m
\]  
Equation 22

where \(b = \text{method}, sa = \text{subassembly}, m = \text{material type}, P_m = \text{unit price of material} \ m, \) and \(U_{b,sa}^m = \text{unit usage of material} \ m \ \text{for a method} \ b \ \text{in subassembly} \ sa.\)

Energy costs in the assembly model are based on energy consumption rates for each machine (\(E_{iE}\)). Energy costs are then calculated as:

\[AC_{\text{Assembly,Energy}} = \sum_{b} \sum_{sa} reqE_{sa,b} \cdot E_i \cdot P^e\]  
Equation 23
where $E_{i} = \text{Energy intensity of step } i \text{ in kiloWatts (kW)},$ and $P^e = \text{price of electricity in kW/hr}.$

We compute the annual cost of labor as described below:

$$AC_{\text{Assembly, Labor}} = APT^{dl} \cdot P^{dl} + APT^{il} \cdot P^{il}$$  \hspace{1cm} \text{Equation 24}$$

where $APT^{dl} = \text{annual paid direct labor time},$ $APT^{il} = \text{annual paid indirect labor time},$ $P^{dl} = \text{direct labor wages (US$/hr) including benefits},$ and $P^{il} = \text{indirect labor wages (US$/hr) including benefits}.$ Here, the annual paid labor time for each station is calculated differently than in the component model. In the assembly model, we calculate annual paid labor time as follows:

$$APT^{dl} = DPY \cdot (24 - NS - UB) \cdot \sum_{b} \sum_{a} (d_{lb} \cdot s_{a,b})$$  \hspace{1cm} \text{Equation 25}$$

$$APT^{il} = DPY \cdot (24 - NS - UB) \cdot \sum_{b} \sum_{a} (i_{lb} \cdot s_{a,b})$$  \hspace{1cm} \text{Equation 26}$$

where $d_{lb} = \text{fractional labor required per station for method } b,$ $i_{lb} = \text{fractional indirect labor required per station for method } b,$ $s_{a,b}$ represents the number of stations required by a particular method for a particular subassembly, $\text{DPY is operating days per year},$ $\text{NS is ‘no operations’ (hr/day the plant is closed)},$ and $\text{UB is unpaid breaks (hr/day)}.$

A.1.2.2. Fixed Costs

We discuss of how the assembly model calculates equipment requirements in the beginning of this section (A.1.2). Building on these equipment requirements, we calculate capital costs for each fixed cost element as follows:

$$I_{\text{Equipment}} = \sum_{a} E_{sa}$$  \hspace{1cm} \text{Equation 27}$$

$$I_{\text{Tool}} = \sum_{a} \sum_{b} (reqE_{sa,b} \cdot T_{b})$$  \hspace{1cm} \text{Equation 28}$$

$$I_{\text{Building}} = \sum_{a} \sum_{b} (s_{a,b} \cdot B_{b})$$  \hspace{1cm} \text{Equation 29}$$

Annual costs for each assembly cost element are then calculated according to the following:

$$AC_{EI} = R_{EI}, \ \forall \ E_{I} \in$$  \hspace{1cm} \text{Equation 30}$$