The Impact of Manufacturing Offshore on Technology Development Paths in the Automotive and Optoelectronics Industries

by

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Submitted to the Engineering Systems Division
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Engineering Systems
at the
Massachusetts Institute of Technology

June 2006

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Abstract

This dissertation presents a two-case study of the impact of manufacturing offshore on the technology trajectory of the firm and the industry. It looks in particular at the automotive and optoelectronics industries. The dissertation uses an innovative combination of engineering modeling and qualitative research methods to provide insights into this question. The results suggest an important difference between the two cases. In the automotive case, the results do not show that manufacturing offshore changes the path of technology development. In the optoelectronics case, the results do suggest that manufacturing offshore may be changing the path of technology development. The cross-case analysis reveals several important similarities between the two cases: (1) the relative economic positions of the emerging technology and the prevailing design shift when production is transferred to developing East Asia; (2) while the emerging design is more cost-competitive in the U.S. production structure, the prevailing design is more cost-competitive in the developing East Asia production structure; (3) firms initially do not understand the implications of moving offshore for the competitiveness of their designs; (4) firms choose to produce the prevailing design offshore; and (5) although the firms' decisions to produce the prevailing design offshore are rational in a static model, they fail to take into account dynamic diseconomies – specifically, disincentives and disadvantages for innovations critical to long-term markets. In its conclusion, this dissertation suggests a generalizable framework for how technology may influence manufacturing location and how manufacturing location may influence technology. To develop a more representative framework will require additional case studies.

Acknowledgements

This dissertation would not have been possible without the support of many people both from within and outside the M.I.T. community.

I have been particularly lucky in the diverse and complementary roles played by the members of my dissertation committee. First and foremost, this thesis would not have been possible without the support of Professor Randolph Kirchain. Randy has not only provided the home and funding for my work but also my connection to the optoelectronics industry and the M.I.T. Microphotonics Consortium. Throughout my thesis, Randy has provided an open door through which to bounce off ideas and organize my research efforts and thoughts. I am extremely thankful for the support and freedom Randy has given for me to seek and find my own academic voice. It has been a pleasure to have had the opportunity to work with Randy both first for my Masters, and now for my Ph.D.

The other members of my committee have played equally critical roles. I am very grateful to Professor Michael Piore for the role he has played in my life. Mike has been an incredible mentor to me both personally and intellectually. I feel that it is within the walls of Mike's office that this thesis truly took shape. After knowing me for over eight years, I believe that Mike can often see my path ahead better than I can see it myself.

I am likewise very thankful to Professor Louis Wells for taking an interest in my work, and agreeing to be on my committee. Lou has been a constant, steady force – managing, pushing, and encouraging – at the right times throughout my dissertation. I am particularly thankful to Lou for his emphasis on clarity both of writing and thought. With Lou's help, I am just beginning to understand the powerful role of words, not only in communicating to others, but also in clarifying an argument to myself.

Finally, I am thankful to Professor Joel Clark. Since I joined the Materials Systems Lab six years ago, Joel has provided unwavering guidance and support. As my work developed, Joel's pragmatic insights into academia and industry have been critical to keeping me on track and to keeping my eyes open to the road ahead.

Two people, not on my committee, have played a significant role in my time as a Ph.D. The first, Dr. Frank Field, has been an amazing mentor and intellectual sounding board, particularly in the final months of this dissertation. I don't know what I would do without Frank, both as a guiding light and as a friend. Second, Professor Edward Steinfeld, since advising my Masters work, has continued to be a source of unfaltering encouragement and guidance. I can't express the importance of Ed's quiet insights and constant faith in my abilities in pulling my research forward.

I have had the honor of interacting with several other exciting faculty during the course of my research. First, Rajeev Ram, from the Electrical Engineering Department, proved to be a wonderful resource. Rajeev was not only extremely supportive of my work, but also provided wise guidance on my first publication out of this thesis. Second, Charlie Fine's early interest in and insights into my work were a great source of encouragement. I cannot express how much I appreciate his more recent support as I have begun to explore academic positions. From Engineering Systems, Professor Richard deNeufville has been a steady and wonderful source of support, as has been more recently Professor Dava Newman. Over the last nine months, I have also been thankful for the interest of Professors James Utterback and Eric VonHippel.

I have been lucky to be part of very supportive communities during my time as a Ph.D. First, in the M.I.T. Materials Systems Lab, Dr. Richard Roth has repeatedly been available to provide honest guidance and advice. Second, this research would not be possible without the

funding and support of the M.I.T. Microphotonics Center and its director, Professor Lionel Kimerling. George Kenney has gone out of his way to provide insights into negotiating the business world. I am likewise thankful to Elisabeth Bruce for her early help and insights navigating the optoelectronics industry. Also from the Microphotonics Center, Mindy Baughman, Tamarleigh Lippegrenfell, and Mark Beals have all been extremely kind in their support. Third, I am grateful to the MIT International Science and Technology Initiative – in particular Sean Gilbert, Sigrid Berka, and Patricia Gercik – for their support, not to mention their funding of my research stay in China. Finally, I am thankful to the M.I.T. Industrial Performance Center (IPC). The IPC has not only funded my final semester as a Ph.D., but also provided an additional academic home in my final year. My sincerest thanks go to Anita Kafka and Professor Richard Lester for their warmth and support over the past year.

Various students from Engineering Systems, Sloan, and both of my research groups have been a continued source of advice and support. Thanks in particular to Douglas Fuller for reading early versions of my job paper and my application for funding to the Industrial Performance Center. Many thanks also to Ruthanne Huising, John-Paul Ferguson, Karim Lakhani, Kevin Boudreau, and especially Lourdes Sosa for helping me negotiate new waters in the field of management. Thank you also to Christine Ng, Travis Frank, Rebecca Dodder, Ralph Hall, James McFarland, Wei Gao, Ari Goelman, and Gabrielle Gaustad for being wonderful traveling companions en route to our Ph.D.s. Finally, I am in great debt to Materials Systems Lab alumni Professors Francisco Veloso (Carnegie Mellon University), Sebastian Fixson (University of Michigan), and Elicia Maine (Simon Frasier University). All three of them have gone out of their way to guide my debut into the academic world.

Life and work are impossible without family and good friends. I have been very lucky to have Marcus Sarofim as a friend and companion through my Ph.D. Likewise, Anne Lightbody has been an infallible source of strength and companionship, not to mention an incredibly faithful running partner. I will continue to remember great telemark skiing trips and other mountaineering adventures with Christopher Glazner, Gregory Wallace, Justin Fitzpatrick, and Christiaan Adams. I will likewise maintain fond memories of heart-to-hearts with fellow graduate resident tutors Solar Olugebefola and Ryan Simkovsky. I have been extremely lucky recently to find my old friend David Schiller back in town. Close to my heart, Sophie Currier and Jeremie Gallien (and now Theo!) continue to be like family. Likewise, although not in close proximity, Sachiyo Minegishi, Joylette Portlock, Bryan Pendleton, Carla Heitzman, William Nickerson, and Mimi Nameki remain parts of my life which I hold very dear. Finally, this last year would not have been the same without my new-found friend and office-mate Carlos Martinez-Vela.

I have been lucky enough to spend the past three years as the graduate resident tutor for a slowly shifting assortment of 38 undergraduates at First East, East Campus. The creativity of these undergraduates has been endlessly inspiring. More importantly, these students formed for me a community. At the end of any day, my conversations on First East helped remind me of the things in life that really matter.

There are only a few times in life when you are lucky enough to meet someone who is destined to become a life-long friend. I met Jennifer Atlee in September 2003, just after my brother, Geoffrey S.H. Fuchs' death. Her companionship is a regular source of warmth and joy. Her life choices are a regular reminder that there are many paths in this world and many definitions of success.

Finally, I thank my parents, Peter and Myrna Fuchs. Their unconditional support for whatever paths in life I choose and their unfaltering faith in me achieving my goals has been a constant source of strength in my life. The love, honesty, caring, and openness with which they approach their own lives and the lives of others continue to be for me a source of inspiration.

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1 Introduction: The Geography of Design, Product Development, and Innovation

Walter Isard in 1956 and Paul Krugman in 1995 criticize economics for occurring in a "wonderland of no spatial dimensions"(Krugman 1995). The same is true today for engineering design and the management of technology. Current schools of thought on design, product development, paths of innovation, and the management of these processes see geographic location as secondary to other considerations or as having impact on only a single aspect of the process (e.g., cost of labor or knowledge transfer). Geography, however – in the form of institutions, resources, and regulations – has system-wide impact on the development, manufacturing, and market environment facing a technology. Further, the geographic properties of a location cannot be isolated from one another. It is not feasible to choose one location's institutions and another's resources, at least not without incurring additional transaction costs (Williamson 1985, Grossman 1986, Antras 2004) and costs of knowledge transfer (Polanyi 1958, Arrow 1969, Rosenberg 1976, Teece 1977, VonHippel 1994). Thus, in the same way it is impossible to design a part without taking into consideration the properties of the part's materials (Ashby 1999), it is impossible to remove technology development and manufacturing from the geographic location in which they take place.

This dissertation focuses on only a very small piece of the geography of design, product development, and innovation. Specifically, this research asks the question:

> *Are firms' manufacturing location decisions changing their technology development incentives, and thereby the technology development path of the firm and the industry?*

This research looks in particular at firms' decisions to move manufacturing "offshore."[1]

To answer this research question, this dissertation defines four terms: prevailing technology, prevailing design, emerging technology, and emerging design. As used in this dissertation, the term *prevailing technology* refers to a mature technology used in a design (called the *prevailing design*) sold on today's market. The term *emerging technology* refers to an early stage technology, using an alternative design (called the *emerging design*). The emerging design provides a substitute for a prevailing design sold on today's market, and has physical properties associated with demand preferences expected in the long-term. This dissertation studies two cases of emerging technologies. In both cases, the emerging technology is a sustaining technology (Christensen 1997). In both cases, the emerging design requires a radical architectural change (Henderson 1990) from the prevailing design. Further, although in both cases there has been some early introduction of the emerging technology in the marketplace, the success of the emerging technology is not yet certain, and a dominant design (Utterback 1994) has not yet emerged.

It is important to explore each part of the question posed by this dissertation separately. First,

> *Are firms' manufacturing location decisions changing their technology development incentives?*[2]

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[1] For the rest of this dissertation, "manufacturing offshore" is used interchangeably with "a developed country firm manufacturing in a developing country."

[2] Conventional theory in economics assumes a product can be produced using different mixes of inputs. The possibilities are contained in a production function. In a two-factor model, as the price of one input varies relative to the other, a firm will choose processes that substitute the lower price input for the for the high price one. For example, in a developing country with low wages, a firm would chose to use more labor- and less capital-intensive processes than it would to produce the same output in a developed country environment. This conventional wisdom assumes that differences in factor costs between nations lead only to differences in inputs and processing decisions, and not to differences in technology choice. The exception is E.F. Schumacher, who argues in his book, Small is Beautiful, that low-capital labor-intensive technologies should be developed to meet the local needs of developing country villages. Schumacher believed, if produced locally, the labor-intensive nature of these

This first part of the question and the accompanying literature lead to the first seven propositions shown below in Table 1.

Table 1: Propositions Regarding the Impact of Manufacturing Offshore on Technology Development Incentives

	Proposition
P1a	Manufacturing offshore changes production variables.
P1b	These changes in production variables lead to changes in manufacturing cost structure.
P2a	If manufacturing offshore changes only the production variables, the most economic design alternative will not change.
P2b	If manufacturing offshore changes both the production variables and the targeted market, then the most economic design alternative will change.
P2c	Manufacturing offshore does not always change the targeted market.
P2d	The impact of manufacturing offshore on the targeted market is influenced by market differentiation, market-technology match, and product transportability.
P2e	If manufacturing offshore changes a firm's most economic design alternative, it will also change the firm's technology development incentives.

Today more and more firms based in the U.S. are choosing to manufacture offshore in developing countries. Some of these firms locate facilities offshore for market access, while others move offshore to reduce production costs. Unlike in previous decades, developed country firms today can even consider placing their very first manufacturing facility for a product offshore. Based on the existing literature and the author's observations in the real world, this dissertation proposes Propositions 1a and 1b:

Proposition 1a: Manufacturing offshore changes production variables.

Proposition 1b: These changes in production variables lead to changes in manufacturing cost structure.

There is a long history in engineering and management of incorporating manufacturing considerations into design and product development decisions. Design textbooks typically

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"appropriate technologies" would aid villages in their economic development.Schumacher (1973). Small is Beautiful: A Study of Economics as if People Mattered. London, Blond and Briggs. This dissertation reviews the existing engineering and management literature on incorporating manufacturing considerations into design.

provide cost tables or functions to guide engineers in the relationship between design decisions and manufacturing cost (Michaels 1989, Pahl 1996). Key variables determining the cost of manufacturing a design include labor, materials, tooling, cycle time, yields, downtime, and overhead (Ostwald 2004). A significant amount of research studies the relationships among material decisions, design, and manufacturing costs (Ashby 1999). Researchers have gone so far as to codify the relationships between design decisions and production costs into guidelines known as Design for Manufacturing (here manufacturing refers only to the manufacturing of components) and Design for Assembly (Boothroyd 2002). The design textbooks and guidelines created from this research, however, give no consideration to the role manufacturing location may play in determining the cost-optimal design.

A large body of literature suggests that production variables should differ significantly by region,[3] and in particular between developed and developing countries. From early on developmental economics focused on wage differences between developed and developing countries (Lewis 1954). With the popularization of the concept of the knowledge economy (Drucker 1969, Porter 2001), literature has placed increasing focus on the role of "technological capabilities" in determining developing countries' economic success (Kim 1997, Amsden 2001). This research suggests that critical technological capabilities for developing countries include production capabilities (the skills necessary to transform inputs into outputs), project execution or investment capabilities (the skills necessary to expand capacity), and innovation capabilities (the skills necessary to design entirely new products and processes) (Kim 1997, Amsden 2001).

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[3] The body of trade literature is based on the premise that different regions have different resource endowments. Conventional wisdom suggests each region should make the products at which, due to its resource endowment, that region is most efficient. According to free trade proponents, if these regions then trade with each other, all of the regions will have access to more products at lower costs and thereby be better off. This dissertation focuses on the existing developmental economics literature which has focused on production challenges commonly experienced in developing nations.

Finally, influential in determining the production variables in any country is the institutional environment of that country, including history, organizational structures, social structures, and cultural norms (Geertz 1963, North 1990, Womack 1990). Research has shown that a region's manufacturing history is particularly important in determining firm-level success (Geertz 1963, Amsden 2001). Based on the above literature, it would seem natural that labor (cost and skills), materials (cost and quality), cycle times, yields, downtimes, and overhead should differ significantly in a developing country's manufacturing environment. Aside from wages, however, there is little quantitative data on the impact of manufacturing in a developing country on such production variables.[4] Table 2 links potential regional differences in a developing country's production environment to the affected production variables.

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[4] There have been attempts to quantify a few of these variables individually. Much work has focused on the product development process rather than production process. Specifically, Kim documents the gaps in development time and shipment time between advanced countries and Korea in the semiconductor industry. Kim, L. (1997). Imitation to Innovation: The Dynamics of Korea's Technological Learning. Boston, MA, Harvard Business School Press. Clark and Fujimoto provide data comparing product quality, lead time, and development productivity. Clark, K. a. F., T. (1991). Product Development Performance: Strategy, Organization, and Management in the World Auto Industry. Boston, MA, Harvard Business School Press. There have also been multiple attempts to correlate labor costs with productivity in different industries. Gourevitch, P., Bohn, R., and McKendrick, D. (1997). Who is Us? The Nationality of Production in the Hard Disk Drive Industry. U.C. San Diego Information Storage Industry Papers. San Diego, Amsden, A. (2001). The Rise of 'The Rest', 1850-2000: Late Industrialization Outside the North Atlantic Economies. New York, Oxford University Press. Finally, Terwiesch et al. provide very nice data on in yields, downtimes, and tact times experienced during product transfer from development in the U.S. to off-shore production. This data, however, is for the ramp-up stage of production and only for one firm. Terwiesch, C., Chea, K., and Bohn, R. (1999). An Exploratory Study of International Product Transfer and Production Ramp-Up in the Data Storage Industry. U.C. SanDiego Information Storage Industry Center. SanDiego. As will be discussed later, this dissertation uses firm-level data in the U.S. versus offshore on eight of the production variables shown in Table 1, plus several additional variables which were not initially anticipated. The work aims with this data is to provide a quantitative picture of common production environment differences experienced on- versus offshore by firms in an industry. The research studies two industries.

Table 2: Effect of Developing Country Differences on Production Variables

Category	Regional Differences	Affected Production Variables
Labor	Wage	Wage
	Skill	Downtime, Yield, Scrap, Cycle Time
	Experience	Initial Investment, Labor Availability
	Absenteeism	Fixed/Variable Labor Accounting, "Buffer" Labor
Raw Materials	Price	Original Price, Transportation Cost, Tariffs/Fees
	Quality	Yield, Scrap, Line Rate, Design
	Reliability	Inventory, Secondary Supplier, Yield
Electricity	Price	Price per KWhr
	Reliability/availability	Downtime, Capital (e.g. Industrial Boiler)
Real Estate	Price	Price per Square Meter
Components	Imported from Supplier	Transportation Cost
	Imported by OEM	Transportation Cost
	Produced by Local Firm	Transportation Cost, Yield, Line Rate, Overhead
	Produced Locally by OEM	Transportation Cost, Yield, Line Rate, Overhead
Capital	Risk	Discount Rate
	Imported from Supplier	Transportation Cost
	Produced by Local Firm	Transportation Cost, Yield, Scrap, Downtime, Overhead

Even if Propositions 1a and 1b are true, a change in manufacturing cost structure may not be significant enough to change which design is most economic. Thus, although the manufacturing cost structure has changed, the incentives for technology development could be the same. Hence, Proposition 2a:

Proposition 2a: If manufacturing offshore changes *only* the production variables, the most economic design alternative will not change.

Notably, manufacturing offshore does not necessarily change only the production variables; it can also change the targeted market. Hence, Proposition 2b:

Proposition 2b: If manufacturing offshore changes both the production variables and the targeted market, then the most economic design alternative will change.

Recent literature shows that Proposition 2b does not provide a whole picture. Hence, Proposition 2c:

Proposition 2c: Manufacturing offshore does not always change the targeted market.

Work by Vernon and Porter suggests that local demand conditions are important determinants of national advantage and firm innovativeness (Vernon 1966, Porter 1990). Given today's global markets, however, it is unclear how manufacturing location influences targeted demand. Automobiles, for example, are generally produced in regional production systems close to the end market (Humphrey 2003). The production of electronic components, on the other hand, occurs in vertically disaggregated global production networks (Sturgeon 2002).

This dissertation suggests that three variables have a moderating effect on whether manufacturing offshore affects the targeted market. Hence, Proposition 2d,

Proposition 2d: The impact of manufacturing offshore on the targeted market is influenced by market differentiation, market-technology match, and product transportability.

Economic geography models use minimum efficient plant size and transportation costs to estimate how the proximity of manufacturing to the source of demand would vary by industry (Krugman 1995). These same indices are initially used here to create the three moderating variables. See Table 3 below.

Table 3: Influence of Manufacturing Offshore on the Targeted Market

Variable	Definition	Influence
Market Differentiation	Global extent of variance in market preferences.	Demand for product differentiation
Market-Technology Match	(Global Market Size) / (Minimum Efficient Plant Size) The number of production facilities efficiently sustained by the global market.	Feasibility of product differentiation
Product Transportability	Ease of transporting the final product (as a function of size, weight, shelf life, etc.)	Feasibility of separating manufacturing from market

This dissertation starts with the expectation that a firm's most economic design alternative will directly correlate with that firm's technology development incentives. Hence, Proposition 2e,

Proposition 2e: If manufacturing offshore changes a firm's most economic design alternative, it will also change the firm's technology development incentives.

Table 4 shows the proposed moderating effect of the variables in Table 3 on the impact of manufacturing offshore on technology development incentives.

Table 4: Impact of Manufacturing Offshore on Technology Development Incentives

Market Differentiation	Market-Technology Match	Product Transportability	Expected Outcome	Proposition
Low	Low	High	Manufacturing location does not change targeted market	Manufacturing location does not change technology development incentives
High	High	Low	Manufacturing location changes targeted market	Manufacturing location changes technology development incentives

The relationships among these first seven propositions can be seen in Figure 1.

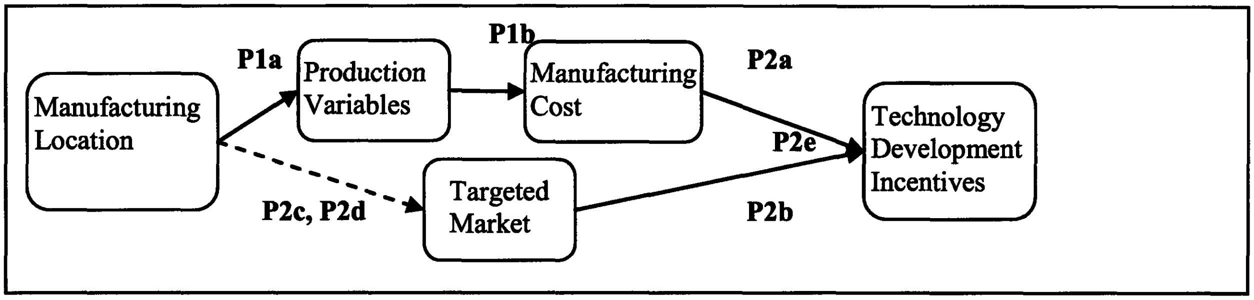

Figure 1: Impact of Manufacturing Location on Technology Development Incentives

The impact of manufacturing location on technology development incentives is only part of this dissertation. Recalling the original question, this dissertation asks:

> Are firms' manufacturing location decisions changing their technology development incentives, *and thereby the technology development path of the firm and the industry?*

Building on Propositions 1-2e, this dissertation makes Proposition 3,

> Proposition 3: If manufacturing offshore changes a firm's technology development incentives, it will also change the firm's path of technology development.

Current theories on technology development and innovation overlook the possibility that manufacturing offshore may change the technology development path of firms. Previous work on technology development has shown that technology paradigms play a role in establishing technology trajectories (Dosi 1982), that dominant designs can emerge and fix the path of innovation (Utterback 1975), and that disruptive technologies can shift the path of technology development (Christensen 1997). None of this work, however, explores the role of manufacturing location in affecting the path of technology development.

Research on international management and information management has explored the relationship between location and innovation. Much of this work sees nations as recipients or benefactors of technology. Vernon's product life cycle theory suggests that goods are initially manufactured in the North where product development takes place. As the good matures and becomes standardized, manufacturing is shifted to the South. (Vernon 1966) Subsequent work explores how developing countries can assimilate, adopt, and improve imported technologies (Kim 1997, Amsden 2001), as well as how the rate of host country imitation may influence the rate of home country innovation (Krugman 1979, Grossman 1991). A large body of work explores the importance of geographic proximity for knowledge transfer (Arrow 1969, Teece 1977, Manfield 1982, Allen 1984). Building on this work, Porter shows the importance of industry clusters in encouraging innovation (Porter 2001). VonHippel, on the other hand, focuses on how the type of information influences its transferability and, thus, the locus of problem solving (VonHippel 1994, Fuller 2005). A large body of literature has questioned the extent to which manufacturing and innovation can be geographically separated (Vernon 1966, Cohen 1987, Fuller 2005). Still, none of this work suggests that manufacturing in a foreign nation may change the technology trajectory of the firm and the industry.

The relationships explored in Propositions 1-3 can be seen in Figure 2 below.

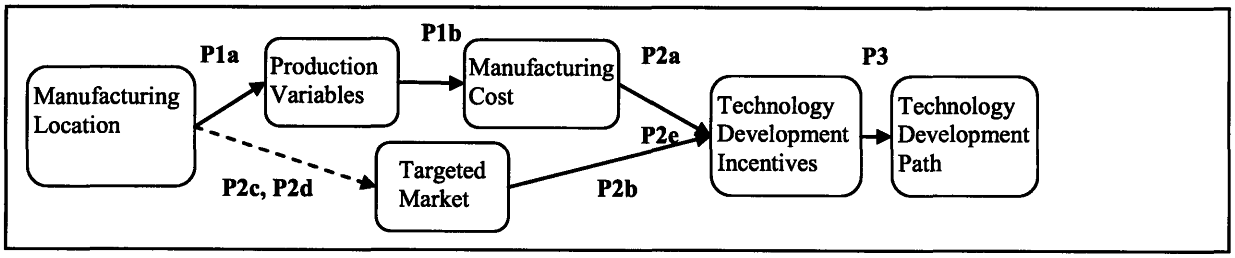

Figure 2: Impact of Manufacturing Location on Technology Development Path.

This dissertation uses an innovative combination of engineering modeling and qualitative methods to provide insight into the dynamics that can cause manufacturing location to influence the path of technology development. Given the lack of previous work in this subject, the dissertation focuses on in-depth analysis of two cases (Glasner 1967, Eisenhardt 1989, Yin

1989). These two cases are fiber-reinforced polymer bodies in automobiles and integrated designs in optoelectronic components. The dissertation presents results based on data collected in each case on how key production variables change with manufacturing location. The dissertation then explores how those factors affect the cost-preferred design.

Process-based cost modeling techniques (Kirchain 2000) are used to create a model of manufacturing based on the plant-level manufacturing data collected at firms. This model is used to evaluate the cost-competitiveness of the emerging designs against the prevailing designs, and how this cost-competitiveness changes if production is in developing East Asia instead of in the U.S. The quantitative analysis is supplemented by information collected in semi-structured interviews. These interviews are used to test whether firms do what the results of the model suggest would be most economic. The interviews are also used to understand the environment in which the firms are making their product development decisions. Market data is combined with model data and interview data to provide a more holistic view of the firms' decision-making and product development environments (Jick 1979).

The results show five similarities across the two cases. Two similarities emerge from the model results: (1) the relative economic positions of the emerging technology and the prevailing design shift when production is transferred to developing East Asia; and (2) while the emerging design is more cost-competitive in the U.S. production structure, the prevailing design is more cost-competitive in the developing East Asia production structure. Three additional similarities emerge from the qualitative data: (3) firms initially do not understand the implications of moving offshore for the competitiveness of their designs; (4) firms choose to produce the prevailing design offshore; and (5) although the firms' decisions to produce the prevailing design offshore are rational in a static model, they fail to take into account dynamic diseconomies – specifically, disincentives and disadvantages for innovations critical to long-term markets.

These five similarities raise import issues for future work. Results (1), (2), and (3) together suggest a need for firms to develop new ways to integrate geography into design, product development, and technology management decisions. Results (2), (4), and (5) raise troublesome questions for economic theories on gains from trade (Krugman 1994, Rodrik 1997, Baghwati 2004, Samuelson 2004). Conventional trade theory predicts that the gains of the winners from trade will be more than sufficient to compensate the losers (Samuelson 2004). Yet, technological change has come to be generally accepted in economics to contribute as strongly to economic growth as traditional factors of production.[5] If the static economies of offshore manufacture create patterns of factor substitution that encourage dynamic diseconomies – specifically, reduced innovation – gains from trade may be less than conventional trade theory predicts. This last issue can, however, of course, not be resolved through these two case studies alone.

In addition to the five similarities between the two cases, the results also show a critical difference between the two cases. Specifically, although the results suggest that manufacturing offshore may be changing the path of technology development for firms in the optoelectronics industry, the results do not show that manufacturing offshore is changing the path of technology development for firms in the automotive industry. This difference between the two cases is the *opposite* result as that predicted by the propositions presented in this chapter. As such, a new theoretical framework is required.

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[5] Economists from Mill and Marx to Schumpeter and Solow argue for the critical contribution of technology to growth in the economy. In 1988, Robert Solow won the Nobel Prize for his famous "Solow residual" which ascribed the part of output growth that cannot be attributed to the accumulation of any input to technological progress. Solow, R. M. (1988). "Growth Theory and After." American Economic Review 78(3): 307-317.

This dissertation consists of eight chapters. Chapter 2 discusses the choice of methods and early theory-building involved in this research. Chapters 3 and 4 discuss the automotive case. Chapters 5 and 6 discuss the optoelectronics case. For each case the first chapter (Chapter 3 in the automotive case and Chapter 5 in the optoelectronics case) provides details on modeling the competitiveness of the emerging versus prevailing designs. This first chapter also presents the outcome of the models if offshore manufacturing and market differences are not included (in other words, from the perspective of manufacturing in the U.S.). For each case the second chapter (Chapter 4 in the automotive case and Chapter 6 in the optoelectronics case) discusses the models' outcome if offshore manufacturing and market differences are included, and the impact, if any, of these differences on the technology development paths of the firms. Chapter 7 brings together Chapters 3-6 into new intermediate-stage theory on the impact of manufacturing offshore on the technology development path of the firm and the industry. Drawing on the results of the two cases, this chapter proposes a generalizable framework to explain why manufacturing offshore might not change the path of technology development in the automotive industry but would change the path of technology development in the optoelectronics industry. Chapter 8 outlines a plan for future work.

2 Methods: Grounded Theory-Building Combining Simulation Modeling and Qualitative Methods

This chapter describes the dissertation's use of simulation modeling and qualitative social science methods to develop grounded theory. The chapter has four sections. The first section argues that the existing literature on theory-building, simulation modeling, hybrid research methods, and methodological fit suggest that a combination of simulation modeling and social science research methods might be the most desirable approach for this study. This first section addresses (a) why it is important under some conditions to combine simulation modeling and social science methods in the same study, (b) what those conditions are, and (c) what makes up strong theory-building under those conditions. The remaining three sections of this chapter detail how the author combines simulation modeling and social science research methods in this dissertation. These three sections describe (1) question development and case selection, (2) process based cost modeling and interview methods, and (3) data collection. Eisenhardt sets out the aspirations for such research, "Theory building which simply replicates past theory is, at best, a modest contribution. Replication is appropriate in theory-testing research, . . . a strong theory-building study presents new, perhaps frame breaking, insights (Eisenhardt 1989)."

"What theory is" has been an ongoing process of debate. Sutton and Staw argue that theory is the answer to queries of *why*. Sutton and Staw write,

> Theory is about the connections among phenomena, a story about why acts, events, structure, and thoughts occur. Theory emphasizes the nature of causal relationships, identifying what comes first, as well as the timing of such events. Strong theory, in our view, delves into underlying processes so as to understand the systematic reasons for a particular occurrence or nonoccurrence. (Sutton 1995)

Weick provides insights into the intermediate outcomes that may occur while developing theory, or in his words, during "the process of theorizing." He writes,

> The process of theorizing consists of activities like abstracting, generalizing, relating, selecting, explaining, synthesizing, and idealizing. These ongoing activities intermittently spin out reference lists, data, lists of variables, diagrams, and lists of hypotheses. (Weick 1995)

Several authors, including Weick, have argued that theory is a continuum rather than a dichotomy (Runkel 1984, Weick 1995, Edmondson forthcoming). The points along this continuum have been given different names (Sutton 1995, Edmondson forthcoming). This dissertation uses the terms nascent, intermediate, and mature theory, as outlined by Edmondson (forthcoming). Edmondson describes nascent theory as proposing tentative answers to novel questions of how and why, often merely suggesting new connections among phenomenon. Mature theory, in contrast, presents well-developed constructs and models that have been studied over time with increasing precision by a variety of scholars, resulting in a body of work consisting of points of broad agreement that represent cumulative knowledge gained. Along the theory continuum, mature theory, and sometimes intermediate theory, provides research questions that may allow the development of testable hypotheses. (Edmondson forthcoming)

Regardless of the type of theory, it is widely accepted that both theory-building and the resultant theory must be "grounded." In their seminal work, *The Discovery of Grounded Theory*, Glaser and Strauss describe that it is the intimate connection with empirical reality that permits the development of a testable, relevant, and valid – in other words, grounded – theory (Glasner 1967).

As written by Bouchard and emphasized by Edmondson, "The key to good research lies not in choosing the right method, but rather in asking the right question and picking the most powerful methods for answering that particular question" (Bouchard 1976, Edmondson forthcoming). This dissertation focuses on theory-building in an area where this is little to no prior research. A significant amount of literature suggests that qualitative data are appropriate for studying phenomena that are not well understood, and thus for theory-building (Glasner 1967, Eisenhardt 1989, Edmondson forthcoming). Similarly, the literature agrees that the strengths of case study research are particularly well-suited to new research areas, research areas where phenomena are poorly understood, or research areas for which existing theory seems inadequate (Eisenhardt 1989, Yin 1989, Edmondson forthcoming).

Simulation methods have become increasingly accepted as an additional tool for the development of theory (Sterman 2000, Repenning 2003, Davis forthcoming). Davis et al suggest that simulation methods should be used in the "sweet spot" between theory creation, using methods such as inductive case studies, and theory testing, using methods such as multivariate statistical testing of hypotheses (Davis forthcoming). Davis et al do not, however, describe a role for the combination of simulation modeling and traditional social science methods in the same research.

This dissertation differs from the recommendations of Davis et al on four fronts. First, this dissertation focuses on an iterative back-and-forth between simulation[6] modeling and social science methods. Second, this dissertation uses this iteration between simulation modeling and social science methods to provide *grounding*. Third, echoing (Jick 1979), this dissertation

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[6] This dissertation distinguishes simulation models from optimization models according to Sterman 1991. According to Sterman, the output of an optimization model is a statement of the best way to accomplish some goal. The purpose of a simulation model is to mimic a real system so that it's behavior can be observed. Sterman, J. D. (1991). A Skeptic's Guide to Computer Models. Managing a Nation: The Microcomputer Software Catalog. G. O. e. a. Barney. Boulder, CO, Westview Press: 209-229.

suggests that the benefits of combining simulation modeling with social science methods are *synergistic*. Fourth, unlike Davis et al, this dissertation uses simulation modeling combined with social science methods, to provide critical insights *throughout the theory-building process* – i.e. for nascent, intermediate, and mature theory.

Much literature on theory-building recommends iterative practices. Eisenhardt emphasizes the iterative nature of theory-building using case study research (Eisenhardt 1989). Likewise, Edmondson describes field research as an iterative, learning procedure in which ideas and methods become more focused over time (Edmondson forthcoming). In describing modeling methods for consulting practices, Sterman writes, "Effective modeling involves constant iteration between experiments and learning in the virtual world and experiments and learning in the real world (Sterman 2000)." When building grounded theory, a constant back-and-forth between the controlled environment of model building and analysis and real-world observations using social science methods enables researchers to ground model developments and to quicken the pace of theory development through continual checks with the real world.

A significant amount of literature on social science research advocates the use of multiple – or "hybrid" – methods (Jick 1979). This literature tends to see qualitative and quantitative methods as complementary rather than rival approaches. Triangulation, or "the combination of methodologies in the study of the same phenomenon" is often aimed at convergent validation (Denzin 1978, Jick 1979). Jick points out that triangulation, rather than merely providing convergent validation, can provide a more complete, holistic, and contextual portrayal of the unit(s) under study – in other words, the sum of the methods may be greater than the parts (Jick 1979). Edmondson goes so far as to argue that to build high-quality intermediate theory it is *necessary* to use hybrid methods (Edmondson forthcoming)

Simulation modeling and social science methods each provide a researcher with very different insights. A simulation model offers a known structure in which a researcher can run controlled experiments (Sterman 2000). The virtual world of this model enables a researcher to isolate the influence of individual variables, constructs, or phenomena. In the case of this dissertation, the model enables the author to run controlled experiments on how manufacturing location changes the most cost-competitive design. Using the model, the author is able both quantify the impact of manufacturing location on the most cost-competitive design, as well as to isolate manufacturing costs from other factors that might influence technology development incentives.

In contrast to modeling methods, which are aimed at creating a virtual world of known structure, science methods are aimed at *observing* the real world so as to develop and test theoretical relationships. Methods to observe the human aspects of the world, or social science methods, include ethnography, unstructured interviews, semi-structured interviews, structured interviews, surveys, and quantitative data collection. In the case of this dissertation, the author uses qualitative methods – including observation, semi-structured interviews, and market data – to understand the relationship between manufacturing cost incentives, technology development incentives and the technology development path of firms. The author uses the qualitative data to create a picture of firm decisions, the reasoning behind those decisions, and the market environment in which those decisions were made. By combining simulation modeling and qualitative research the author is able to achieve a more complete, holistic, and contextual portrayal of the impact of manufacturing offshore on technology development.

Where, however, in the process of theory building should modeling begin and end? This dissertation argues that modeling can begin as early as the nascent stages of theory development and maintain relevance through mature theory testing. In the process of iterations, the researcher can initially draw system boundaries in the model very narrowly – isolating the relationships between only a few constructs. The researcher can next observe, using qualitative methods, how outcomes in the real world differ from those in the model. Having observed differences between the real world and the model, the researcher can consider what new constructs to add to the model. Likewise, the researcher can, based on real-world observations, consider re-defining the boundaries of the model, either shifting them, enlarging them, or otherwise. Such iterations between the modeling and real world observations can continue until theory saturation, but can also spin out questions for new theory directions (e.g. why?) or questions with policy or management implications (e.g. how could the system be impacted, influenced, or improved?) For example, the research in this dissertation has lead to new strategy questions such as, "Why don't firms understand the impact of manufacturing offshore on their technology competitiveness?" and new management questions such as, "How should firms be incorporating manufacturing location into their design decisions?"

The process of building grounded theory that combines modeling and social science research methods is shown below in Figure 3. This process occurs for all stages of theory building – nascent, intermediate, or mature. The researcher can choose to iterate between the model and field data at each step in the process. The issues addressed within the model can be a subset of the total issues involved in the question. Each step can lead back to previous steps.

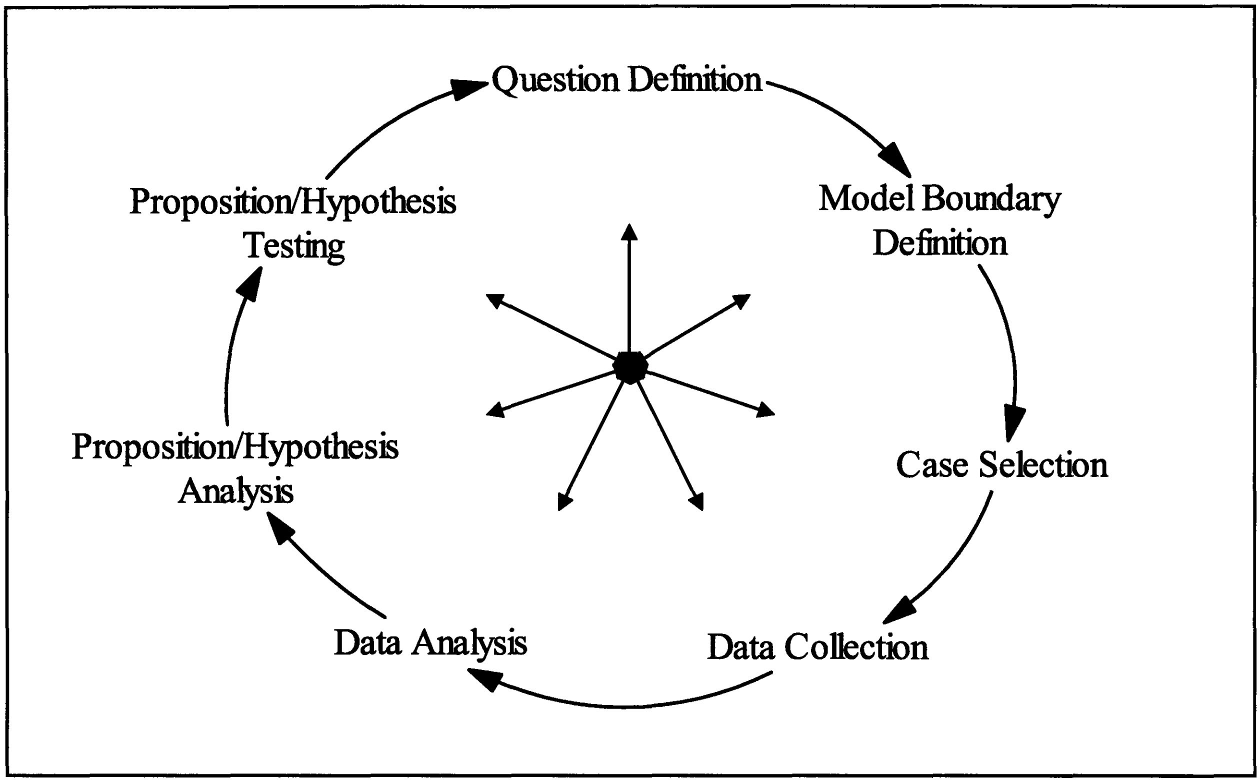
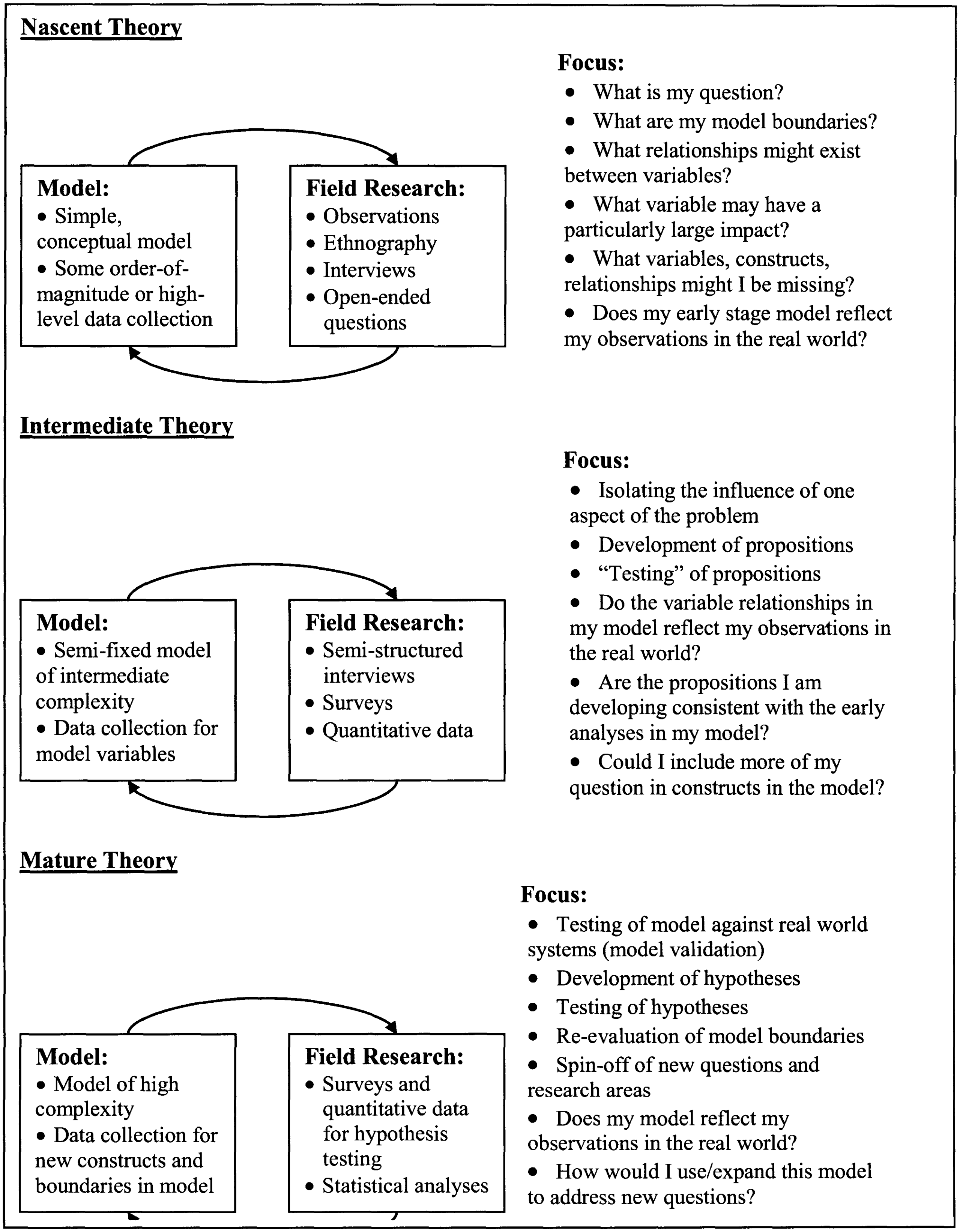


Figure 3: Grounded theory-building combining simulation modeling and social science research methods.

Although this dissertation focuses on theory-building, it is worth noting that the synergistic benefits to iterating between modeling and social science methods need not be limited to theory-building alone. Sterman, for example, suggests that theory testing methods can be used to explore model constructs by helping question existing relationships within and outcomes from the model (Sterman 2000). Figure 4 shows the role a hybrid approach combining modeling and social science research methods can play in different stages of the theory-building process.



Nascent Theory

Focus:

- What is my question?
- What are my model boundaries?
- What relationships might exist between variables?
- What variable may have a particularly large impact?
- What variables, constructs, relationships might I be missing?
- Does my early stage model reflect my observations in the real world?

Intermediate Theory

Focus:

- Isolating the influence of one aspect of the problem
- Development of propositions
- "Testing" of propositions
- Do the variable relationships in my model reflect my observations in the real world?
- Are the propositions I am developing consistent with the early analyses in my model?
- Could I include more of my question in constructs in the model?

Mature Theory

Focus:

- Testing of model against real world systems (model validation)
- Development of hypotheses
- Testing of hypotheses
- Re-evaluation of model boundaries
- Spin-off of new questions and research areas
- Does my model reflect my observations in the real world?
- How would I use/expand this model to address new questions?

Figure 4: Combining Simulation Modeling and Social Science Methods in Different Stages of Theory-Building

2.1 Case Selection, Question Development

This dissertation examines two cases to determine the impact of manufacturing offshore on the technology development path of the firm and the industry. Unlike classical "cases" in the management literature, which often study only one firm, a case in this dissertation is an *emerging technology*, as defined in Chapter 1. In each case, the emerging technology is studied in the context of a particular industry. Each case involves many firms, as appropriate for the respective industry. Given the lack of previous work in this area, this dissertation studies polar cases (Pettigrew 1988, Eisenhardt 1989). The analysis then seeks to understand similarities and differences across the two cases. As is common in theory-building, both the case selection and the research question emerged during the course of the early-stage research (Eisenhardt 1989).

This dissertation research was motivated by a set of observations in the real world. In 2000, the Automotive Composites Consortium approached the author (as part of the Materials Systems Lab at M.I.T.) to help it examine the competitiveness of its new, consortium-developed, carbon-fiber reinforced polymer composite automobile body design. Around the same time, the author caught wind of a "top secret" project at General Motors to produce an automobile with a fiber-reinforced polymer composite body in China for the Chinese market. With a bit more research, the author found that GM was not the only automobile manufacturer trying to produce vehicles with composite bodies in China. Daimler Chrysler had decided to bring a composite bodied vehicle to China two years earlier, and a Chinese-owned company was also ramping up production of a composite bodied vehicle. These fiber-reinforced composite bodies are considered in the U.S. to be the "wave of the future," and potentially critical to solving fuel economy and air emissions challenges, but still many years out.

Puzzled that an emerging technology would be produced in China and not the U.S., the author explored in (Fuchs 2003) the following question: *Why are polymer-reinforced polymer* *vehicle bodies being moved towards production in China and not in the U.S.?* Four results emerged from (Fuchs 2003) that were particularly influential in driving the research in this dissertation: (1) production variables in China differed significantly from those in the U.S., (2) this difference in production variables caused the manufacturing cost structure in China to be significantly different than that found in the U.S., (3) when combined with differences in market structure between the U.S. and China, this shift in cost-structure had significant implications for the most cost-competitive design alternative, and (4) the impact on the competitiveness of the design alternatives was the opposite of what was expected by firms.

The above-described results suggest that manufacturing offshore changes the most economic design alternative in automotive bodies. The author therefore asked the following question: *Does manufacturing offshore also influence the most economic design alternative in other industries?* Given the lack of previous work on this topic, the author decided to continue to follow the automotive case, and to seek a second, polar case (Pettigrew 1988, Eisenhardt 1989). Drawing from the results in (Fuchs 2003), the following proposition was developed: The impact of manufacturing offshore on the most economic design alternative is dependent on the transportability of a product and the extent to which market preferences for that product vary by region. If a product is easily transportable and there is little variance in market preferences for the product by region, manufacturing location should not change the most economic design alternative. If a product is difficult to transport and there is a lot of variance in market preferences for the product by region, the most economic design alternative will vary by region. (See Figure 5.)

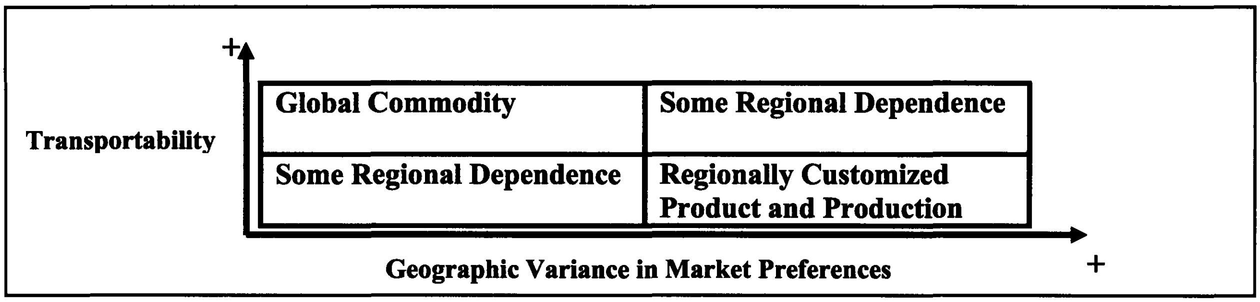


Figure 5: Impact of Manufacturing Offshore on Most Economic Design Alternative: Original Proposition

In the proposition described above, the automotive case fits in the lower right hand quadrant of Figure 3. As such, the author sought a second case with high transportability and low regional variance in market preferences. Around this time, the M.I.T. Microphotonics Consortium approached the author (as part of the M.I.T. Materials Systems Lab) to help them analyze the competitiveness of integration in optoelectronic components. Given that the optoelectronics industry fit in the opposite quadrant (upper left) from the automotive industry the opportunity was accepted. The initial question was, *Does manufacturing offshore also influence the most economic design alternative in optoelectronic components?* Based on the assumptions in Figure 5, the original hypothesis was that manufacturing offshore would not influence the most economic design alternative in optoelectronic components.

Drawing from existing literature, the author developed a list of case-dependent variables which might influence the impact of manufacturing offshore on the most economic design alternative in each case. A table comparing the values for these variables in each case is shown below (see Table 5). Provided the lack of prior research in this area, the author felt that the polar nature of the automotive and the optoelectronics case were a benefit in understanding the conditions under which manufacturing offshore influences the most economic design alternative.

Table 5: Variables Potentially Relevant to the Impact of Manufacturing Offshore on the Most Economic Design Alternative

	Automotive	Optoelectronics
Value Chain Dispersion	Regional (Humphrey 2003)	Global (Sturgeon 2002)
Economies Of Scale	= Regional Mkt.	>/= Global Mkt.
Transportability	Low	High
Market Preferences	High Geographic Variance	Low Geographic Variance
Maturity (Vernon 1966)	Mature Technology Mature Industry	Growth Technology Growth Industry
Development Time	3 yrs	0.5 yrs
Product Life (Fine 1998)	6 yrs	1.5-3 yrs
Capital Life	20+ yrs	10 yrs
Architecture (Fuller 2005)	Integral	Modular
Production (Arrow 1969, Teece 1977)	Standardized	Non-standardized, High tacit knowledge

As the author began collecting data for the optoelectronics case, the author concluded that manufacturing offshore may not only change the most economic design alternative, but also the path of technology development. In fitting with grounded theory-building the author re-evaluated her ideas and arrived at the dissertation question which appears in Chapter 1:

> *Are firms' manufacturing location decisions changing their technology development incentives, and thereby the technology development path of the firm and the industry?*

Building on Table 4 in Chapter 1, the starting proposition for these two cases is shown below:

Table 6: Proposition for the Impact of Manufacturing Offshore on Technology Development Incentives in the Automotive and Optoelectronics Industries

Case	Market Differentiation	Market-Technology Match	Product Transportability	Expected Outcome	Proposition
Optoelectronic Components	Low	Low	High	Manufacturing location does not change targeted demand	Manufacturing location does not change technology development incentives
Automotive Body-In-White	High	High	Low	Manufacturing location changes targeted demand	Manufacturing location changes technology development incentives

In addition to the variables shown in Table 5, the automotive and optoelectronics cases also differ in the motivation of the firms for going offshore. Specifically, in the case of fiber-reinforced polymer composites in the automotive industry, the firms go offshore for market access. In the case of integration in optoelectronic components, firms go offshore for cost reductions. The author felt this difference fit with the proposition shown in Table 6. This difference also plays an important role in the future work proposed in Chapter 8.

2.2 Description of Methods

This dissertation triangulates quantitative modeling data, qualitative interview data, and market data to provide a more holistic view on the drivers of technological change (Jick 1979). On the modeling side, process-based cost modeling techniques are used to map technical design decisions to their manufacturing cost implications and thereby isolate cost incentives for technology development. On the qualitative sided, interviews and market data are used to develop a picture of the actual design and location choices being made by firms in the industry, and the short- versus long-term implications of those decisions for firms' technology development path, and ultimate competitiveness.

Technical (or process-based) cost modeling was developed as a method for analyzing the economics of emerging manufacturing processes without the prohibitive economic burdens of trial and error innovation (Busch 1988). The application of this cost 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 2000). 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 the engineering approaches at work within these physical models to avoid expensive strategic errors in product development and deployment (Kirchain 2000).

A process-based cost model, like any other engineering process model, serves as a mathematical transformation, mapping a description of a process and its operating conditions to measures of process performance; in this case, cost (Kirchain 2000). As shown in Figure 6, the modeling of cost involves three major steps:

1) Correlating the effects of physical characteristics of the desired product (e.g., size, weight, …) on the required processing conditions (e.g., cycle time, equipment performance requirements),

2) Relating these processing requirements to manufacturing resource requirements (e.g., kg of material, number of laborers, number of machines and/or tools), and

3) Translating these requirements to a specific cost. (Kirchain 2000)

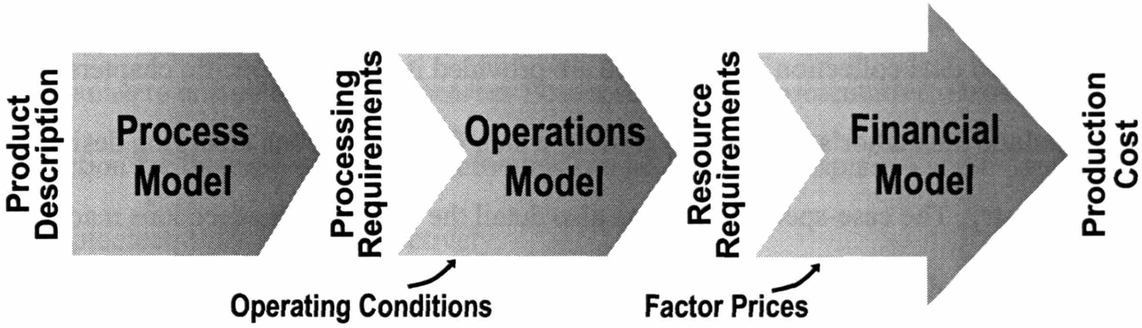


Figure 6: Mapping Product Parameters to Process Requirements, Operating Conditions, and Manufacturing Costs

In the manufacturing both of auto components and of optoelectronic components, equipment and tooling requirements, cycle times, and yields of key process steps are the most typical attributes to change with design parameters. The relationships between part design parameters and process requirements can be developed either based on existing empirical evidence or according to basic scientific and engineering principles. A detailed discussion of the calculation of such variables in the cases studied can be found in the modeling chapter for each case. (See Chapters 3 and 5 for the automotive and optoelectronics cases, respectively.)

In extending process based cost modeling to address the implications of location on the relative economic advantage of technology alternatives, the author identified a set of factors that would lead production costs for identical technologies to differ across two regions. Each factor was mapped to the set of process variables that would be affected, as shown in Table 2 in Chapter 1. The process variables in Table 2 each correspond with a variable in the process-based cost model. A detailed discussion of the process variable difference between manufacturing regions can be found in the technology development incentives chapter for each case. (See Chapters 4 and 6 for the automotive and optoelectronics cases, respectively.)

2.3 Data Collection

The details on data collection for each case are provided in the case-specific chapters. These details include the author's decisions regarding which firms and which emerging design to study in each industry. The case-specific chapters also detail the case-specific decisions made by the author in collecting data for each process-based model. The type of data collected, however, was the same in both cases. These similarities in data collection across the two cases are discussed below.

For the process-based cost models, data collection at each firm focused on three main areas:

(1) Design: (a) current design technology (material, process, and geometry) and (b) emerging design alternatives;

(2) Production: (a) production data for current manufacturing technology and processes and (b) new production requirements for emerging design alternatives; and

(3) Location: differences in production variables between the U.S. and the offshore manufacturing location.

Data were collected under non-disclosure agreements to encourage companies to provide the maximum amount of information. To increase incentives for participation and honesty, companies were encouraged to add products of interest specific to their individual company to the analyses. Analyses and recommendations were provided back to each company based on the products and information they provided. The authors then developed a public, "generic production scenario" to represent common, industry-wide practice. At all firms, participants were asked to identify what of their processes they felt were non-generic. These confidential practices were excluded from the generic process flow. Mean values across the represented firms were then calculated for each input for each process step in the generic process flow. Unit cost results for the generic process flow were cross-checked with unit cost results of individual companies to ensure the generic process flow results were representative. Details on data collection for the process-based cost models can be found in Chapters 4 and 6 for the automotive and optoelectronics cases, respectively.

In addition to collecting data for the process-based cost model, the author also collected qualitative data. The qualitative field work included semi-structured interviews, consortium participation, plant visits, and multi-day on-site observations of employee interactions. Notes were taken throughout company visits during process-based cost model data collection, plant visits, employee observations, discussions, and interviews, and transcribed within 24 hours. The interviews focused on two main areas: (a) what design (material, process, and geometry) was produced in the home-country versus the offshore manufacturing location, and (b) what companies' explanations or logic were for the design decisions in (a). In both cases, the interviewees ranged from factory workers and design and production engineers up through executive level managers. The interviews were primarily informal, occurring naturally during the process of product and process data collection. In a few situations, when dealing with higher levels of management, actual times for interviews were arranged. All interviews were semi-structured, allowing interviewees to bring-out the most important points in their individual experience. Additional details on the qualitative field data collection can be found in Chapters 4 and 6 for the automotive and optoelectronics cases, respectively.

The next four chapters of this dissertation (Chapters 3, 4, 5, and 6) focus on the two cases studied. For each case, the first chapter (Chapter 3 in the automotive case and Chapter 5 in the optoelectronics case) discusses the details of the model, and model's outcome if offshore manufacturing and market differences are not included (in other words, from the perspective of manufacturing in the U.S.). The second chapter (Chapter 4 in the automotive case and Chapter 6 in the optoelectronics case) discusses the model's outcome if offshore manufacturing and market differences are included, and the impact, if any, of these differences on the technology development paths of the firms.

3 Modeling the Cost-Competitiveness of a Fiber-Reinforced Composite Body-In-White

This chapter analyzes the cost-competitiveness of a fiber-reinforced polymer composite automotive body from the perspective of manufacturing in the United States.

Since Henry Ford began mass-producing the Ford Model T, production costs have been a major driver of design decisions in the automotive industry. In today's market, along with cost, the prestige, performance, safety, and comfort of a design all play a major role in determining competitiveness. On the horizon, energy, environment, and security issues threaten to become relevant to the competitiveness of motor vehicle designs.

Since the late 1980's, cost of ownership models have been used widely in industry to support investment decisions. Activity-based costing (Kaplan 1987) and other process-based cost research (Bloch and Ranganathan 1992) have extended these methods to include the implications of both non-manufacture and individual process activities. These costing approaches, however, are unable to predict the implications of engineering design decisions for production costs. For an industry with such long product development cycles, high product development costs, and high capital costs as the automotive industry, it is important to be able to forecast the cost-implications of technology advances while those advances are still in their early stages of development. With energy, environment, and security issues threatening to influence competitiveness in the automotive industry in the near future, now is a particularly important time for automotive manufacturers to be able to assess the cost implications of major shifts in technology.

Process-based (or technical) cost modeling was developed to address just such a problem, serving as a method for analyzing the economics of emerging manufacturing processes without the prohibitive economic burdens of trial and error innovation (Busch 1988). Its application has been extended to the implications of alternative design specifications and process operating conditions on production costs within and across manufacturing processes (Kirchain 2000). In the same way that present-day engineering 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 the engineering approaches at work within these physical models to avoid expensive strategic errors in product development and deployment.

Process-based cost modeling (PBCM) has a long history of being used in the automotive industry to look at the cost-implications of technologies still in their early stages of development. This research builds on previous work applying PBCM to the economic questions associated automotive component production and assembly. This research focuses on the feasibility of a particular technology – a fiber-reinforced polymer composite unibody – to cost-compete against a traditional steel body-in-white. This study builds on the work in (Fuchs 2003). The main difference between the results presented in this chapter and those presented in (Fuchs 2003) is the price of carbon fiber. (Fuchs 2003) assumes a carbon fiber price of $11/kg. Although some firms claim they could supply carbon fiber at this price if there was a large demand, carbon fiber is unlikely to reach this low price in the near term. This study instead assumes a carbon fiber price of $22/kg. This price is the price at which carbon fiber is currently sold on the market. For the ease of the reader, the product and process design choices in the model are summarized from (Fuchs 2003) in the Case Study section below.

3.1 Background: Materials Selection in Automotive Body-In-Whites

Concern over automobile energy consumption has influenced vehicle development for over three decades. Public concern over automobile energy use grew with the energy shocks of the 1970's, and was institutionalized in the U.S. with the passing of the Corporate Average Fuel Economy (CAFE) standards in the Energy Policy and Conservation Act of 1975.

In response to these federal mandates, automakers began exploring alternative materials, architectures, and powertrains which would improve fuel economy while still satisfying consumer demand. Although the CAFE requirements have not become more stringent over the past two decades, automakers have continued to pursue technologies to improve vehicle fuel efficiency to accommodate consumer preferences for increased vehicle performance, size, and convenience features. One key technical dimension in improving vehicle efficiency is the management or reduction of vehicle mass.

The light-weighting of vehicles not only can enhance fuel efficiency, but also may lower vehicle emissions and improve driving performance. (Alternatively, lighter structures allow for additional weight in the form of electrical conveniences such as DVD players, navigation systems, and additional motorized options.) Lightweight subsystems (e.g., hoods, decklids, and instrument panel beams) are already employed throughout the industry to achieve small weight savings needs. Significantly improving the efficiency of the vehicle, however, will require larger changes in mass. A primary target is the body-in-white, whose standard steel version comprises 20-25% of total vehicle curb weight.

Two main alternatives exist for reducing weight in the body-in-white – architectural changes and material substitution. Among architecture alternatives, the unibody is considered most mass efficient and is already ubiquitous. As such, the primary mechanism available for reducing the weight of the body-in-white is using alternative materials. This study examines the cost-competitiveness of two unibodies – one made out of carbon fiber reinforced composite and one made out of glass-fiber reinforced polymer composite – against the prevailing steel unibody design. A passenger vehicle with an all-composite unibody is not available on today's market. The composite unibody design used in this study is based on an advanced, consortium-developed design.[7]

3.1.1 Previous Work

Most work on the competitiveness of polymer composite technology came out in the early- to mid-1990s along with the 1993 establishment of the Partnership for a New Generation of Vehicles (PNGV).[8] Little new work has emerged in the past decade re-evaluating the economic feasibility of structural polymer composite applications in automobile body-in-whites. Common understanding in the industry has remained that economic justifications do not yet exist for using a polymer matrix composite in the automobile.[9,10] A 1995 study by IBIS and the Rocky Mountain Institute based on GM's 100-day first cut ultra-light BIW concept car argued that concerns over the economic viability of carbon fiber advanced composites in the BIW may be misplaced.[6] A more recent study by the Rocky Mountain Institute has suggested that polymer composite BIW alternatives may be well-suited to platforming goals, but it suggests using the BIW as the customized part of the vehicle (thereby producing it at low production volumes) and

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[7] The use of polymers in U.S. automotive applications has risen dramatically from their average of approximately 60 pounds per vehicle in 1970 APC (2001). About the American Plastics Council, American Plastics Council..[7] Ward's Motor Vehicle Facts and Figures place plastics and composites at 253 pounds in the typical 2001 vehicle, or 8% of vehicle weight, and 3.9% of total U.S. plastic consumption. Most of the plastic applications in vehicles are lower-performance commodity polymers, such as SMC and random-glass RTM. These lower-performance commodity polymers are used in sportside truck models in fascia, fenders, and trims, and in heavy truck applications for cab steps, bumpers, spoilers, doors, fenders, toolbox doors, and even full cabs Kobe (1999). Some passenger vehicles have incorporated low-performance, commodity polymers in non-structural body panels applications. Vehicles with non-structural polymer body panels have included GM's Saturn, EV1, Corvette, Firebird, and Camaro, as well as Ford's Tarus/Sable, Mustang, and Windstar Kobe (1999). Advanced composites in structural vehicle body applications have been far less extensive. The two most well-known advanced composite applications have been the GM 800 truckbox and the GM 805 tailgate, both of which are structural reaction injection molded. On the horizon sit many prototypes – Jeep's Commander, Lotus's answers to Porsche's Boxster and Porsche's Elise, Honda's hybrid SUV, DaimlerChrysler's ESX-3, and VW's "One-Liter Car" – sporting advanced composite bodies RMI (2002). Hypercar$^{(SM)}$ Chronology: Elements of Hypercar Vehicles are Emerging, Rocky Mountain Institute..

[8] Coates 1992, DeLong 1994, Dieffenbach and Mascarin 1993, Eusebi 1995, Gyostein 1995, Prescott 1995

[9] "Ch7: Case Study: Polymer Matrix Composites in Automobiles. Advanced Materials by Design." June 1988. US Congress, Office of Technology Assessment. Washington, DC: US Government Printing Office

[10] Mascarin et al. 1995. "Costing the Ultralite in Volume Production: Can Advanced Composite Bodies-in-White Be Affordable?" Procs. 1995 Intl. Body Engineering Conf.

not as a competitive technology in large-scale platform-sharing BIW designs. The work presented in (Fuchs 2003) and this chapter differs from these previous studies in several ways: (1) It is based on up-to-date detailed data collection with resin and fiber reinforcement suppliers, polymer composite equipment suppliers, polymer composite component producers, and the Big Three. (2) It applies new, more advanced component and assembly modeling techniques. (3) It evaluates the competitiveness of polymer composites against the actual models produced in North America in 2002. (4) It looks at how production volume changes due to actual platform sharing in GM's vehicles changes the competitive position of polymer composites again steel in BIW applications.

3.2 Case Study

3.2.1 Product Design

In evaluating the competitiveness of fiber-reinforced composite technology for automotive body-in-white applications, this study looks at three design alternatives. One impetus for this study, and the first of the three designs, is the innovative carbon-fiber reinforced composite unibody design developed in 2002 by the Automotive Composite Consortium (ACC). Given the often-cited high-costs of carbon-fiber, the second design is a hypothetical version of the ACC design using glass-fiber reinforcement. These two composite unibody designs are compared against the most prevalent BIW design – a steel unibody. Although other body architectures have been proposed for composites, and also occur in steel, a unibody architecture is maintained in all three cases to focus the study on the competitiveness of the alternative materials.

3.2.1.1 Design One: Carbon Fiber-Reinforced Polymer Composite Unibody

Design and processing information for the composite case vehicle is drawn from the Automotive Composite Consortium's (ACC) Focal Project III. The ACC was formed in

August 1988 as a collaborative effort of Ford, GM, and Chrysler (now Daimler-Chrysler). The focus of the ACC is to conduct joint research on structural polymer composites in pre-competitive areas that leverage existing resources and enhance competitiveness. The design goal of the Focal Project III was to produce a body-in-white with minimum mass, which maintained structural integrity and cost-competitiveness at medium to high production volumes (20,000-250,000 body units per year).

The Focal Project III vehicle design is a four door mid-sized sedan. The sedan has a 108" wheelbase, is 186" long, 71"wide, and 54" high. The design consists of 25 components and 37 inserts. The components are 60wt% of two-component polyurethane[11], and 40% carbon fiber reinforcement. The joining inserts are mild steel. All of the components are designed to be produced by the SRIM (structural reaction injection molding) process. The preforms for the bodyside inners, outers, and caps, the floor pieces, the firewall, the seatback, the front and rear wheel arches, the radiator, the front and rear headers, the right and left lower longitudes and the cowl are created using a robot spray-up process[12]. The preforms for the front floor, front lower longitude, rear floor, and roof are created layered carbon-fiber fabric to create the preform. The assembly of the 25 components and 37 inserts is achieved by joining the parts with a two-component adhesive[13]. The order of assembly is shown in Figure 7.

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[11] The two-component polyurethane polymer chosen by the ACC and used in this study was Bayer AG's Baydur 420.

[12] The specific spray-up preformming process used is called P4 (programmable powder pre-form process).

[13] The adhesive chosen by the ACC and used in this study was SIA's Plastilock 731SI.

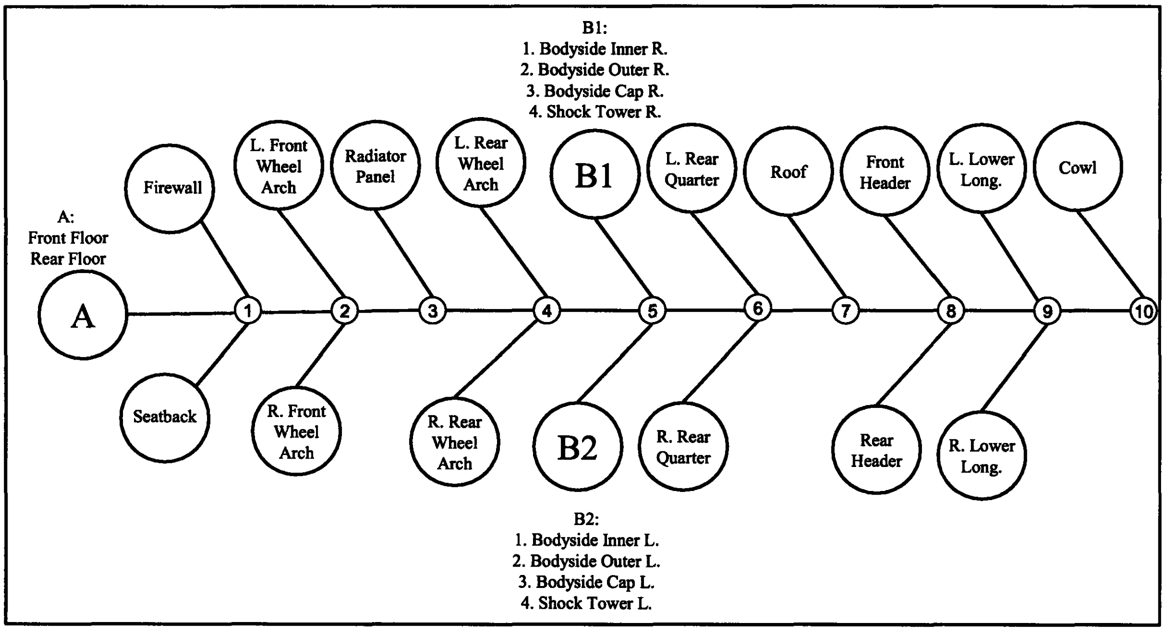

Figure 7: Automotive Composite Consortium Final (Modeled) Vehicle Assembly Order

3.2.1.2 Design Two: A Glass-Fiber Reinforced Polymer Composite Unibody

In addition to the highly innovative carbon-fiber reinforced design, a second less high-performance fiber option is examined – a hypothetical glass-reinforced fiber composite body. As shown in Table 7, carbon fiber's material properties allow significant weight reduction over glass fiber reinforced parts, and is as such an ideal choice for the Focal Project III's design goal of a minimum mass vehicle. Although a glass fiber reinforced polymer composite is a lower strength material than a carbon fiber reinforced polymer composite, and thereby requires thicker part designs, glass fibers have unit prices five to ten times less than carbon fiber. A glass fiber reinforced polymer composite body-in-white design thus provides an interesting comparison.

The hypothetical glass-reinforced design has the same general layout as the carbon-reinforced ACC vehicle. For each of the 25 components, height and width are kept identical. To maintain structural integrity, the thickness of the components is increased. The most common form of loading that body structure parts experience is stresses from bending (Kang 1998). 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:

$$h_G = \sqrt[\frac{1}{3}]{\frac{E_C}{E_G}}h_C$$ **Equation 1**

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 . Each of these moduli, is modeled as a function of the volume fraction of resin versus reinforcement, and the moduli of the resin and reinforcement as follows:

$$\boldsymbol{E_C = V_c E_c + V_r E_r} \qquad \textbf{\textit{and}} \qquad \boldsymbol{E_G = V_g E_g + V_r E_r}$$ **Equation 2**

where V_c is the volume fraction of carbon reinforcement E_c is the modulus of the carbon reinforcement, V_g is the volume fraction of the glass reinforcement, E_g is the modulus of the glass reinforcement, V_r is the volume fraction of the resin and E_r is the modulus of the resin. The volume fraction of glass reinforcement was assumed equal to that used in the carbon-reinforced components. The values for V_c, V_r, E_c, E_g, and E_r can be seen in Table 7.

Table 7: Physical Properties of Composite Components

V_c (=V_g)	V_r	E_c	E_g	E_r
35.1%	64.9%	230 Gpa	72.4 Gpa	3.5 GPa

The increase in thickness of the glass-reinforced parts has consequences throughout the SRIM process, affecting material quantities, preform spray times, molding cycle times, and line requirements. It is possible, in theory, that the switch from carbon to glass may have additional process implications. For example, differences in glass chemistry and conductivity may lead to longer part and assembly cure times. Given a lack of empirical evidence substantiating these differences, however, they are not included in the current process model calculations.

The assembly of the glass-reinforced components is modeled identically to the assembly of the carbon-fiber components. Due to their insulating qualities, two glass-fiber-reinforced composite components may actually require a slightly longer adhesive cure time. Again, however, due to a lack of empirical evidence and due to expert opinion that the effect is negligible for the geometries and processes studied, differences in adhesive cure times are not assessed.

3.2.1.3 Mild-Grade Steel Case

The baseline comparitor against the two composite designs, a steel unibody, represents the typical body design currently on the market. The design used for this comparitor is based on an in-production four-door mid-sized sedan. This sedan's design has a 103" wheelbase, and is 185" long, 67" wide, and 57" high (compared with the 108" wheelbase, 186" long, 71"wide, and 54" high composite design). The minor dimensional differences between the steel and composite body designs are, for the comparison in this study, insignificant. The steel body is made up of 120 components and 130 inserts (compared with 25 components and 37 inserts for the composite design).

3.2.2 Process Design

3.2.2.1 Structural Reaction Injection Molding

The SRIM process is modeled as a four-step process: (1) pre-form making, (2) pre-form trimming, (3) injection molding, and (4) part trimming and inspection.

3.2.2.2 Preforming

Pre-form making shapes the reinforcement material into the form of the part. This shaping of the reinforcement material is modeled in two ways to accommodate different design specifications: 1) through the spraying of fibers and 2) through the cutting and layering of woven fiber fabric. The type of pre-form method most appropriate for each part was chosen by design engineers from the ACC team, and then actuated in the model.

The "spray method", creates the perform shape by spraying chopped fibers onto a screen in the shape of the part along with either a powder or string binder. The screen is held in a press. Once the spraying is completed, the press closes, and the perform is heated to bind the fibers in place for handling. The model is programmed to assume a manufacturing line with a two-robot spray station at lower production volumes, and a manufacturing line with a six station carousel for higher production volumes. The modeled cycle time for the spray station consists of four stages: press opening (5 seconds), spraying, pre-form curing (2.5 minutes), and part unloading (30 seconds.) The spray time is a function of the amount of fiber (in weight) required for each pre-form and the chopper gun rate. The chopper gun rate is modeled as 1.6kg reinforcement per minute for carbon fiber and 2.29kg reinforcement per minute for glass.

The cost of the screen for the spray system is based on a regression of varying screen costs tied to the weight and surface area of the part. For carbon this regression is as follows:

$$C_{screen,C} = 8000 * W_C + 5000 * SA_C + 73040, \qquad \textbf{Equation 3}$$

where W_C is the weight of the carbon-reinforced part, and SA_C is the surface area of the carbon reinforced part. For glass, this regression is

$$C_{screen,G} = 8000 * X * W_G + 5000 * SA_G + 73040, \qquad \textbf{Equation 4}$$

with W_G the weight of the glass-reinforced part, and SA_G the surface area of the glass-reinforced part. The additional multiplier, X, is required due to the differences in density of the glass-reinforced versus carbon-reinforced parts.

$$X = \frac{\rho_C}{\rho_G} \frac{1}{3}\sqrt{\frac{E_C}{E_G}} \qquad \textbf{Equation 5}$$

Component densities are calculated as follows:

$$\rho_C = V_c \rho_c + V_r \rho_r \quad \textit{and} \quad \rho_G = V_g \rho_g + V_r \rho_r, \qquad \textbf{Equation 6}$$

whereby p_C is the density of the carbon-reinforced composite, p_c is the density of the carbon reinforcement, p_G is the density of the glass-reinforced composite, p_g is the density of the glass reinforcement, and pr is the density of the resin. The densities of carbon reinforcement and glass reinforcement are given in Table 2 in the previous section.

The "lay-up method," uses fabric sheets of reinforcement. The fabric is pulled directly from the roll onto the forming machine, where it is cut to the required pattern. The cut patterns are then stacked two to five sheets thick directly on the SRIM press. To better form the stack of fabric sheets to the shape of the part, blocks in the reciprocal shape of the part, called conformers, are used to press the fabric into position. 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. Vacuum pressure is used to pull the sheets (note, these sheets are dry fabric, not pre-pregs) into the shape of the mold. This entire process takes 2 ½ minutes to complete. Three-dimensional shaping of the pre-form occurs with the closing of the press during injection molding.

The capital equipment assumptions used in this study in association with the two performing methods are shown below in Table 8.

Table 8: Pre-form Making Alternatives

	Spray System: Two-Robot	Spray System: Carousel	Lay-Up System
Equipment	$1.6M; two robots, two molds, automated robot inputs from cad, molds stationary, robot moves	$1.6M; robot, six molds, automated robot inputs from cad, automated shuttling	Cutting table (wheel cutter, computer, and vacuum system): $150K
Tools	$80K-$150K, $78K for i. & o. pillar	$80K-$150K	"Conformers": $500 ea., last 5000 cycles
Material	Carbon Fiber: $11.05/kg	Carbon Fiber: $11.05/kg	Hexcel Fabric (woven 24K): $6/lb
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	3min 5sec + (pre-form weight /chopper gun rate)	3min 5sec + (pre-form weight /chopper gun rate)	2 ½ min

3.2.2.3 Pre-form Trimming

During pre-form trimming, the edges of the shape are refined, removing any unwanted scrap. This "trimming" is estimated to remove 3% of the fiber originally sprayed and binded into form, and to require 90 seconds per part.

3.2.2.4 Injection Molding

The SRIM step is modeled in this study as consisting of five stages: a 30 second load, a 20 second partial closing of the mold and injection of the resin, a 2.5 minute completion of the closing of the mold and cure of the resin, a 30 second opening of the mold and unloading of the part, and a 10 second clean and prep before the loading of the next part. To reflect current practice in industry, injection time, closing time, and mold closed time is held constant in the model, regardless of part dimensions, by varying the number of injection sites and dispensers. During injection molding, between one and four resin dispensers, depending on the size and complexity of the part, inject the resin into the mold. The model assumes a typical two component polyurethane thermoset resin for the reaction injection molding of structural automotive components. The cure time is modeled as 2.5 minutes or 4 minutes in accordance with whether a powder or string binder, respectively, is assumed to be necessary for the part. The cycle time breakdown described above is used for both the carbon- and the glass-reinforced parts in the model.

Press costs for the injection molding set are estimated in the model as a function of part length, part width, and the force required of the press. The press cost estimation was developed by Kang, and is independent of the component material (Kang 1998). Kang's regression is as follows:

$$\boldsymbol{Press\ Cost = 49{,}400 + 590.0 * (Required\_Force) + 94{,}000 * (Part\_Length * Part\_Width)}$$

Equation 7

Resin can be expected to flow radially outward from central sites. Based on this assumption, the required fill time is calculated in the model as follows:

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

Equation 8

And the maximum required mold force as follows:

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

Equation 9

Here K is the permeability of the preform, ϕ is the porosity of the preform, $R_{initial}$ is the radius of the dispenser's injection port, and R_{max} is the radius of the mold. For a more detailed discussion of these relationships see Kang 2000.

In the case of SRIM processing, the resin must be injected at a sufficient number of sites to achieve an even resin distribution and to ensure infiltration before gelling. The number of dispensers required for successful resin distribution was estimated by the ACC engineering team, according to the size and geometry of each part for the purposes of this study.

Tool costs for the SRIM press are also estimated in the model as a function of part weight and surface area. The tool cost estimates for the SRIM press were originally developed in Kang's study based on empirical production data for glass-reinforced parts. This equation for estimating tool costs, shown below, is also used to estimate tool costs for the glass components in this study:

$$C_{tool,G} = 26300 + 71350 * W_G^{0.67} + 24800 * SA_G \qquad \textbf{Equation 10}$$

To estimate tool costs for the carbon-reinforced components, this study uses the following equation, where the second coefficient is changed to compensate for the difference in material density from the glass-reinforced components:

$$C_{tool,C} = 26300 + 71350 * X^{-0.67} * W_C^{0.67} + 24800 * SA_G \qquad \textbf{Equation 11}$$

The value of X in the above equation is the same as used in the glass screen cost regression described in the section on preforming.

3.2.2.5 Final Trimming and Inspection

After being unloaded from the press, the part is ready for final trimming and inspection. The final part trimming removes the resin flash escaped beyond the mold walls. This step is modeled as requiring 120 seconds during which 3% of the original material is removed.

3.2.3 Assembly

Although there are some examples of prior composite part sub-assemblies, there is to-date no experience in medium- to high-volume production of a composite unibody. In developing the assembly model for this study, several assembly configurations and technologies were reviewed, including technologies under development. Based on this survey of methods, a single combination of methods was selected as most likely and feasible for use in the near future. Only this option is described and modeled in this paper. The interested reader should refer to Fuchs 2002 for a more detailed discussion of eliminated options.

The bonding step in assembly entails positioning the first part or already-joined sub-assembly, laying down adhesive, and then positioning subsequent parts or sub-assemblies on top of the adhesive along the join. Bonding requires pumps, a metering system, adhesive guns, a heated hose, and switch-over pumps to carry out the dispensing of the adhesive. A standard hydraulic metering system is typically used for low production volumes at a cost of around $120K. A manifold system with a larger pump system and a vat of adhesive is typical for high annual production volumes (above 70K) at a cost of $300-350K. A mix tube is attached to the end of the adhesive robot, and the two components of the adhesive, supplied from different drums, are frequently pumped to the mix tube from a location elsewhere in the plant. The mix tube, which is 12-18" long, requires purging approximately once per shift. The purging takes around 10 minutes, and is accomplished by throwing out the mix tube ($2/tube) and replacing it with a new one. Approximately 1-5% of the epoxy in the process is lost through purging. The actual laying of the adhesive can be accomplished at about 0.3m per second. Additional time must be allotted for the robot switching between joins as well as for the beginning and end of each part's cycle, these additional time increments are estimated at two seconds per join and three seconds per cycle, respectively. Generally, around an 3/8" diameter bead is typical, although parts with bad tolerances can require up to a ½" bead, while parts with an extremely refined tolerance can require as small as 1/8" beads.

Both the carbon and glass composite bodies are modeled as being assembled using 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. From a production perspective, a heat cure epoxy has the advantage of an infinite open time – the time at room temperature during which adhesion to the other surface must occur for optimal join properties. This infinite open time increases flexibility in the length of adhesive which can be laid down at one time along the join, and, therefore, in the number of parts which can be joined at a given station. A heat cured adhesive also leads to less adhesive waste due to premature curing than a room temperature cured adhesive. This study models the adhesive step assuming no primer and no pre-heating is necessary on the joining surfaces of the parts. According to the heating conditions assumed for this study, cure times within the model range between two and three minutes, depending on the length of the join.[14] The price of the adhesive used for this study is $17.50/kg.

The researchers surveyed seven different cure methods before choosing one for use in the model. These seven methods are as follows: hot blocks, hot air impingement, RS induction cure, radio frequency cure, microwave frequency cure, and oven curing. Based on discussions with experts in the industry, this paper uses hot air impingement as the cure methods in the model. Hot air impingement uses a large fan to draw ambient air down through a tube heater and out vents within the assembly fixture each carefully aligned with the bond line, Heaters are generally placed every 50" along the join, with each heater costing between $8K and $12K. The system as a whole also requires a thermocouple sensor, as well as a control panel for the thermocoupler.

In addition to bonding equipment and curing equipment, fiber reinforced polymer composite component assembly also requires fixturing investments. The fixture costs used in this analysis are shown in Table 9 along with the associated curing system for different sized sub-assemblies.

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[14] The cure time for a heat cured epoxy can range between one and seven minutes depending on the magnitude of heat used for cure.

Table 9: Fixture and Equipment Investments, Based on Assembly Order in Figure x

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

The layout of assembly activities assumed in the model is shown in Figure 2 in the earlier section during the introduction of the case studies. The order of operations involves constructing an underbody including the interior structures around the instrument panel beam and behind the rear seat and then creating a frame the addition of build up bodysides and roof. The actual layout of the assembly line is dependent on this order of operations, as well as the number of parts, the type and intensity of joining, and the production rate. Higher production rates incorporate more stations, more robots, and more automation, while smaller production runs assume fewer stations, more time at each station, and more manual labor.

3.3 Results

This section presents the model cost results for the three body-in-white (BIW) designs that were examined: mild steal uni-body (steel), carbon fiber reinforced polyurethane composite (carbon), and glass fiber reinforced polyurethane composite (glass).

3.3.1 Baseline Results

Figure 8 shows the unit cost of producing and assembling each of the three alternative BIW cases in the U.S. The steel BIW costs range from $900/body unit at 250,000 APV to $3500/body unit at 20,000 APV. Carbon costs range from $1700/body unit to $2200/body unit, and glass from $1600/body unit to $1100/body unit at those same production volumes. At annual production volumes under 120,000, the glass-reinforced BIW is more competitive than the steel, and at annual production volumes under 50,000, the carbon-reinforced BIW is also more competitive.

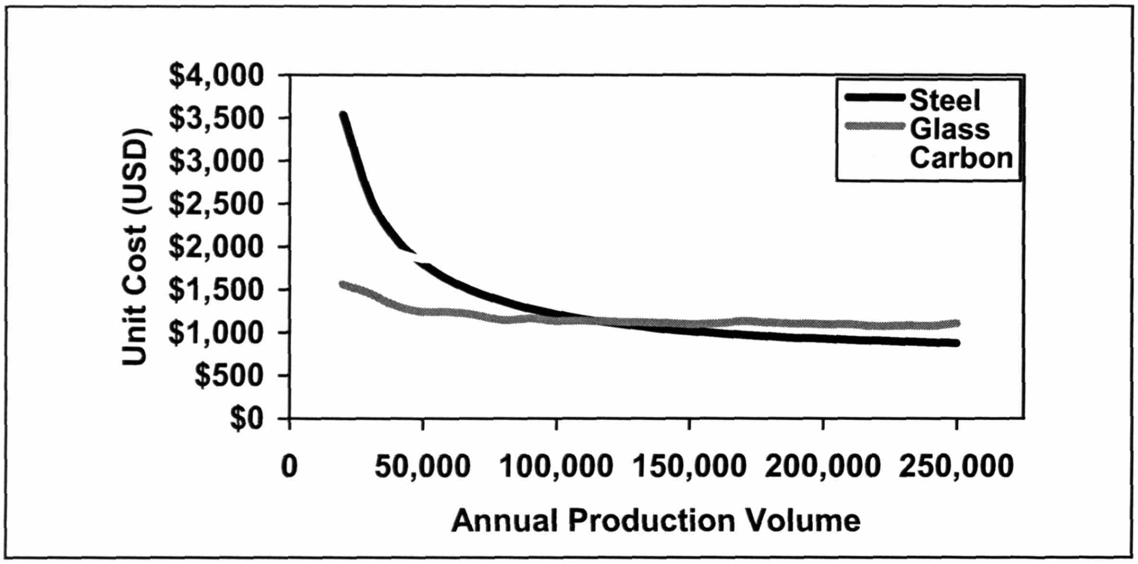

Figure 8: U.S. Body-In-White Unit Cost Sensitivity to Production Volume

The steel option dominates at high production volumes, because of its low material costs and exceptionally fast cycle times. However, the steel design becomes less cost-competitive than composites at lower production volumes under due to the under-utilization of the costly steel stamping equipment. For example, 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 add up to only 24% of carbon, and 40% of glass BIW costs. (See Figure 9.) As these capital investments must be spread across fewer and fewer steel products, unit costs climb rapidly.

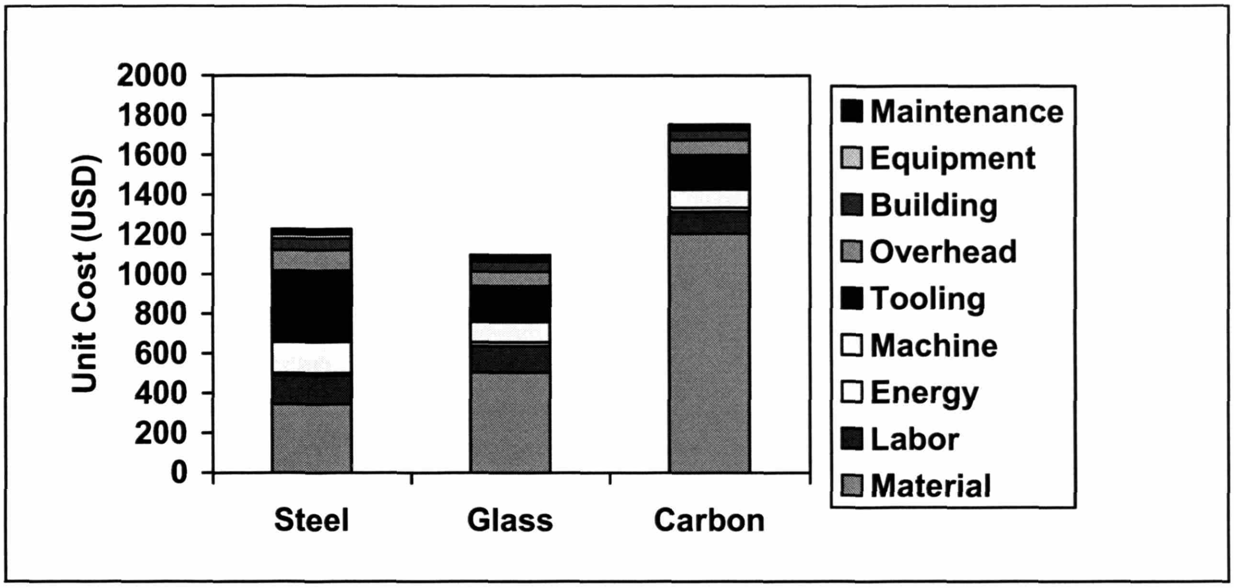

Figure 9: U.S. Body-In-White Unit Cost Breakdown at an Annual Production Volume of 100,000 Units

Figure 10 isolates component production from assembly costs. This figure shows that although the composite BIW has far fewer total components than steel, the sum of the composite component and insert costs adds up to significantly more than the sum of the steel component and insert costs (so long as annual production volumes are above 30,000 for glass.)

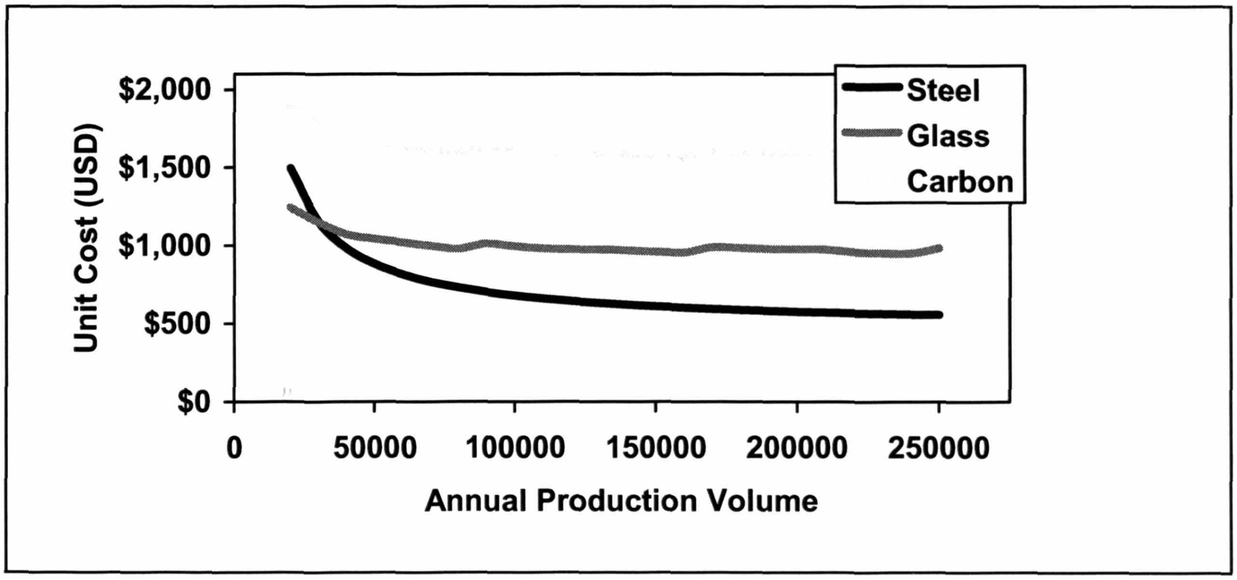

Figure 10: U.S. Body-In-White Component and Insert Cost Sensitivity to Annual Production Volume

The cost of assembling the composite BIW, however, is significantly cheaper than that of the steel BIW assembly, as can be seen in Figure 11.

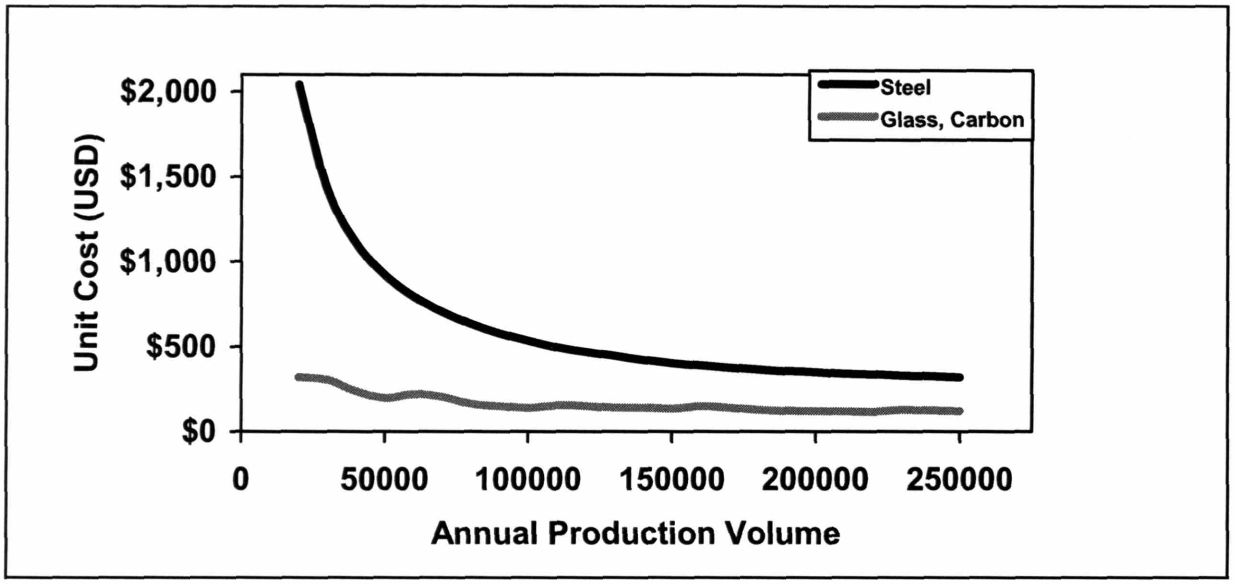

Figure 11: U.S. Body-In-White Assembly Cost Sensitivity to Annual Production Volume

3.3.2 Exploring the Sensitivity of Results

The results which follow show the sensitivity of the previous cost analyses to changes in carbon fiber price, performing scrap rate, injection molding reject rate, and assembly adhesive price. As can be seen in Figure 12, the carbon fiber price has by far the largest impact on final

BIW cost.

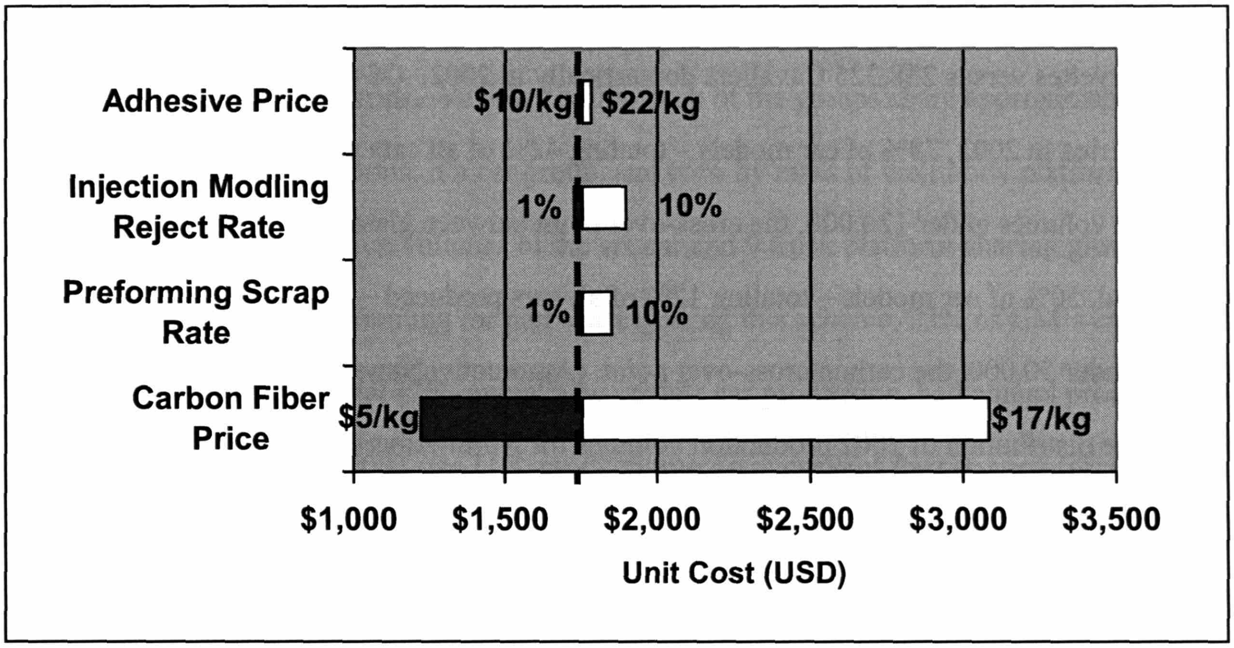

Figure 12: U.S. Body-In-White Unit Cost Sensitivity to Key Production Factors

The shown range of potential carbon fiber reinforcement prices, changes the annual production volume at which the carbon composite body design has cost-parity with steel from 30,000 units annual to 100,000 units annually, depending on whether carbon fiber can be sourced at $40/kg versus $10/kg, respectively. In contrast, the expected range of performing scrap rates only has the potential to shift the carbon fiber design's cost parity with steel by 5000 units, from annual production volumes of 50,000 if scrap rates are between 1-3% to annual production volumes of 45,000 if scrap rates rise to 10%. The reject rate during injection molding has a slightly larger impact on the cost-competitiveness of the carbon BIW against steel, increasing the cost-parity point by 10,000 to an annual production volume of 40,000 units, if reject rates are 10% instead of 1-3%. Changing the adhesive cost within the expected range has no discernable impact on the carbon composite design's cost parity point with steel.

3.4 Discussion

Typical production volumes for a vehicle on the U.S. market vary greatly. GM produced 32,555 Corvettes versus 238,225 Cavaliers domestically in 2002. Of vehicle bodies produced in North America in 2002, 78% of car models – totaling 42% of all cars produced – have annual production volumes under 120,000, the cross-over point between glass and steel. During that same period, 50% of car models – totaling 12% of all cars produced – have annual production volumes under 50,000, the carbon cross-over point. (AutomotiveNews 2003). **Figure 3-7** presents the distribution of 2002 production volumes for North-American produced vehicle models. Figure 13 shows the percentage of total vehicles which fall below the composite-steel cross-over points from Figure 8.

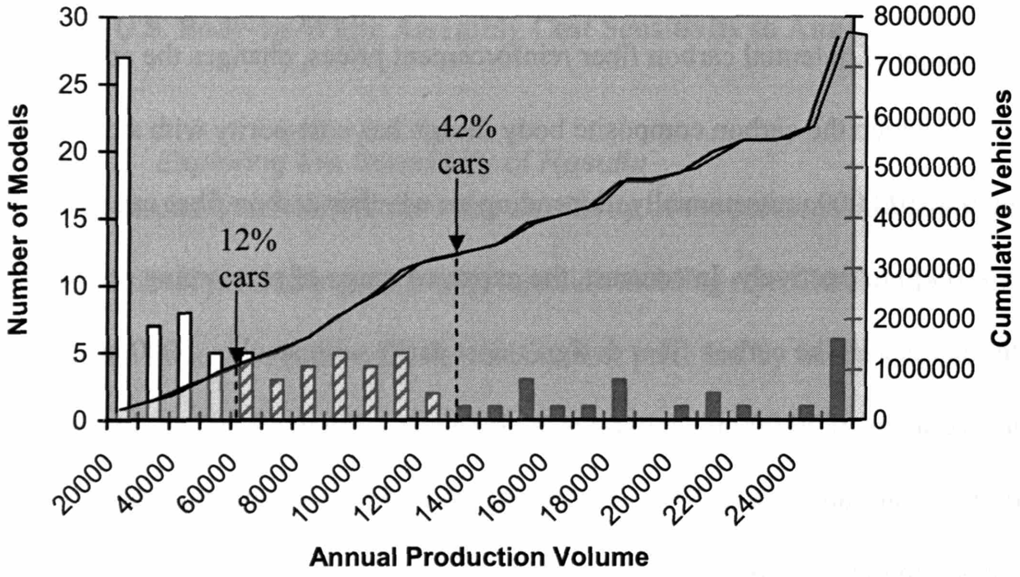

Figure 13: Vehicles Sold in North America with Annual Production Volumes below Composite-Steel Cost Parity

Figure 13 provides a first-cut estimate for composite cost-competitiveness. Some components, however, are shared across model platforms, causing the relevant production volume across which to spread capital equipment costs potentially higher. An analysis of GM's

North American production showed that GM cars could be grouped into six groups according to sharing of component platforms, and GM trucks could be grouped into nine groups according to sharing of component platforms. Vehicles within each of the groups share approximately 50% by mass of their body platforms, if a car group, and 65% by mass of their body platforms, if a truck group.[15] The production volumes of the six car and 9 truck platform-sharing groups can be seen in Table 10. Even accounting for part sharing using this scheme, 22% of GM's car models, making up 11% of GM's total U.S. annual new vehicle car production, had annual production volumes under 120,000 in 2002 (the U.S. production crossover point for glass reinforced composite with steel). Considering platform sharing, 17% of GM's car models and 2% of GM's total U.S. annual new vehicle car production had annual production volumes under 50,000 in 2002 (the U.S. production crossover point for carbon reinforced composite with steel.)

Table 10: Car Model Groupings According to Platform Sharing for One Company's Models

(Shaded platform groups have production volumes at or below the composite-steel cost parity)

Platform	Platform Type	Vehicles Sharing Platform	Total Vehicles Produced Annually
1C	Car	Century, Regal, Impala/Lumina, Monte Carlo, Intrigue, Grand Prix	702,738
2C	Car	LeSabre, Park Avenue, DeVille, Eldorado, Aurora, Bonneville	310,381
3C	Car	CTS, Seville	70,500
4C	Car	Cavalier, Sunfire, Ion, S Series	548,775
5C	Car	Corvette	35,938
6C	Car	Joy/Swing, Monza	86,983

A full analysis of which components to make out of steel versus which to make out of composite would require assessing cost-competitiveness at the appropriate vehicle or platform production volume of each subassembly. The results presented in this section, regarding the relevant competitiveness of steel, carbon-reinforced, and glass-reinforced BIWs, are only relevant for a BIW constructed entirely of the respective material, and not for the cost-

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[15] Platform sharing in the groups when looking at the whole vehicle (not just the body) was higher, ranging between 70% and 85%, depending on the group.

competitiveness of individual subassemblies. Only at U.S. annual production volumes below 30,000 for glass reinforced composite components is the production of composite components less expensive than steel. At these low production volumes, it would be possible to substitute glass-reinforced composite for steel components in a body-in-white for, for example, light-weighting purposes, without assembly or consolidation of parts benefits being necessary to achieve cost-competitiveness. At higher production volumes, composites only begin to gain cost-advantage at the sub-assembly level. This advantage does not exist within all sub-assemblies. Work-to-date has shown both the roof and the bodyside subassemblies are cheaper in steel than in composites for all production volumes. Kang's 1998 thesis discusses a cost-optimizing body-in-white combining composite and steel subassemblies. Further study is required to find the ACC Focal Project III subassemblies which are more cost competitive out of composite versus those more cost-competitive out of steel, given appropriate vehicle or platform-sharing production volumes.

Future analysis of the cost-competitiveness of composites versus steel at the individual sub-assembly level incorporating platform-sharing considerations as well as hybrid-material options for the BIW would provide extensive insights. As a first cut, the above review of annual new vehicle production in the U.S. suggests, that from a production cost perspective over 70% of current vehicle models should be being evaluated for composite-steel hybrid body-in-whites, and 16% of truck and 22% of car models should be being considered for entirely composite body-in-whites. Industry trends indicate that these values will only increase as build-to-order and custom initiatives lead to an increase in the number of distinct models, and, therefore, a decrease in the production volumes for individual components.

3.4.1 Assessment of Model Assumptions

Scrap rates, reject rates, and adhesive costs, as shown in the tornado diagram in Figure 7, have little impact on overall costs, regardless of annual production volumes. Within the annual production volume ranges explored in this study, neither scrap rates, nor reject rates, nor adhesive costs should be of immediate concern in the interest of minimizing manufacturing costs.

Materials, on the other hand, make up 69% of the overall costs of the carbon-reinforced BIW. At a price of $22/kg, carbon fiber makes up 81% of these material costs. The market price of carbon fiber thus has a huge impact on the cost-feasibility of producing a carbon-fiber reinforced BIW, and is worth scrutinizing here in greater depth. Car manufacturers claim only to be willing to buy carbon fiber at or below $11/kg. Claims by carbon fiber suppliers have gone as far as to state carbon fibers could eventually reach $6.6/kg. Proof of carbon fiber production methods, which would enable such a low price, has yet to be seen. To-date, carbon fiber is generally $22/kg (the price used in this study), and can still run as high as $40/kg, depending on the quantities purchased. The work of the ACC has led to improvements in the design and processing of the carbon composite BIW, compared to the vehicle analyzed by Kang in 1998. The results of the model show that the carbon-composite BIW goes from being competitive with steel below annual production volumes of 19,000 to being competitive with steel below annual production volumes of 50,000. If a carbon fiber market price of $11/kg can be achieved, the carbon composite BIW becomes more cost-competitive than steel below annual production volumes of 90,000 units. Regardless of production volume, the carbon fiber reinforced BIW is approximately $600 more expensive than a glass-reinforced BIW – a cost premium that may eventually become feasible if the market valuation of vehicle light weighting, either for environmental or fuel economy reasons, rises. The impact of carbon fiber prices on the annual production volume at which steel-carbon cost parity is reached, is shown in Figure 14.

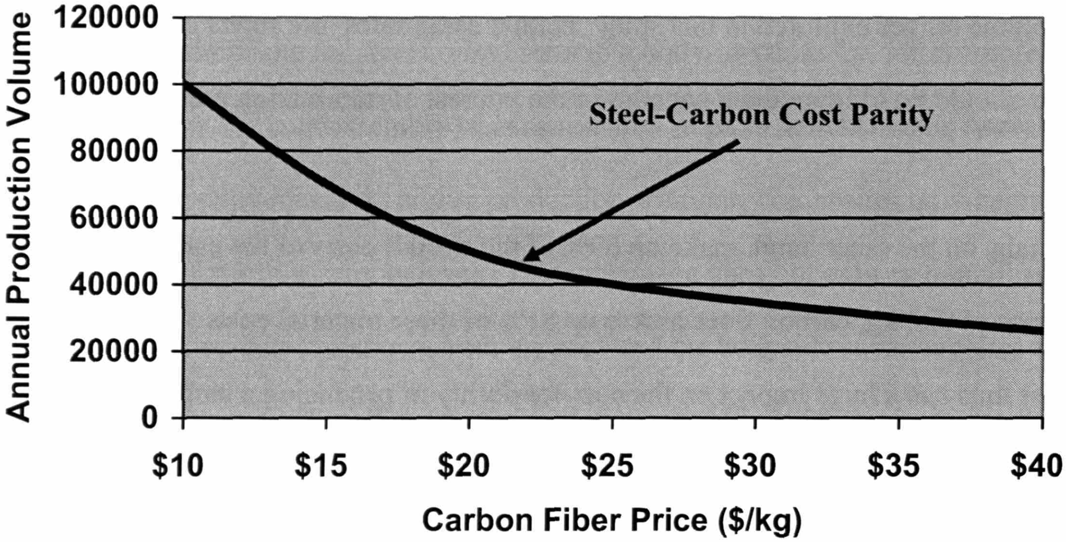

Figure 14: Sensitivity of Steel-Carbon Cost Parity to Carbon Fiber Price

3.5 Conclusions

Automobiles on the road today have material compositions over 92% steel. Fiber-reinforced polymer composite body technologies provide a way of light-weighting the vehicle, both to increase fuel economy and to allow for additional electronic devices. Several advances have occurred in the past decade in fiber-reinforced polymer composite body-in-white design, component processing, and assembly technology. This study uses process-based cost modeling, which allows the user to evaluate technology alternatives before investments are made, to gain insights on the manufacturing cost-feasibility of fiber-reinforced carbon composite body-in-white technology in comparison to the typical steel BIW. The results show fiber-reinforced composite body-in-whites to have greater potential today to be competitive against steel than they did in the past. Platforming reduces, but does not eliminate, the competitiveness of composites. Including platforming considerations, approximately 12.4% of the vehicles produced in North America in 2002 would have been cheaper if produced using the ACC Focal Project III design guidelines and glass-fiber reinforcements.

3.6 Future Work

Previous work suggests that composite component technology may be more competitive in some subassemblies than other (Kang 1998). The high cost of composite component production in comparison to steel suggests that composites would be particularly competitive in subassemblies where they provide extensive consolidation of parts, and not competitive in applications where little or no parts consolidation is possible. A future analysis focusing on the production volume at which individual composite subassemblies become cost-competitive against their steel equivalent would provide helpful insights on the ideal application of polymer composites. Such an analysis should also explore possible technical complications which would limit the structural or processing potential of a steel-composite hybrid design.

Two scenarios are not covered in this study, but would be of interest for future work. The first is the competitiveness of the composite cases against other light-weighting body materials. The most common material other than composites competing for a place in automotive body components is aluminum. Aluminum may have lower investment costs than steel, but the cost per kilogram of aluminum is much higher. Aluminum has the advantage over composites of being perceived as having lower technical risk. A second scenario warranting further study is the competitiveness of composites versus steel for body-in-white applications with annual production volumes under 30,000. At these low production volumes, metal space-frame designs would become a competitor against the alternatives in this study, as would RTM and other low tooling investment processes.

4 Opportunities Lost: Reconsidering Technology Strategy in the Global Automotive Industry

This chapter explores the impact of manufacturing offshore on technology development incentives, and thereby the technology development path of the automotive industry. With the lowering of trade barriers over the past decade, today's firms have many new opportunities to choose where to manufacture and for what market. The implications of these new options for firm technology strategy are unclear. It is also uncertain whether U.S. firms will be able to learn the right lessons fast enough to survive global competition. For firms to compete in the global economy, they may need to take a new approach to technology and product development decisions.

This chapter looks at the implications of new global manufacturing opportunities for technology strategy in the automotive industry. There are several important, distinguishing features of the automotive case. As discussed in the section on Case Selection, Question Development in Chapter 2, the value chain in the automobile industry tends to be organized regionally (Humphrey 2003). Similarly, market preferences vary with region, and economies of scale approximate regional markets for a majority of vehicles. (See Chapter 2 Table 5.) As a consequence of this market and industry structure, automobile firms for a majority of vehicle models manufacture locally for the local market. Given the industry's market-technology match and the small number of competing firms, the existing multinational firms are able to have numerous manufacturing plants globally. These same firms currently perform the majority of their R&D in their home country close to their international headquarters.

This research uses an innovative combination of engineering modeling and qualitative methods to motivate the need for a new approach to technology strategy in the global automotive industry. Given the lack of previous work on this subject, this chapter focuses on in-depth analysis of one case – fiber-reinforced polymer composite body designs in the automotive industry (Glasner 1967, Eisenhardt 1989, Yin 1989). The work presented in this case is based on data collected at Ford, General Motors, DaimlerChrysler, and 15 related firms in the automotive supply chain. The research presents results on how key process variables (yield, cycle times, downtimes, wage, materials) change with manufacturing location. The research then explores how those factors affect the cost-preferred design. Process-based cost modeling techniques (Kirchain 2000) are used to create a model of manufacturing based on the plant-level manufacturing data collected at firms. This model is used to evaluate the cost-competitiveness of emerging designs against the prevailing technology, and how this cost-competitiveness changes if production is in China instead of in the U.S. The quantitative analysis is supplemented by information collected in semi-structured interviews. These semi-structured interviews are used to understand actual firm decisions, as compared with what the model might predict, as well as to understand the general product development environment. The paper complements the model data and interview data with market data to provide a more holistic view of the firms' decision-making and product development environments (Jick 1979).

In the case of the automotive industry, manufacturing offshore does not change the path of technology development. Although both GM and DaimlerChyrsler initially consider manufacturing the emerging technology offshore, in both cases the firms pull out of their original efforts. Although the firms may have learned in the process, it is unclear if they have learned the right lessons. Further, the extent of confusion and monetary losses by both firms suggests the need for a new approach. This work shows that offshore manufacturing can change the most cost-competitive design alternative. This work also demonstrates that decision tools, such as process based cost modeling, may provide distinct advantages in informing firms' design decisions prior to offshore investment. It will important for future modeling work to explore the implications of offshore production differences for platform strategy. Just understanding the implications of production cost differences offshore would not, however, have solved the firms' inefficiencies, since they also did not understand the offshore market. Future work should also explore what factors may be causing the extensive misunderstandings observed in this case.

4.1 Background: Rising Trends in the Automotive Industry

Resource scarcity, security, and environment issues associated with oil consumption continue to be a large and growing global concern. Motor vehicles constitute one third of global oil consumption and are the number one air pollutant (Davis 2004). In the U.S., the problems are far greater. Specifically, motor vehicles constitute two thirds of all oil use in the U.S., and contribute to 60% of U.S. air pollution (80% in cities) (Davis 2004). The U.S.'s oil consumption is not only a problem with regards to oil scarcity and air pollution, it is also a problem for national security. As can be seen in Figure 15, within the past 50 years the U.S. has gone from importing 0% to importing 70% of the oil it consumes.

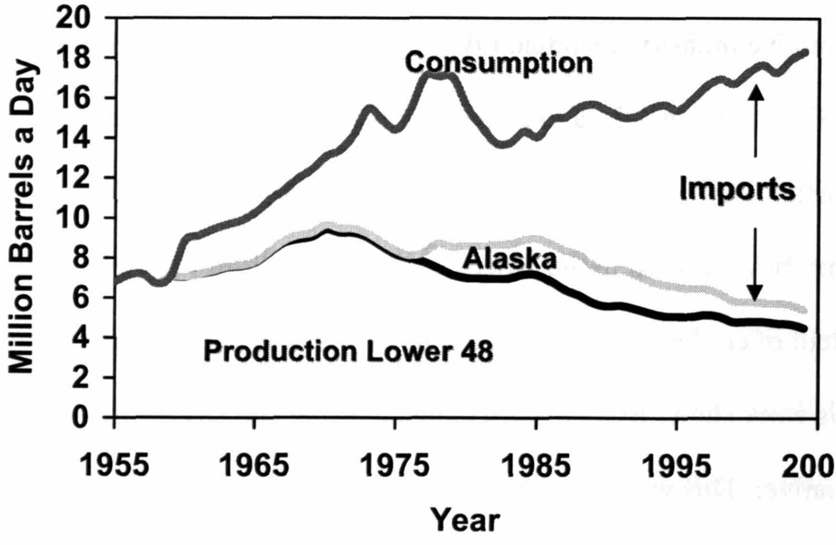

Figure 15: Growth in U.S. Dependency on Foreign Oil (Davis 2004)

With the exception of the oil shocks of the 1970s, these trends have to date had little impact on the consumer trends, at least in U.S. automobile market. Recently, the Iraq war has given rising prominence to the problems oil imports pose to U.S. national security. It is unclear, however, if this increased prominence will have any impact on consumer spending. Resource scarcity and global warming problems are not likely to go away. Forecasts for an oil production peak range from within a year or two to a peak sometime in the 2030-2050 time period (Zucchetto 2006). The International Energy Agency forecasts a moderation in price increases by 2010, with real prices increasing after 2030 (Zucchetto 2006). To slow (no less stop) global warming trends, changes are required already now (Hoffert 2002, Pacala 2004).[16]

At the same time as these concerns in energy, security, and the environment are growing, so is passenger vehicle demand in the Chinese market. Chinese passenger car ownership has had an average annual growth rate of 20% over the past decade. (See Figure 16.) Demand for a family car from the rising middle class in China is forecast to emerge sometime between 2005 and 2010 (Ward'sCommunications 1995). Forecasts expect Chinese annual light vehicle sales to be 7M by 2010 (Fourin 2004), and to exceed sales in the U.S. market by 2015 (IBM 2005).

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[16] Proposals to limit atmospheric CO2 to a concentration that would prevent most damaging climate change have focused on a goal of stabilizing CO2 levels at 500 parts per million (ppm), or less than double the pre-industrial concentration of 280ppm. Very roughly, to stabilize CO2 levels at 500ppm requires that emissions be held near the present level of 7 billion tons of carbon per year for the next 50 years. Emissions are currently on a course to more than double in that time period. Both Hoffert et. al. and Pacala and Socolow recommend strategies to stabilize global climate change. Hoffert claims that research and development is urgently needed to produce technological options that can allow both climate stabilization and economic development. Pacala and Socolow call for changing our energy consumption practices with an emissions-reducing portfolio of existing technologies. Either strategy would require dramatic changes in our current lifestyle and choice of technologies. Hoffert, M. e. a. (2002). "Advanced Technology Paths to Global Climate Change Stability." Science **298**(1): 981-987, Pacala, S. a. S., R. (2004). "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." Science **305**: 968-972.

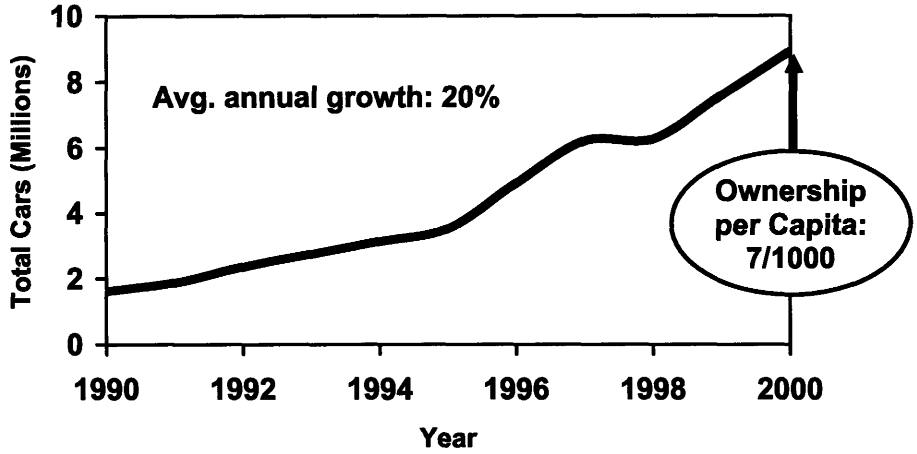

Figure 16: Growth in Chinese Passenger Car Ownership (Source: (Ward'sCommunications 2003).)

It is difficult to know at what point energy, environmental, and security concerns will begin to play a significant role in the automotive market. New CAFÉ standards in the U.S. or elsewhere globally could make the need for fuel economy improvements a rapid reality for vehicle manufacturers. Other impacts on consumer preferences, such as increases in oil prices, could still be 25 years out. From a product development standpoint, there are few "easy fixes" to significantly improve fuel economy. One substantial and already existing solution to improving fuel economy is vehicle light-weighting (NRC 2002). A primary available mechanism for reducing the weight of the vehicle body is material substitution. This research examines the economic competitiveness of a fiber-reinforced polymer composite vehicle body against the steel alternative currently on the road.

Fiber-reinforced polymer composites vehicle bodies have both advantages and disadvantages in today's market. A primary advantage of fiber-reinforced polymer composites 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 not only has 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 fiber-reinforced polymer composites 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 fiber-reinforced polymer composites in vehicle bodies. Automobile manufacturers currently lack design and production experience with fiber-reinforced polymer composites. Gaining this experience would require both time and development costs. Building a polymer-composite body production plant would also require additional capital investment not required for producing steel or even other metal components in existing facilities. From a market perspective, the public currently has a poor perception of the crashworthiness of fiber-reinforced polymer composite – aka "plastic" – vehicles. The less glossy appearance of composite body components (without additional finishing corrections), is also generally not well-received by the appearance-conscious American public. Finally, additional difficulties may exist for the repair and replacement and the recycling of composite components.

Given the previously discussed long-term trends in the global automotive industry, producing a polymer composite vehicle in China for the Chinese market seems, at first, like an obvious choice. Based on conventional academic and industry wisdom, low-capital high-labor intensive processes are well-suited to developing country production economics. The lower investment required for a composite production facility also entails lower risk for the automobile manufacturer if the venture fails. It is also possible that developing country consumers may act as a more forgiving market for the less shiny composite appearance and any other unforeseen difficulties. Finally, current greenfields in China may provide the perfect environment for experimenting with products, such as composites, requiring different capital investments.

This research studies two large-scale initiatives, one by General Motors and one by DaimlerChyrsler, to manufacture automobiles with glass-fiber reinforced polymer composite bodies in China for the Chinese market. In both cases, after significant time and investment, the firms pulled out of producing composite-bodied vehicles in China. This work uses process-based cost modeling to understand the cost incentives that may have driven such a decision. This research triangulates the cost-modeling analyses with semi-structured interviews and market data to gain a more holistic understanding of firms' decision-making processes, and the reasons they may have pulled out. The chapter concludes by returning to the modeling analysis to draw lessons for future work on how automotive firms may need to be adjusting their approach to global product development problems.

4.2 Methods

This chapter presents a case study from which the author inductively builds grounded theory (Glasner 1967, Eisenhardt 1989, Yin 1989). The chapter triangulates quantitative modeling data, qualitative interview data, and market data to provide a more holistic view on the drivers of technological change (Jick 1979). On the quantitative side, process-based cost modeling techniques are used to map technical design decisions to their manufacturing cost implications and thereby isolate cost incentives for technology development. The qualitative interviews and market data are used to develop a picture of the actual design and location choices being made by firms in the industry, and the short- versus long-term implications of those decisions for firms' technology development path, and ultimate competitiveness.

This work uses three process-based cost models to forecast the production and assembly of an automotive vehicle body – one for steel component production, one for fiber-reinforced polymer composite component production, and one for component assembly. The details of these models can be found in (Fuchs 2003) and in Chapter 3. In extending this work to address the implications of manufacturing location on the relative economic competitiveness of the design alternatives, this work identifies a set of factors that would lead production costs for identical technologies to differ across two regions. (See Table 2 in Chapter 1.) The section below discusses the product selection, company participation, model data collection, and interviews for this case.

4.2.1 Product Selection

As discussed in Chapter 3, design and processing information for the composite vehicle body used in this study is drawn from the Automotive Composite Consortium's Focal Project III. The design goal of the Focal Project III was to produce a body-in-white with minimum mass, which maintained structural integrity and cost-competitiveness at medium to high production volumes. The design uses carbon-fiber reinforcement and has a unibody architecture, both of which have significant advantages in achieving the design goal of minimizing mass and maintaining structural integrity.[17]

The designs developed by the automotive firms for implementation in China had significantly different aims. In both cases, the firms were interested in experimenting with fiber-

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[17] As discussed in Chapter 3, although there has been a dramatic rise in the use of fiber-reinforced polymer composites in vehicles over the past three decades, there does not currently exist on the market a vehicle with an all-composite unibody. Some passenger vehicles have incorporated low-performance, commodity polymers in non-structural body panel applications. Vehicles with non-structural polymer body panels have included GM's Saturn, EV1, Corvette, Firebird, and Camaro, as well as Ford's Tarus/Sable, Mustang, and Windstar Kobe (1999).. These vehicles use an internal metal frame, or "space frame" to develop their structural integrity. The body panels are then hung off of the space frame. A unibody, in contrast, uses welding or bonding processes to connect the body components into a single unit. In the case of a unibody, there is no internal frame. Instead, the structural integrity of the vehicle derives from the body parts themselves.

reinforced composite technology, given its potential advantages in meeting long-term market trends. The firms' short-term design aims, however, were to develop a minimalist, low-cost "family car" for the Chinese people. Such a low-cost car would most likely not use carbon fiber reinforcement, but rather its weaker, cheaper alternative – glass fiber reinforcement – along with an internal space frame for structural integrity.

This study focuses on how the competitiveness of the cutting-edge Focal Project III design studied in Chapter 3 changes with manufacturing location. Given that the automotive firms design prototypes most likely used glass fiber reinforcement, this Chapter focuses on the comparison between the glass-fiber reinforced alternative and the steel base case from Chapter 3. By focusing on the cost-competitiveness of the Focal Project III design, this research emphasizes the impact of manufacturing offshore on the cost-competitiveness of emerging technology. Additional modeling work will be necessary to understand the competitiveness of a composite vehicle with an internal space frame, and how that competitiveness may change with manufacturing location. Although the space frame design has fewer weight-savings advantages, it may have additional cost advantages in a developing country production environment.

4.2.2 Company Participation

The original impetus for this research was to explore the cost-competitiveness of the Automotive Composite Consortium's Focal Project III design. As discussed in Chapter 3, the Automotive Composite Consortium was formed in August 1988 as a collaborative effort of Ford, General Motors and Chrysler (now DaimlerChrysler). The author worked with all three of these companies over the course of the project, and had by far the most extensive interaction with General Motors. Over the course of the project, the author also had extensive interaction 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.

4.2.3 Process-Based Cost Model Data Collection

Details on the design and process data collected are provided in Chapter 3. Details on data collection with regards to production environment differences in the U.S. versus China are provided below.

To pursue country differences for all of the factors listed in Table 2 in Chapter 1 as well as to extract the quantitative impact on the associated model variables for each factor was beyond the scope and time constraints of this analysis. Instead of pursuing links between factor inputs and model variables, given limited time, direct data was sought on a subset of model variables, estimated based on the above mapping to be most significant in creating manufacturing cost differences between the two countries. Data was gathered from companies in each country on these factors through a survey. (See (Fuchs 2003).) Some additional overarching questions were included to add insight on driving forces in each country. The results of the survey were incorporated into the model as country differences in direct wages, capital recovery rate, installation costs, price of building space, building recovery life, working days per year, average downtime, reject rates, scrap rates, machine costs, raw material costs, and tool costs.

Table 11 shows the change in cost inputs between the U.S. and China at an actual vehicle body production plant of one major U.S. OEM manufacturer in China. The "i" in Table 11 represents the step of the component production or the station number in assembly. The steps of glass- or composite-reinforced composite component production are (1) preforming, (2) pre-form trimming, (3) injection molding, and (4) final trimming. The steps of steel stamping component production are (1) blanking, (2) blank trimming, (3) stamping, and (4) final trimming. The number of stations in assembly varies with production volume.

Table 11: 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}.[2] (Revised from (Fuchs 2003).)

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

4.2.4 Interviews

The author used a combination of semi-structured interviews and news reports to develop an understanding of why a firm might choose to manufacture a polymer-composite bodied vehicle in China. This qualitative data collection focused both on (a) the existence and timing of the firm's decisions and (b) the company's explanations or logic behind those decisions. In the case of General Motors, the author became aware of the firm's decision to manufacture a polymer composite China car in 2000 while the company was ramping-up to execute this decision. The author had the opportunity to communicate with GM employees both after the original decision to manufacture the composite vehicle design in China, as well as after they chose to pull out. The author performed a total of eight semi-structured interviews with employees involved in the China car program at General Motors. Five of these interviews occurred after the original decision to manufacture a composite vehicle in China and three after the decision to pull out.

After learning about GM's decision, the author collected news report data on other companies which had either previously or currently also chosen to pursue a polymer-composite vehicle in China. After discovering DaimlerChrysler's similar decision in 1997 to produce a polymer-composite vehicle in China, the author was able to arrange two interviews with employees involved in the China Car project at Daimler Chrysler. Both of these interviews occurred in 2003, three years after Daimler Chrysler decided not to pursue a composite-bodied People's Car in China.

The author also conducted one interview with Ford, and one interview with the CEO of the World Transit Organization. The interview with Ford aimed to understand whether the company had ever considered producing a polymer-composite bodied vehicle, and what its design plans were for China. The interview with the CEO of the World Transit Organization discussed his decision to produce polymer-composite bodied vehicles in the developing world, and his current plan to produce such a vehicle in China.

4.3 Results

4.3.1 Interview and News Reports: Two Attempts to Manufacture Polymer-Composite Body Vehicles in China

Both DaimlerChrysler and General Motors attempted to produce a minimalist, fiber-reinforced polymer composite body vehicle for the Chinese market. The stories of each firm's decision to produce a composite-bodied car in China are recreated from news and interview data below.

Figure 17, situated at the end of this section, shows the relative timing of the two firms' China car programs. DaimlerChrysler decided to produce a composite-bodied car for the Chinese people several years earlier than General Motors. In 1995, Chrysler initiated plans for a China concept vehicle and a plastic car strategy for the company. In 1997, Chrysler officially announced that it planned to produce a small inexpensive plastic "people's" car for China and other emerging markets. This $6000, four-seat, compact "Composite Concept Vehicle," was designed to require 5x less investment and 7x less factory space than its traditional steel alternative, and achieve 60mpg (Vasilash 1997, RMI 2002). The body panels were made by injection molding thermoplastic polyethylene terephthalate (PET) with 15% glass reinforcement. Although Chrysler's four-part design had a tubular steel frame that was bonded and bolted to the bottom of the plastic structure for additional stiffness and load-carrying capacity, the body components were structural and created a true unibody construction (Vasilash 1997, Winter 1997). Chrysler planned to eventually put the experience it gained producing these emerging market vehicles towards production of light-weight low-cost sports cars and ultra-high mileage sedans (Priddle 2002).

Three years after Chrysler's announcement, General Motors also decided to pursue producing a composite vehicle in China. The General Motors top-secret "Asian Family Car" program aimed at producing a more sophisticated, $12,000 polymer composite vehicle in China for the Chinese market. The design returns to a steel space frame architecture with body panels hung from the space frame. GM's Asian Family Car program started with the technology – specifically, a decision within GM to pursue manufacturing a vehicle with an all-composite body. A team was created, and sent around the world to examine which of GM's six key markets would be most appropriate for production of a composite car. In each market, the team evaluated the suitability of labor rates, skill levels, and equipment and tool availability for implementing the technology. Given the extremely labor intensive nature of the composite technology, the team decided it would be most appropriate to carry out the project in one of its emerging markets. Other advantages of producing in a developing country market included a potentially more forgiving market. Of particular interest to GM was experimenting in one of the eight emerging markets – Russia, China, India, Indonesia, Thailand, Mexico, Brazil, or South Korea – experiencing 85% growth in vehicle sales. In the end, GM felt China was the best place for the first attempt, and decided to shift the project to South Africa, Russia, or Egypt if the venture in China didn't work out.

In 2000, while General Motors was still secretly moving forward with its Asian Family Car, DaimlerChrysler announced that it would discontinue the Composite Concept Vehicle project, and to hold off on further investment in China. Within a year, DaimlerChrysler also ended its plastic car initiative. According to the news, the program's initiative, already losing momentum, "was lost in the ensuing shuffle of people and budgets" when Daimler management took over the company (Priddle 2002). Conversations with people inside the company, however, reveal that the Composite Concept Vehicle project actually met its end when the prototype was poorly received in tests with Chinese consumers. In tests with prototypes in both China and India, DaimlerChrysler found consumers uninterested in the minimalist design. It is unclear if technology uncertainty played any role in DaimlerChrysler's decision to pull out of developing a Composite Concept Vehicle for China. A 2002 news report points out that DaimlerChrysler experienced technical problems with tooling, paint, and production of the composite Wrangler hardtops with which it planned to "prove the thing out" (Priddle 2002). The same news article, however, points out that the plastic was able to prove itself out in development efforts using the Composite Concept Vehicle molds (Priddle 2002).

At the same time DaimlerChrysler was pulling out of its Composite Concept Vehicle project, GM was rapidly moving forward. By 2001, GM had signed into a three-way joint venture, and was setting up production facilities for their composite Asian Family Car outside Shanghai. In 2003, however, GM pulled out of its composite plans, and instead decided to ship over dated steel production equipment from its Mexican facility. In talking with people within General Motors, the major reason cited for pulling out of the composite China car plans was the car's poor reception with Chinese consumers. Given the product's poor market reception, renewed concern over the technological risks involved in producing an all-composite vehicle also emerged, and contributed to the decision. In prototype tests in both China and India, GM found the consumers uninterested in the less glitzy appearance of the planned polymer composite body. Although the lower risks associated with the lower investment costs of the composite vehicle was originally an attractive part of the proposition, by bringing over existing facilities from Mexico, GM was able to avoid the costs of a new investment altogether. Looking back, one employee remarks, "It was just cheaper to take an old design and ship it there. It's marketing. In the end, the non-composite version was viewed to be higher-end in the eyes of the consumer."

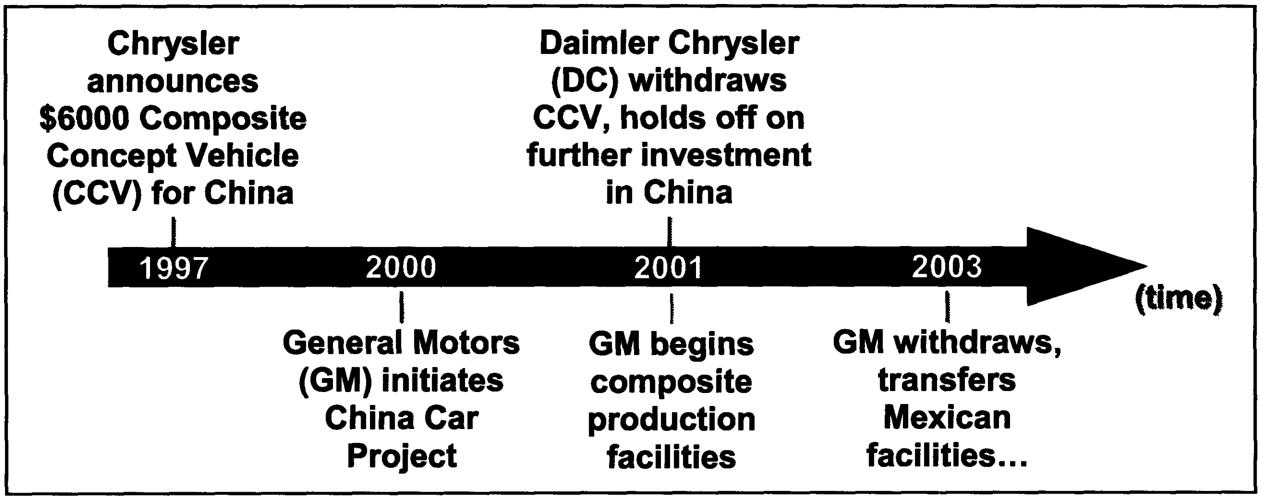

Figure 17: Timeline for DaimlerChrysler and General Motors Polymer Composite Initiatives

4.3.2 Process-Based Cost Modeling: A Different Perspective[18]

In China, a steel body-in-white is the most competitive alternative at plant production volumes above 105,000 units annually. At annual production volumes below 105,000, the glass-reinforced BIW is the most cost-competitive option. (See

Figure 18.)

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[18] Several of the figures from Fuchs, E. (2003). The Significance of Production Cost Inputs in Regional Technology Choice: Composite Automotive Body-In-Whites in the U.S. versus China. Engineering Systems Division: Technology and Policy. Cambridge, M.I.T. are revised and reproduced below to aid in the analysis and discussion that follows.

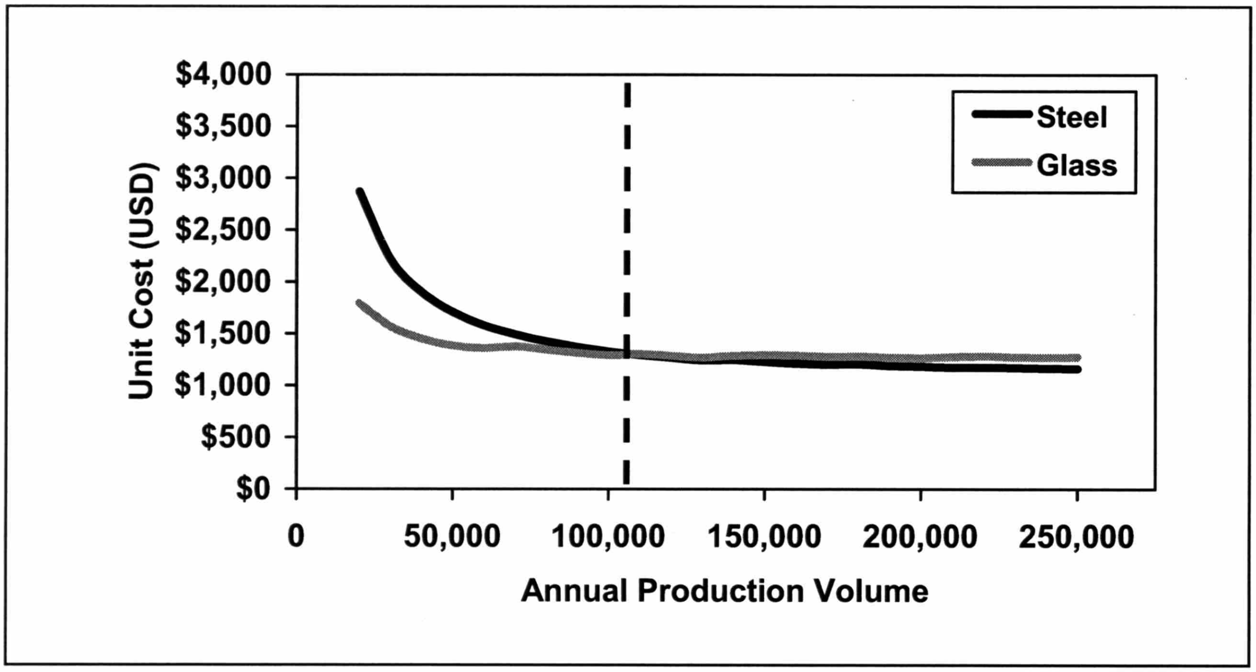

Figure 18: P.R.C. Body-In-White Unit Cost Sensitivity to Annual Production Volume (Revised from (Fuchs 2003).)

As can be seen in

Figure 19, the cost curves for production in the U.S. take a different form than the cost curves for production in China. The cost curve for production of a steel body-in-white in the U.S. is much steeper than the steel body-in-white cost curve in the China. The steel-glass and steel-carbon cost parities for manufacturing production in China are slightly lower than the same cost parities in the United States. In the U.S. glass is the more cost-competitive alternative at production volumes under 115,000 (10,000 annual units higher than China).

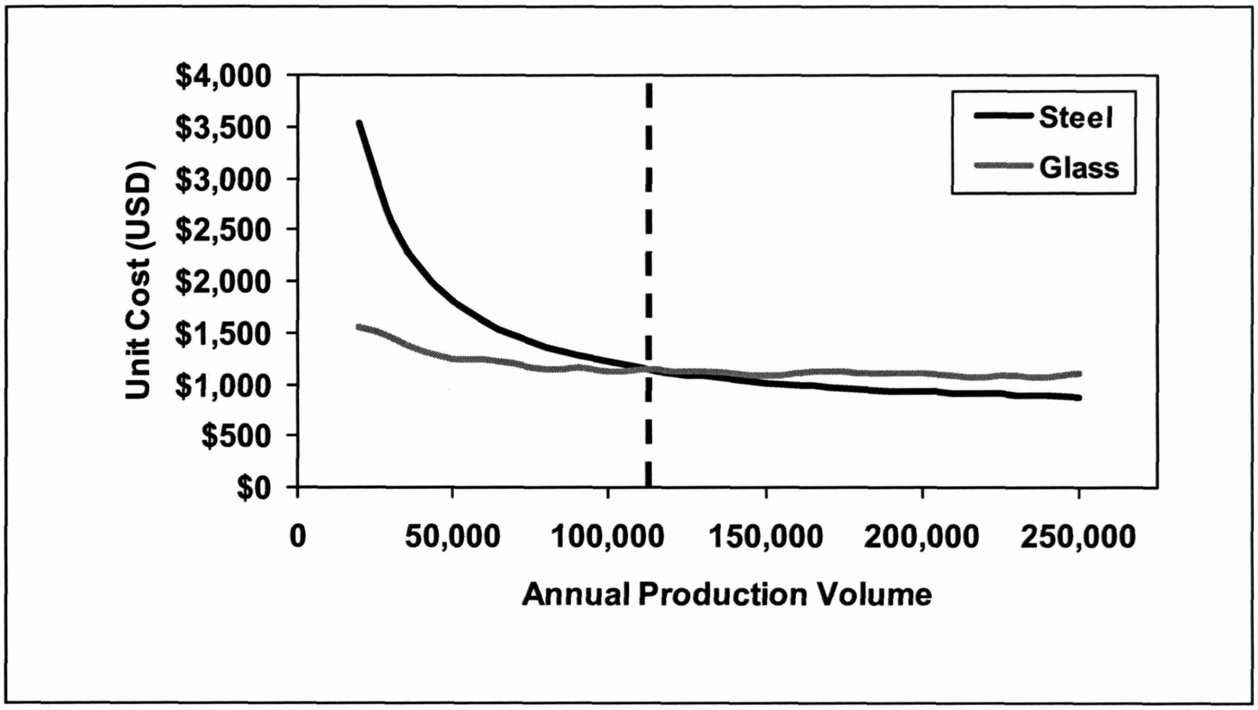

Figure 19: U.S. Body-In-White Unit Cost Sensitivity to Annual Production Volume (Revised from (Fuchs 2003).)

In understanding these cost curve differences, it is instructive to look how each technology's production cost break down, as shown in

Figure 20. In China, steel body-in-white production is dominated by equipment costs, followed by material costs. The polymer composite body-in-white technologies in China are dominated by material costs, followed by machine and tooling. In the U.S., steel body-in-white production costs are dominated by tooling costs, followed by material costs, and then machine and labor costs. Polymer composite body-in-white production costs in the U.S. are dominated by material costs, followed by tooling and then labor. (See Figure 20.)

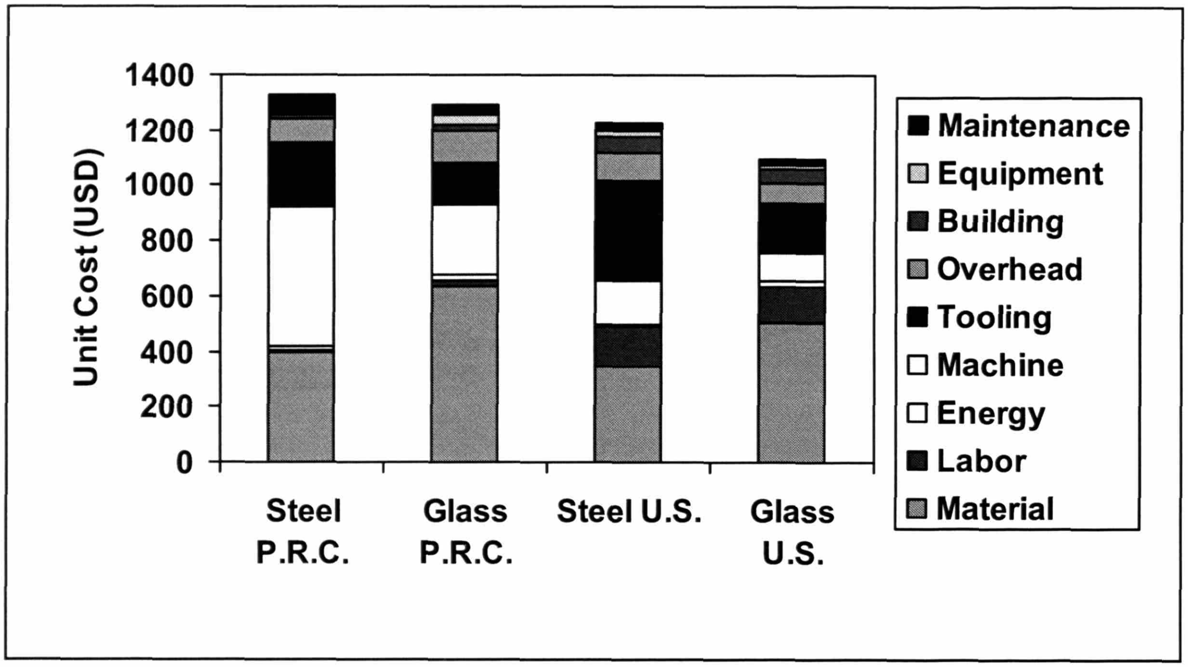

Figure 20: Body-In-White P.R.C. and U.S. Production Cost Structure Breakdown at Annual Production Volumes of 100,000 Units (Revised from (Fuchs 2003).)

Figure 21 through

Figure 24 show the separate cost contributions of component production versus assembly. As can be seen in

Figure 23 and

Figure 24, the composite body-in-white production cost advantages come from parts consolidation during assembly. The labor-intensive nature of assembly, however, makes the cost-advantages of part consolidation less significant in China than in the U.S., due to China's lower labor rates. As can be seen in the figures, both the production and the assembly of the steel components are more competitive relative to the composite alternative in China than they were in the U.S. As a whole, the steel body is thus more competitive than the composite alternative at lower production volumes if both bodies are manufactured and assembled in China instead of the U.S.

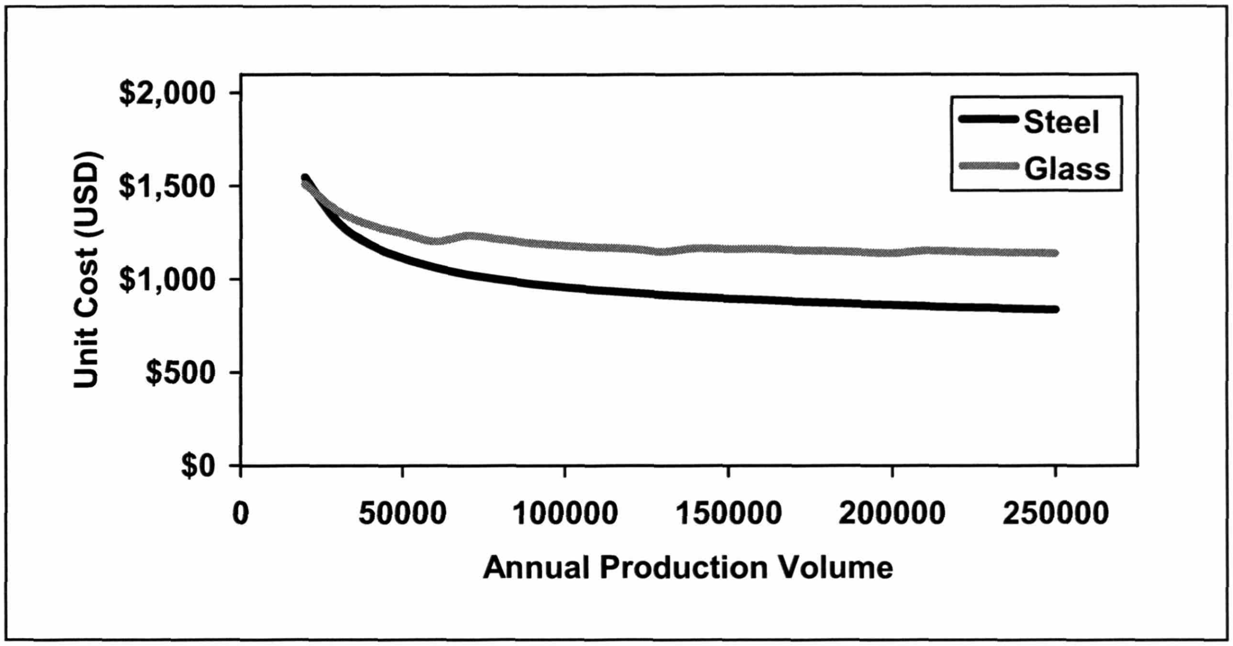

Figure 21: P.R.C. Body-In-White Component and Insert Cost Sensitivity to Annual Production Volume

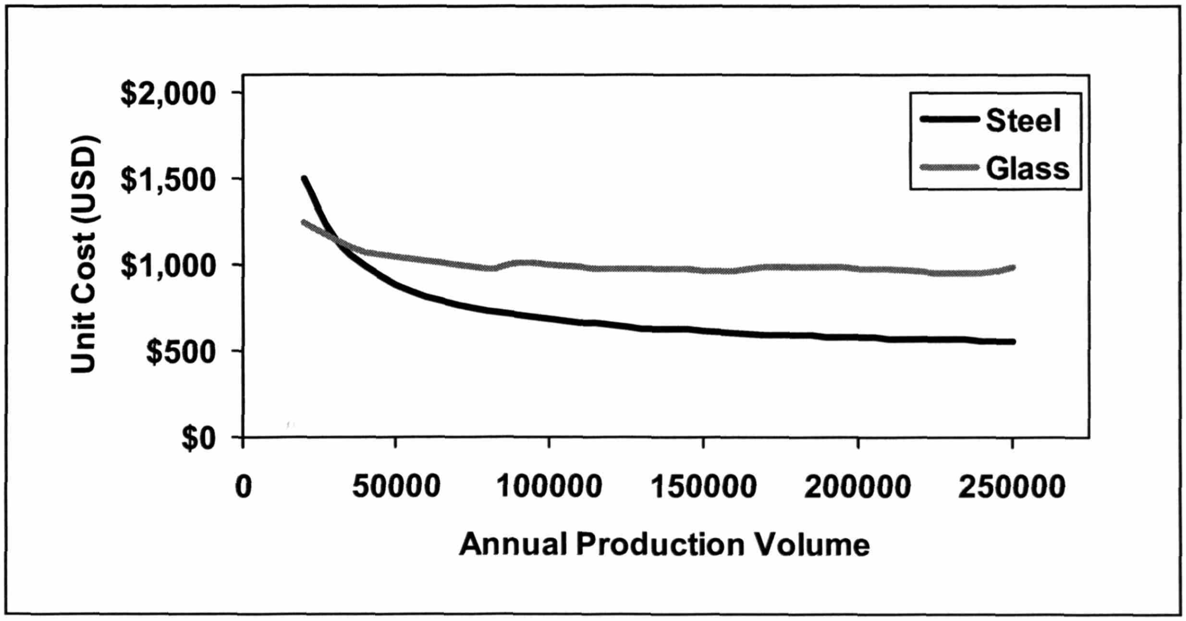

Figure 22: U.S. Body-In-White Component and Insert Cost Sensitivity to Annual Production Volume

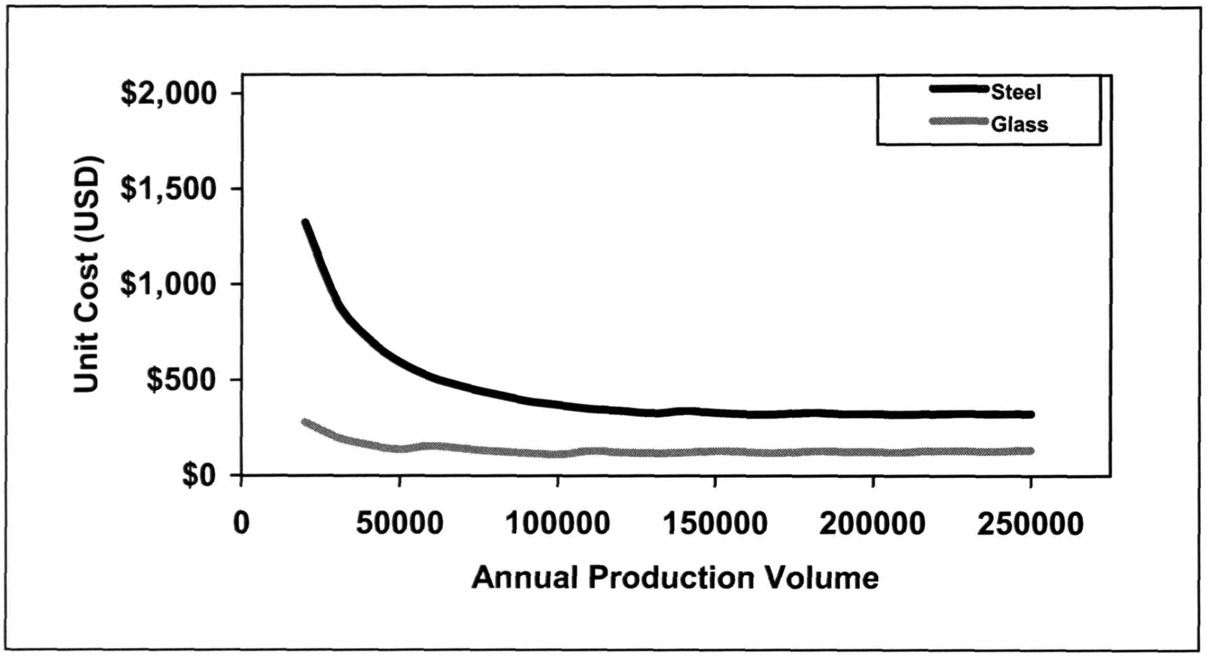

Figure 23: P.R.C. Body-In-White Assembly Cost Sensitivity to Annual Production Volume

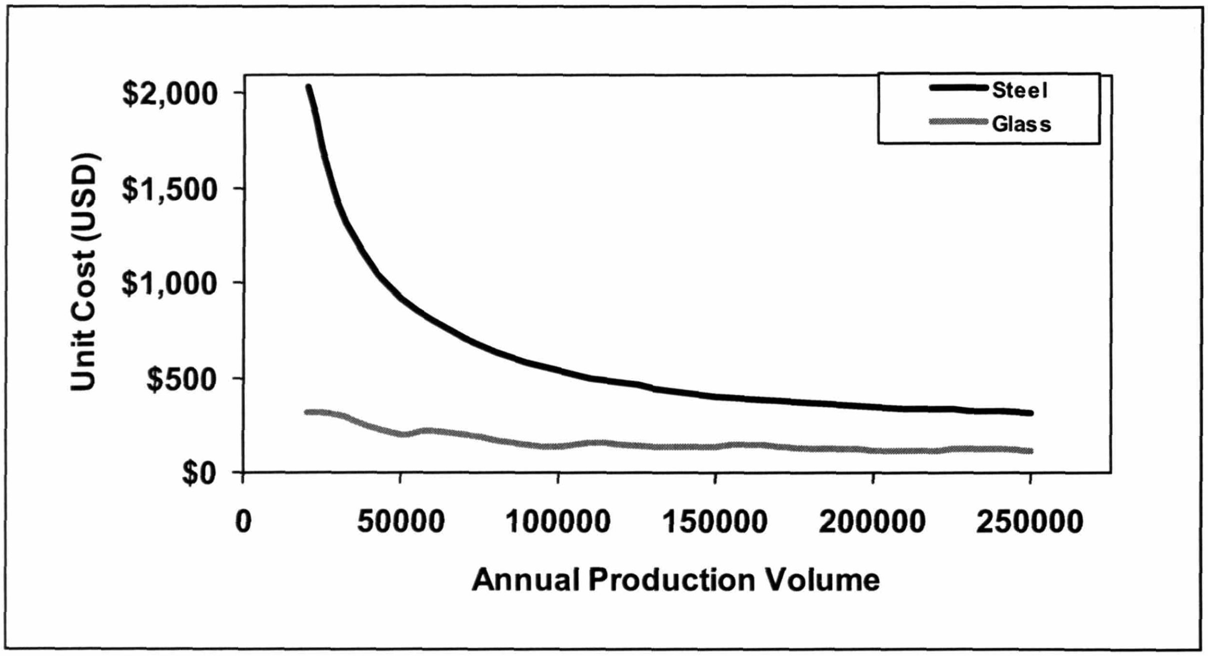

Figure 24: U.S. Body-In-White Assembly Cost Sensitivity to Annual Production Volume

4.3.3 Market Results

Figure 25 and Figure 26 below use available data on 2002 North American Vehicle production and on 2001 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, 27.8% of the vehicles produced by multinationals in China in 2001 would have been cheaper if produced with a glass-fiber body-in-white unibody, and 42% of vehicles produced by multinational in the U.S. would have been cheaper if produced with a glass-fiber body-in-white. (See Figure 25 and Figure 26.)

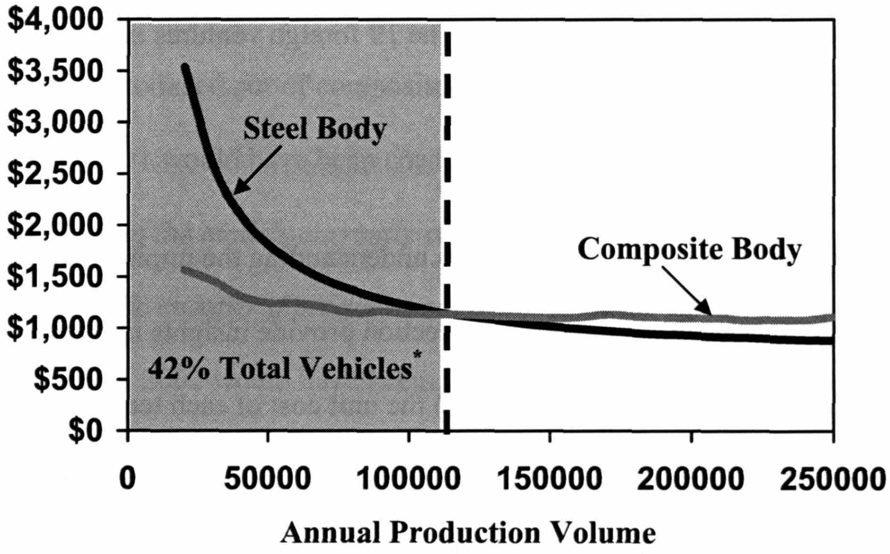

Figure 25: Cost-Competitiveness of Polymer Composite Body-In-White[19] given a U.S.-Based Manufacturing Environment (Component and Insert Production, Body Assembly)
* "Total Vehicles" based on total vehicles manufactured in North America in 2002 (Source: (AutomotiveNews 2003))

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[19] Fiber-reinforced polymer composite body-in-white based on the Automotive Composite Consortium Focal Project III design.

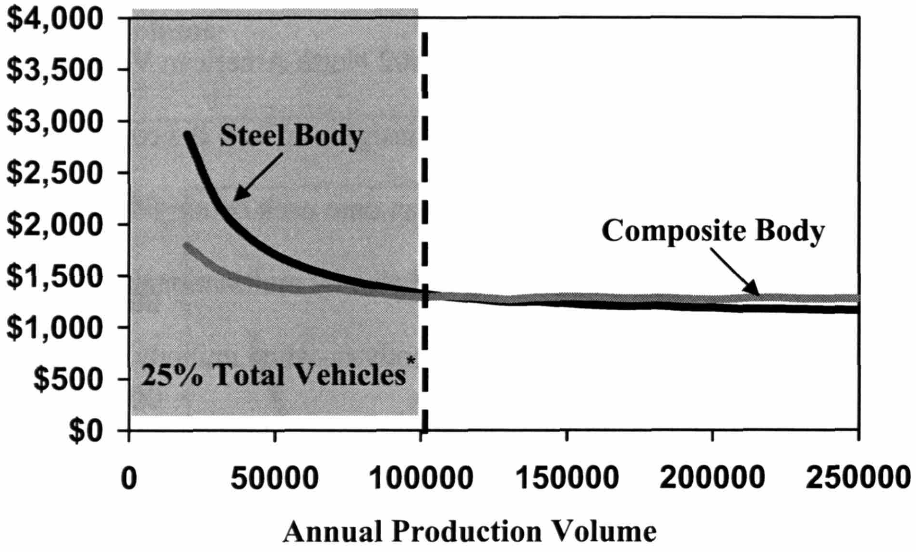

Figure 26: Cost-Competitiveness of a Polymer Composite Body-In-White[19] given a China-Based Manufacturing Environment (Component and Insert Production, Body Assembly)
* "Total Vehicles" based on total vehicles manufactured by the 19 foreign ventures in People's Republic of China in 2000 (Source:(AutoInChina 2001).)

4.4 Analysis and Discussion

4.4.1 Synthesis of Results

Evaluating a technology investment decision requires understanding the implications of that decision from many angles. The results in the previous section provide insights into several important decision parameters. These parameters include (1) the unit cost of each technology alternative at different production volumes, (2) the financial risk associated for each technology with misjudging the magnitude of market demand, and (3) the match between the number of vehicle models (and thereby total vehicles) produced in a country at a given production volume and the results of the process-based cost model. There are several important take-aways from the results in the previous section with respect to each of the above parameters. First, *the composite body-in-white is 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 120,000 units or less in the U.S. In contrast, composites are cheaper than steel at annual production volumes of 110,000 units or less in China. Second, *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 110,000, at 250,000 units annually composites are only $50 more expensive per unit in China. In contrast, at annual production volumes of 10,000 units, steel is $1080 per unit more expensive than composites when produced in China. *Thus, firms which choose steel stand to lose much more money if they misestimate their expected annual production volumes.*[20] Third, *a lower percentage of the total vehicles currently produced in China have annual production volumes such that they would be cheaper if produced out of composites*. Based on the analyses presented in this chapter, 42% of total vehicles produced in the U.S in 2002 would have been cheaper if produced out of composites. In contrast, only 25% of the total vehicle produced in China in 2001 would have been cheaper if produced out of composites. However, *a higher percentage of the models currently produced in China have annual production volumes such that they would be cheaper if produced out of composites*. Specifically, 78% of the models produced in the U.S in 2002 would have been cheaper if produced out of composites. Meanwhile, 82% of the models produced in China in 2001 would have been cheaper if produced out of composites.

4.4.2 Firm Sense-Making

Both DaimlerChrysler and General Motors explored manufacturing a no-frills polymer-composite car in China for the Chinese market. The firms' decisions were driven by (1) the assumption that composites production economics would be particularly well-suited to a developing country manufacturing environment and (2) the assumption that the non-shiny

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[20] A more detailed discussion of the sensitivity of composite versus steel unit costs to plant utilization can be found in Fuchs, E. (2003). The Significance of Production Cost Inputs in Regional Technology Choice: Composite Automotive Body-In-Whites in the U.S. versus China. Engineering Systems Division: Technology and Policy. Cambridge, M.I.T. The results presented in (Fuchs 2003) further confirm that a firm entertains less financial risk if it misestimates annual production volumes for a composite body-in-white facitlity.

appearance and uncertain performance characteristics of composites would be more readily accepted by a developing country consumer.

In choosing to pull-out of their composite car initiatives in China, both DaimlerChrysler and General Motors primary motivation was the poor reception of their prototypes by the Chinese consumer. In particular, in both cases the Chinese consumer was not interested in purchasing a minimalist, non-shiny, non-prestigious vehicle. Concerns about problems with polymer composite technology also played a secondary role in influencing General Motors', and possibly also DaimlerChrysler's decisions. These seemed, however, only to be concerns, as no examples were given of actual problems experienced with the technology by either company. Nothing in the discussions with DaimlerChrysler or General Motors suggested that they were aware of the cost results shown in this chapter – in particular, that a polymer composite body would actually be less competitive relative to steel in a Chinese production environment than it is in the U.S.

It is unclear if DaimlerChrysler and General Motors learned the right lessons in their experience in China. First, the firms' *product and design* choices, not their *technology* choices, caused their prototypes to be poorly received by the Chinese market. The firms' decisions to pull out of their plastic car strategies suggest, however, that the polymer composite technology, rather than marketing, ended up getting blamed. Second, assuming that neither DaimlerChrysler nor General Motors gained in their experience a better understanding of the implications of Chinese production environment for design competitiveness, they are most likely failing to appropriately incorporate these differences in production economics into their global product development strategies.

4.4.3 Opportunities Lost?: The Potential for Polymer Composite Automobile Body Technology in China

Investment in an emerging technology is inevitably fraught with uncertainty. As discussed in the background section, there are many disadvantages to polymer composites applications in automobile bodies. Several facts, however, speak in favor of multinational automotive firms choosing to pursue 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.*

As described in the background section, automakers are facing rapidly approaching problems with the fuel consumption caused by their current designs. The peaking of global conventional oil production is forecast to occur within the next 10-45 years (Zucchetto 2006). EIA predicts a moderation in oil price increases by 2010, and real prices increasing after 2030 (Zucchetto 2006). Consumer demand for fuel economy may appear non-existent at the \$1.20-\$1.35/gallon prices typical in the 1980s and 1990s. The Congressional Budgetary Office, however, estimates a long-run fuel economy elasticity in the U.S. of about +0.22 – meaning that a 10% increase in the price of gasoline would in the long-run lead to changes in consumer technology choices that would reduce gasoline consumption by 2.2% (Austin 2003). Although difficult to predict, government regulation – in the form of new CAFÉ standards or a gasoline tax – could also put new pressures on automobile manufacturers to improve fuel economy. If the U.S. courts support California's right to limit vehicle greenhouse gas (primarily CO2) emissions, other states are likely to follow California's lead with their AB 1493 legislation. New federal greenhouse gas legislation could also emerge out of the Kyoto Protocol post-2012. A recent report by Hamilton, suggests that if gasoline price stay at their current levels, the demand for higher fuel economy may already be here now (Hamilton 2005).

One of the few "ready available" fixes to improve fuel economy is vehicle light-weighting. Given a looming demand for improved fuel economy, automakers would be well-served to continue to increase their experience with light-weighting technologies. China's Greenfields provide an interesting opportunity to experiment with new production technologies. Future work should explore the viability of experimenting with polymer composite vehicle technology in the U.S. Future work should also explore the advantages and disadvantages of other light-weighting alternatives. Points (2)-(4) below present the potential production cost advantages of producing vehicles with polymer-composite bodies in China.

(2) *Although polymer composite body-in-whites are cheaper for a smaller range of production volumes in the China than in the U.S., the lower plant production volumes expected in China for the upcoming decade may make polymer composite bodies a good match for many vehicle models.* Current plant production volumes for auto giants with ventures in China tend to be between 20,000 and 50,000 BIW units per year (Wang 2002). Of the 19 foreign venture vehicle models produced in China between January and December of 2000, all of them had production volumes under 110,000, the glass composite's crossover with steel. Up through 10-20 years out, production volumes are not expected to go above 50,000 to 100,000 units annually (Wang 2002), although plant capacity of, for example, the GM Shanghai plant, is 250,000 annual units (Steinfeld 2003). According to the assumptions of the two future scenarios, a composite glass BIW should remain more competitive than steel up to 75,000 to 80,000 units annually. Given these current and expected future production volumes, composites are and should remain less expensive than steel for many of the vehicle models produced in the P.R.C.

(3) There is high uncertainty regarding the magnitude of market demand in China in the upcoming decades. Investment in a composite, rather than steel, production facility has the

advantage of there being lower financial penalties for misjudging annual production volumes. As can be seen in

Figure 18 and

Figure 19, in the China production environment, the steel body is only slightly cheaper than the composite body at high production volumes. In contrast, the composite body is significantly cheaper than the steel body in the China environment at low production volumes. Thus, particularly if future demand is highly uncertain, there is thus much less risk involved in choosing the composite than the steel investment. A more detailed discussion of how investing in a composite production facility can lead to lower financial penalties for plant under-utilization can be found in (Fuchs 2003).21

The benefit of lower risk in misestimating required plant capacities is particularly important in China, where future production volumes are so unpredictable. The automobile assembler industry and, even more so, the component production industry in China are extremely fragmented. Central leadership is aiming to consolidate the much fragmented auto sector, and nurture three major auto groups (ChinaOnline 2002). This consolidation would lead to larger annual production volumes for remaining firms. It is difficult, however, to know the extent to which the Chinese government will follow through with consolidation efforts. Factors outside the country can also change the demand quantities plants within China are called upon to fill. The Asian Free Trade Agreement is opening all of Asia for the first time to Chinese exports. The WTO is opening China to unrestrained investment levels by foreign producers. Still, these

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[21] As demonstrated in Ibid., at low production volumes, the difference between using 40% and using 90% of the free plant capacity is $190 for composites and $250 for steel. At high production volumes (250,000 APV), the difference between using 40% and 90% of the free plant capacity is still $150 for steel, while all capacity is already used in production for composites. On average across production volumes, the risk of losing money to low market demand and plant under utilization amounts to, a $30 per BIW difference for composites, but a $195 per unit difference for steel BIWs.

internal and the external changes will take time. Finally, most difficult, perhaps, in predicting future production volumes, is forecasting the demand quantities and preferences of the Chinese consumer. Assuming a plant fulfills its investment in 15 years, the production of glass-composite body is likely to remain the lowest-risk alternative for many Asian car models for the immediate future.

(4) *Given the right design, polymer composites may actually have advantages rather than disadvantages, in meeting Chinese consumer preferences*. Both Daimler Chrysler and GM misjudged the prestige-oriented nature of the Chinese consumer. The additional flexibility in design provided by polymer composites may, however, in reality be quite well suited to the fashion and status-conscious nature of the Chinese people. Additional paint coats could provide polymer composites with a shiny finish. The radical, futuristic designs and custom bodies possible with polymers could receive the same warm reception in cars as they received in cell phones, for which the highest-fashion options in the world are currently available in China. Under this strategy, customized, low production volume composite body designs could range from high-end sports vehicle applications to lower cost newly-wed and family car options.

4.5 Conclusions and Future Work

This chapter explores the impact of manufacturing offshore on technology development incentives, and thereby the technology development path of the automotive industry. In the case of the automotive industry, manufacturing offshore does not change the path of technology development. Both GM and DaimlerChyrsler initially consider manufacturing an emerging technology offshore. In both cases, however, the firms pull out of their original efforts. Although the firms may have learned in the process, it is unclear if they have learned the right lessons. Further, the extent of confusion and monetary losses by both firms suggests the need for a new approach.

This work shows that offshore manufacturing can change the most cost-competitive design alternative. The firms studied, however, no not seem aware of the impact of manufacturing offshore on the competitiveness of their designs. Nor do DaimlerChrysler and General Motors seem to learn the necessary lessons in their experience in China. First, nothing in the discussions with DaimlerChrysler or General Motors suggested that they become aware of the cost results shown in this chapter – in particular, that a polymer composite body would actually be less competitive relative to steel in a Chinese production environment. Second, both DaimlerChrysler and General Motors blame polymer composites for the poor reception of their prototypes by the Chinese market. A closer look shows, however, that the firms' *product and design* choices, not their *technology* choices, caused their prototypes to be poorly received.

Decision tools such as process based cost modeling, may provide distinct advantages in informing firms' design decisions prior to offshore investment. In this case, the firms assume that composites would be cheaper than steel for a greater range of production volumes in the Chinese production environment. The model results show that, contrary to the firms' expectations, composites are actually cheaper than steel over a smaller range of production volumes in China. The model results also provide greater resolution into other important factors influencing the investment decision. Specifically, the results show that although the composite alternative is more competitive than steel for fewer production volumes, there are still many models currently produced in China that would have been more competitive out of composites. Also, although steel becomes cheaper than composites at annual production volumes over 105,000, there is less risk with a composite facility in misestimating production quantities. Given the growing likelihood that automakers will have to improve fuel consumption to meet either consumer or regulatory demands, experimenting with composites production in China may be a wise decision.

This research shows that manufacturing offshore changes the relative competitiveness of design alternatives. It will important for future modeling work to explore the implications of offshore production differences for product development and platform strategy in the automotive industry. In reconsidering their product development portfolios, it will be important for automotive firms to balance the advantages of customizing designs to regional manufacturing economics against the disadvantages of the additional product development costs caused by an increased number of designs.

Alone understanding the implications of offshore production differences for design competitiveness, however, is not enough. Not only did the firms in this case not understand the implications of manufacturing offshore for design economics, they also did not understand the offshore market. Future work should also explore what factors may be causing the extensive misunderstandings observed in this case. Many theories should be developed before starting this work. The results of this case, however, suggest five theories that would be particularly interesting to explore. First, political forces within the firm may have caused the composite vehicle to lose viability after it failed in tests with the Chinese market, even if the technology itself was not at fault. Second, organizational or institutional factors may have prevented the necessary conversations from happening between marketing experts and the engineers. Third, cultural barriers may have prevented the DaimlerChrysler and General Motors marketing experts from understanding the Chinese consumer. Finally, the firms' marketing experts may have understood the original market tests correctly, but misestimated the speed at which consumer preferences in China were changing.

5 Modeling the Cost-Competitiveness of a Monolithically Integrated Laser Modulator

This chapter analyzes the cost-competitiveness of an optoelectronic component with a monolithically integrated laser and modulator from the perspective of manufacturing in the United States.

The past four years have seen the optoelectronics industry transform from one dominated by the speed and performance of innovation to one where efficiency and cost play a determinant role in a company's future. The collapse of the optical fiber market and the burst of the internet bubble in 2000, were a driving force behind this transformation. By 2002, actual optical fiber sales fell short of 24 month projections by more than 80 percent (Cahners Business Information 2000, Turbini and Stafford 2003). (See

Figure 27.) This protracted difference between projected and actual sales belies a market dynamic sufficient to change both the operating climate and strategies of stakeholders throughout the industry.

In response to such changes, optoelectronics firms began turning to economic methods, such as cost of ownership models, to support technical decisions. Although the field of activity-based costing and other process-based cost research (Bloch and Ranganathan 1992) has extended these methods to include the implications of both non-manufacture and individual process activities, current costing approaches lack a critical capability for an industry with rapid technology turnover. Critical to such an industry is the ability to forecast the cost-implications of technology advances – in the form of new materials, processes, or architectures – while those advances are still in their early stages of development. For an industry like optoelectronics, early stage understanding of economic implications will be essential to realizing new market potential and avoiding inefficient development.

Process-based (or technical) cost modeling was developed to address just such a problem, serving as a method for analyzing the economics of emerging manufacturing processes without the prohibitive economic burdens of trial and error innovation (Busch 1988). Its application has been extended to the implications of alternative design specifications and process operating conditions on production costs within and across manufacturing processes (Kirchain 2000). In the same way that present-day engineering 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 the engineering approaches at work within these physical models to avoid expensive strategic errors in product development and deployment.

Precedent exists for using process-based cost modeling (PBCM) to look at the cost-implications of electronics technologies still in their early stages of development. The Materials Systems Lab at M.I.T. has shown process-based cost modeling to provide key decision insights in electronic packaging (Sikorski, Krueger et al. 1989), printed circuit board design (Field and Ng 1989, Field and Ng 1989), and materials selection for integrated circuit applications (Dieffenbach 1989, Ng 1991, Dieffenbach and Marallo 1994). This work has been extended by Sandborn to look at early-stage design decisions in electronics system assembly (Sandborn 1998, Trichy, Sandborn et al. 2001). Recently, the need for costing methods that can assess the cost implications of emerging design alternatives has also been identified for the optoelectronics industry. The National Electronic Manufacturers Initiative (NEMI) has begun a cost analysis of optical versus copper backplanes using process-based cost modeling approach. However, progress has been slow and so far only a cost model of the copper backplane exists (Singer

2004). A yield-focused costing approach for evaluating emerging technologies also independently emerged in the late nineties, focused on optoelectronic devices (Stirk 1998, Stirk 1999). This approach is strongly based in theoretical yield models – calculating the yield impact of design changes on thermal dissipation, mechanical expansion and stress, and optical coupling efficiency (Stirk 1998). The work presented in this chapter relies on models built around plant-level performance data, leading to different results from these previous theoretical analyses.

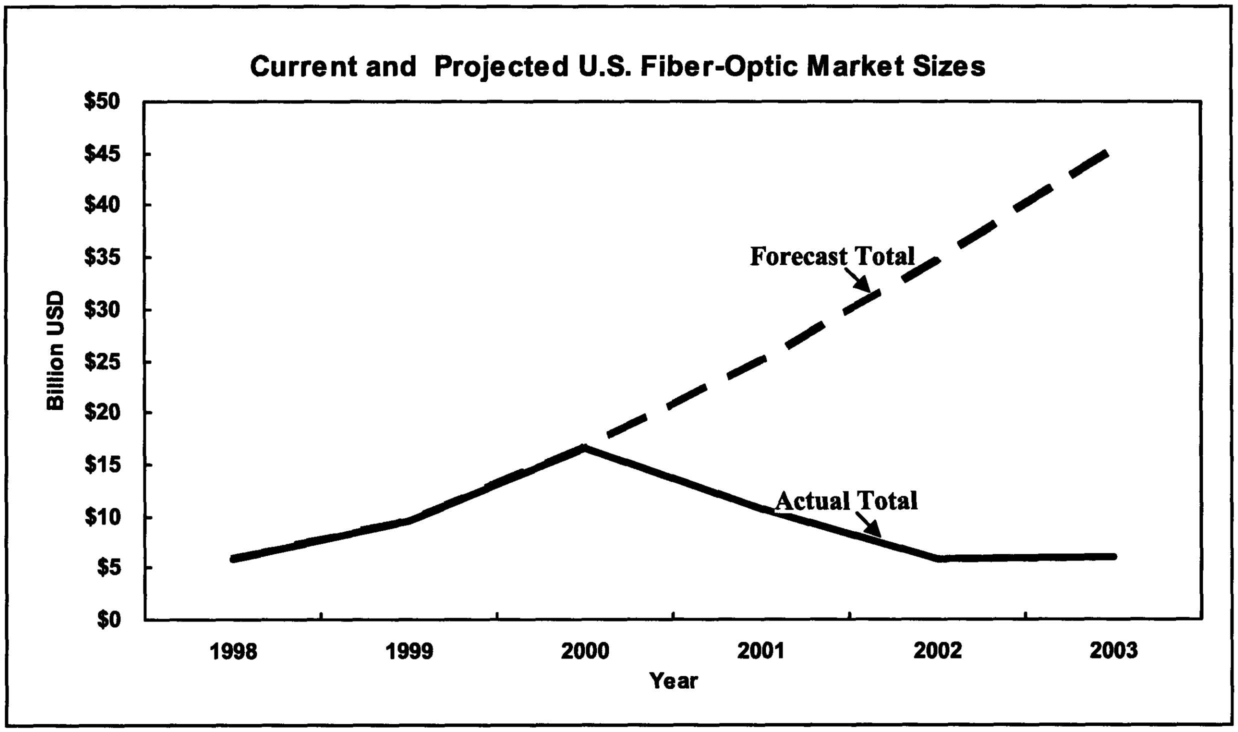


Figure 27: Mid-2000 Optical Communications Market Forecast (Source: (Cahners Business Information 2000)) versus Actual Sales (Source: (Turbini and Stafford 2003).)

This chapter presents the application of PBCM to the economic questions associated with optoelectronic device production. The work focuses on the feasibility of a particular technology solution – monolithic integration – for meeting the industry's need to drive down costs. The monolithic integration of separate components on a single device not only is believed to minimize packaging expenses, but also holds promise to increase network speed and device functionality. However, problems arising from increasingly structured wafer surfaces and increased opportunities for defects during the extended process flow of a monolithic device (Maerz 1996) cause concerns that yield losses will outweigh cost savings. Modeling results are used to demonstrate the importance of yield losses along with several other technological and operational characteristics of device production. The model which is described represents a broad-scope PBCM, developed as an element of the MIT Communications Technology Roadmapping Project (CTR) (Bruce 2005) for the optoelectronics components industry. This process-based cost model is based on data collected during a 1.5 year period (September 2003 – January 2005) from twenty firms across the optoelectronics supply chain located in the U.S., the U.K., and developing East Asia. The cost results which follow are based on the processing conditions found in the U.S.- and U.K.-based manufacturing facilities. The impact of manufacturing in developing East Asia on the cost-competitiveness of monolithically integrated designs is explored in a separate paper (Fuchs 2005). Although the model was developed around a specific InP device case, the aim was to develop a model architecture easily expanded to address new designs, processes, and materials as might be relevant to future questions facing the optoelectronics industry.

5.1 Model Architecture

The CTR PBCM allows the user to project and analyze optoelectronics production cost. The model, using basic engineering principles and industry data, first estimates required processing conditions. These estimates are used to project the resource requirements – capital, labor, materials, and energy – needed to meet specified production targets. These resource requirements can be mapped to corresponding operating and investment expenses and, then aggregated into unit cost figures as detailed subsequently. Ultimately, the model projects the minimum efficient fabrication line that is capable of producing a defined annual volume of good devices and then calculates the cost of installing and operating that line. The scale of the line is determined by the gross devices (both acceptable and rejected) which must be processes to achieve the desired annual volume of good units.

The cost per good device is developed in Equations 12 - 29. Aggregate costs are calculated as follows:

$$C_{Tot} = C_{Material} + C_{Labor} + C_{Energy} + C_{Equipment} + C_{Tooling} + C_{Building} + C_{Overhead}$$ **Equation 12**

$$C_{El} = {AC_{El}}/{PV}$$ **Equation 13**

where C = unit cost ($ per good unit), AC = annual cost ($ per year), PV = good devices per year, and El= cost element (Materials, Labor, Energy, Equipment, Tooling, Maintenance, Overhead).

The cost projections in this chapter are based on a detailed description of component processing including front-end component fabrication, assembly, packaging, and all forms of testing. Model users have full flexibility to define the type and order of process steps as well as set the operating conditions for each process module. Currently, the model comprises 52 sub-models each covering a different process. The user identifies from these options both the types and order of processes required to produce the desired device. The 52 processes (including testing processes) included in the model are shown, classified by process function, in Table 12 and Table 13 below.

Table 12: Front-End Process Modules in the Trasmitter Process-Based Cost Model

Surface Treatment	Growth/Deposition	Etch	Lithography	Thermal
Clean	MOCVD	Plasma Etch	HMDS	Cure
Device Labeling	MBE	Asher	Spin-On Resist	Anneal
	PECVD	RIBE	Pre-Bake	
	H-Ion Implant	Wet Etch	Litho (Photo/UV)	
		Spin-Dry	Develop	
		Descum	Post-Bake	
		E-Beam Evap.		
		Metal Lift-Off		
		Lapping		

Table 13: Cleaving and Back-End Process Modules in the Transmitter Process-Based Cost Model

Backend Assembly	Backend Package	Backend Test
Wafer Cleave	Alignment	Incoming Inspection
Bar Cleave	Bake	Post-Deposition Test
HR Coating	Lidding & Lid Check	Automatic Inspection
AR Coating	Package Clean	Plant Transfer Test Set
Bench Attach	Fiber Attach	Post Wire-Bond Visual
Cooler Assembly	Sleeve Attach	Final Chip on Carrier Visual
Chip Bond		Assembly Visual
Wirebond		Pre-Lid Visual
Burn-In		Post-Ash Visual
Bench Assembly		Chip-On Carrier Test
		Cooler Assembly Test
		Post-Bake Test
		Temperature Cycle
		Final Package Test

In defining the process flow necessary to produce a device, process type and order must by augmented by a description of the materials, actions, and operating conditions occurring at a given process step. In the model, the user may choose from one of several pre-set operational descriptions provided for each process, or may enter his or her own recipe for the model to use at that process step. In all cases, these operational descriptions are created from the 26 inputs shown in Table 14.

Table 14: Process Module Inputs (required for each process step)

Process: (e.g., MOCVD)		
Incidental Yield	Direct Labor: Higher Ed.	Operating Time Per Batch
Embedded Yield	Direct Labor: Technician	Setup Time Per Batch
Machine Cost	Direct Labor: Skilled	Maintenance Freq. (/batch)
Capital Dedication (Y/N)	Direct Labor: Unskilled	Maintenance Time
Capital Usage Life	Installation Cost (%)	Tool/Mask Initial Investment
Max. Batch Size	Maintenance Cost (%)	Tool/Mask Add'l Unit Cost
Average Batch Size	Auxiliary Equipment (%)	High-Grade Cleanroom Space
Unplanned Downtime	Energy Consumption (kWh)	Low-Grade Cleanroom Space
		Non-Cleanroom Space

5.1.1 Materials, Labor, and Energy Costs

The model currently tracks a range of materials, which are either incorporated into the product or used as consumables (e.g., cover gases). Each process module allows the user to specify the rate of consumption of these materials per production batch for that step. For some steps, these material consumption rates are forecast from descriptions of the product, but can be overridden by user input. Regarding primary wafer consumption, users may specify the density of chips that are processed on one wafer. Previous work has suggested there are wafer real estate benefits to system on chip solutions (Shen 2002, Zheng 2004). In the firms studied, the authors found wafer handling requirements to limit the minimum chip size for the case studied in this chapter. Based on this observation, the analysis presented assumes the same component density per wafer, regardless of whether the component is a laser, modulator, or monolithically integrated laser-modulator.

Ultimately, material costs are directly driven by the effective production volume for each step (effPVi), defined as the gross number of units processed at step i to achieve the desired number of good units (PV) after step n. The calculations for effective production volume and material costs are shown in Equations 3 – 6 below:

$$effPV_n = PV / Y_n \qquad \textbf{Equation 14}$$

$$effPV_i = effPV_{i+1} / Y_i \ , \ \forall \ \mathrm{i}\ [1, \ldots, \mathrm{n}\text{-}1] \qquad \textbf{Equation 15}$$

$$effAB_i = effPV_i / Batch_i \qquad \textbf{Equation 16}$$

$$AC_{Material} = \sum_{i,m} U_i^m \cdot effAB_i \cdot P^m \qquad \textbf{Equation 17}$$

where i = process step number, n= total number process steps, Y_i= yield at step i, $effAB_i$ = gross annual batches processed at i, $Batch_i$ = mean batch size for 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 per $Batch_i$.

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:

$$AC_{Energy} = \sum_i reqLT_i \cdot EI_i \qquad \textbf{Equation 18}$$

where EI_i = Energy intensity of step i in kiloWatts (kW) and $reqLT_i$ = the line time required to produce $effPV_i$.

Users may specify direct labor requirements in four separate classifications – higher education labor, technicians, skilled labor, and unskilled labor. The annual cost of these laborers is computed as described below in Equation 8:

$$AC_{Labor} = \sum_{i,l} APT_i^l \cdot P^l$$ **Equation 19**

where l = labor type (PhD, Technician, Skilled, Unskilled), = annual paid labor time for labor type l for step i.

5.1.2 Capital 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 the CTR PBCM, 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 Equation 9) (de Neufville 1990).

$$R_{El} = I_{El} \frac{[d(1+d)^{s_{El}}]}{[(1+d)^{s_{El}} - 1]}, \forall\ El \in \mathbb{Z}$$ **Equation 20**

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, $s_{Tool} = 3$, $s_{Equipment}=10$, and $s_{Building} = 25$).

Along with each machine's direct cost, 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. The details of this forecast are described in the section on operating time. For the purposes of the case analysis presented subsequently, the model was configured based on an assumption that even if a production line is dedicated to a single product, processes which require the same equipment in that production line will choose, when possible, to run on the same machine. This approach was based on observation of industry practice and recognition of the exceptionally low utilization that would result otherwise for low production volume, high performance products. Based on this approach, fixed costs are calculated as shown in Equations 10-12.

$$AC_{El} = AC_{El,ded} + AC_{El,nonded}, \forall\ El \in \mathbb{Z} \qquad \textbf{Equation 21}$$

$$AC_{El,nonded} = \sum_i (R_{El,i} * LR_i), \forall\ i \in \{\text{non-dedicated}\} \qquad \textbf{Equation 22}$$

$$AC_{El,ded} = \sum_j R_{El,j} \cdot \left(\left\lceil \sum_i \left(LR_{ij} - \lfloor LR_{ij} \rfloor \right) \right\rceil + \sum_i \lfloor LR_{ij} \rfloor \right), \forall i \in \{\text{dedicated}\} \text{ and } \forall j \in [1,\ldots,J] \qquad \textbf{Equation 23}$$

Where {non-dedicated} = the set of all steps which have non-dedicated processes, {dedicated} = the set of all steps which have dedicated processes, j = process type, J is the total number of process types, and LR_i is the ratio of required operating time to effective available operating time at step i, as shown in the next section.

5.1.3 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 PBCM: 1) the amount of time that a particular resource (machine, labor, etc.) is required – required operating time, 2) the amount of time that a unit of that resource is available in a given year – available operating time and 3) the amount of time that a laborer would be paid for a full year, annual paid labor time.

Several factors influence the required operating time including: 1) operating time per batch; 2) setup time per batch; 3) machine simultaneous preparation capacity (i.e., maximum batch size); 4) typical simultaneous preparation; 5) maintenance frequency; and 6) maintenance duration.

Annual available operating time is required to compute the number of parallel resources necessary to meet production targets. Several operations metrics for a facility must be integrated to compute available operating time, including unplanned breakdowns, worker breaks, maintenance time, and the time when the facility is not operating. (See Figure 2.) To properly allocate the cost of inefficient capital utilization, available operating time should be modified by also subtracting that time when the plant is operational and staffed but is not producing due to lack of demand (i.e., idle time). This modified quantity, referred to as effective annual available operating time is shown to the right in Figure 28.

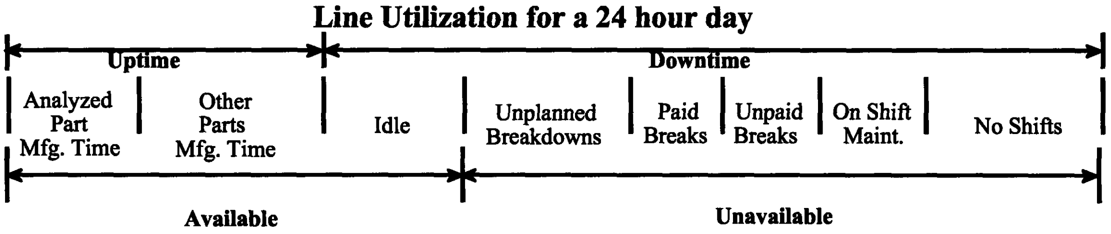


Figure 28: Computation of Available Operating Time Based on Line Utilization for a 24 Hour Day

Annual paid labor time, lines required, required operating time, and available operating time are calculated as follows:

$$APT_i^l = DPY \cdot (24 - NS - UB) \cdot WPL_i^l \cdot LR_i \qquad \textbf{Equation 24}$$

$$LR_i = {reqLT_i}/{availLT} \qquad \textbf{Equation 25}$$

$$reqLT_i = effAB_i \cdot (cycT_i + suT_i) \qquad \textbf{Equation 26}$$

$$availLT = DPY \cdot (24 - NS - UB - PB - UD) \qquad \textbf{Equation 27}$$

where DPY=operating days per year, NS = no operations (hr/day the plant is closed), UB = unpaid breaks (hr/day), = Fractional labor type l assigned to step i, $cycT_i$ = operating cycle time of i per batch, suT_i = setup time of process i per batch, PB = paid breaks (hr/day), and UD = Unplanned downtime (hr/day).

For some processes, selected time quantities are not user inputs, but instead are computed based on descriptions of the product or desired operating conditions. For example, set up time can be correlated to the extent of automation of the machine and operating time per batch can be modeled from processing or product requirements such as thickness deposited, number of wires in wire-bond, or type of epoxy and temperature of oven.

5.1.4 Yield

The unit costs (C_{Tot}) reported in this chapter represent what is often known in the industry as "yielded costs," in other words the effective cost per good non-defective device. Unlike classic industry models, two yield numbers are assigned to each step in the process flow – an incidental yield and an embedded yield. Both of these yield values are inputs provided for each step by the user. The incidental yield represents the yield hit taken immediately at a given step due to obvious problems which can be identified without testing (e.g., occasional wafer breakage). The embedded yield represents defects caused within a process step, but not discarded from the production line until later when identified as defective during testing. Thus, embedded yields accumulate during production until they are identified and removed during a testing step. Although only process steps that are not test steps can have embedded yields, test steps may have their own incidental yield. Equation 17 shows how yield (Y_i) would be calculated for some step, i=k, where $k \in [0, \ldots, n]$:

$$Y_{i=k} = \begin{cases} incY_k \cdot \prod_{x=(t^*+1)}^{k} embY_x, & k = test \\ incY_k & , k \neq test \end{cases}$$ **Equation 28**

where $\boldsymbol{t^*} = \max \Im, \forall \boldsymbol{i} \in \{\boldsymbol{test}\}$, where $\Im = \{\boldsymbol{i}\}_{i=1}^{k-1}$ and {test} = the set of steps which are test steps. In words, t* is the most recent step prior to k that was a test. The user inputs incidental yield ($incY_i$) and embedded yield ($embY_i$) for all i. Assuming a total of n steps in the process flow, the cumulative yield, $Y_{Cumulative}$, can be calculated as:

$$Y_{Cumulative} = \prod_{i=1}^{n} Y_i$$ **Equation 29**

The yields (Y_i) used for the analysis presented in this chapter are based on the yields the studied firms were able to achieve post-rework. Future modeling efforts to integrate the direct cost of rework would be a useful extension of this analysis.

5.2 Case Study

A main goal of this study has been to develop a model whose architecture will become the foundation for investigating future techno-economic questions facing the optoelectronics industry. Particularly important is for the model to provide insights on the cost-feasibility of integrating separate components on a single device. Limits of time and resources required choosing a single case from which future studies and model developments could be built. Three attributes are particularly important in the case chosen for study: (1) the case provides insights on a large range of processes necessary in optoelectronic chip production, (2) the case focuses on emerging but extant technology for which significant data is available within the industry (i.e., from which to develop models of the relevant processes and against which model results can be calibrated), and (3) the case addresses a key integration decision being faced by firms. In light of these criteria, production of a 1550nm DFB laser and an electro-absorptive modulator on an InP platform was chosen as the case for study. This laser-modulator is designed for use in long and short haul STM-64/OC-192 TDM applications over 40km, 60km and 80km with low dispersion penalty (less than 2dB). Such a laser modulator would be suitable for use In SONET & SDH (~ 9.953Gb/s), and as a Digital Wrapper (~ 10.3Gb/s), with FEC (~ 10.7Gb/s).

Table 15: Operational Parameters Used in Case Study Analyses

Facility Description		
Working Days per Year	240	Days / Year
Facility Downtimes:		
No shifts	7	Hours / Day
Worker unpaid breaks	1	Hours / Day
Worker paid breaks	1.2	Hours / Day
Unplanned	*Set in process specifications*	
Cost of Building Space		
High Grade Cleanroom	$3,000	$\$ / \mathrm{m}^2$
Low Grade Cleanroom	$2,000	$\$ / \mathrm{m}^2$
Non-cleanroom	$1,000	$\$ / \mathrm{m}^2$
Building Maintenance (% fc)	5.0%	% Fixed Cost
Indirect workers/ Direct Worker	0.250	
Indirect workers/Line	1.000	

Three scenarios around this case were investigated: (1) a discretely packaged 1550nm InP DFB laser & discretely packaged electro-absorptive modulator, (2) a discrete 1550nm InP DFB laser & discrete electro-absorptive modulator within a single package, and (3) a 1550nm InP DFB laser and electro-absorptive modulator monolithically integrated on a single device. The 182-step, 165-step, and 111-step process flows for production of the discretely packaged laser and discretely packaged modulator designs (1), discrete laser and modulator in a single package (2), and monolithically integrated (3), respectively, are shown at the end of the document. All three scenarios are intended to represent the production of functionally equivalent 10Gbit per second devices with stringent quality specifications. All three product scenarios were modeled using a common set of operational and financial conditions as listed in Table 15.

Data for both the processes and process flows relevant to these cases was collected from 20 firms across the optoelectronics supply chain, including end-users, OEMs and equipment manufacturers. This data was aggregated to construct a scenario illustrative of general industry practice. The process flow and process information for scenario 1 (discrete devices in discrete packages) was derived based on information collected about scenario 2 (discrete devices in a single package). As such, it likely represents an upper bound of cost and lower bound of yield for scenario 1.

The following section details the use of the CTR PBCM to map the technological and strategic characteristics of the tradeoff between packaging gains and processing losses for discrete and integrated designs of a 1550nm DFB laser and an electro-absorptive modulator realized on an InP platform. Particular focus is paid to three economic aspects of this problem: (1) quantifying the impact of production scale growth, (2) identifying cost drivers, and (3) quantifying process performance levels necessary to achieve production cost targets.

5.2.1 Quantifying the Impact of Production Scale Growth

A critical economic characteristic of any technology is the manner in which its production costs change as a function of total units produced. A PBCM forecasts this change in production costs with scale by first determining the minimum efficient fabrication line which is capable of producing a given quantity of good devices and then inferring the cost of operating that line. Figure 3 shows such an analysis for the laser-modulator design options. To generate these results, the model projects technical and operational characteristics of the smallest efficient fabrication and assembly facility capable of meeting the production volume (of good devices) enumerated along the x-axis.

The reported cost figures represent the operating and allocated capital expenses associated with that facility and the product of interest. All three design options -- a discretely packaged 1550nm InP laser & discretely packaged modulator (Discrete Package), a discrete laser & discrete modulator within a single package (Discrete Device), and a monolithically integrated 1550nm InP laser-modulator (Monolithically Integrated) –showed strong economies of scale up to annual production volumes of approximately 30,000 units. At annual volumes above 30,000 units, the production costs of all three devices become effectively insensitive to production scale. The unit cost of the monolithically integrated EML levels out at just above $500 per unit, the discretely produced devices within a single package level out at a cost just below $600 per unit, and the discretely packaged devices level out at a cost around $850 per unit. The Discrete Device case (i.e., within a single package) showed the strongest sensitivity to scale, followed by production of discretely packaged devices. This relative behavior emerges because both discrete products require larger total investments compared to the monolithically integrated design. The monolithically integrated EML requires the least investment, and therefore shows the least sensitivity to scale. The largest contributors to investment cost for each device can be seen in Table 16. Because the discretely packaged devices were found to be cost-inferior to the other two options at all production volumes, this scenario is left out of the analyses for the rest of the chapter.

It may seem surprising that the model would project a smaller capital outlay (and corresponding less volume-sensitive unit cost) for the monolithic device despite its overall lower production yield; lower yield products require more units to be processed which in turn drives higher equipment requirements. While the model does project that production of the monolithic device requires higher capital utilization than its discrete device counterparts, in all three cases, production requirements can usually be satisfied by a single piece of equipment across the range of production volumes being considered. As such, for many processing steps the yield disadvantage of the monolithic device is insufficient to drive additional capital expenditure. However, there are a few processing steps that both have long cycle times (i.e., require multiple units of equipment) and must be repeated for each discrete component. Excellent examples of this are chip bonding and its associated testing operations. In these cases, the additional required instances of these processes in the discrete cases leads to additional capital requirements and the observed cost behavior.

Table 16: Largest Contributors to Investment for Each Design at Annual Production Volumes of 30,000 Units

Design	**Monolithically Integrated**		**Discrete Device**		**Discretely Packaged**	
Total Investment	$61,037,000		$70,697,000		$102,436,000	
Top Contributor	Assembly Test	10.0%	Assembly Test	10.3%	Assembly Test	20.2%
	Device Test	8.5%	Device Test	9.7%	Alignment	11.3%
	Alignment	5.6%	Lithography	6.8%	Device Test	9.7%
	Lithography	4.9%	Alignment	5.6%	Lithography	6.8%
	Burn-In	2.9%	E-Beam Evap	4.5%	E-Beam Evap	4.5%
	E-Beam Evap	2.2%	Burn-In	2.9%	Visual Test	3.2%
	Visual Test	1.9%	Visual Test	2.6%	Bench Attach	2.9%
	Bench Attach	1.5%	Lapping	2.2%	Burn-In	2.9%
	Bench Assembly	1.5%	Chip Bond	1.8%	Bench Assembly	2.9%
	Lapping	1.5%	Bench Attach	1.5%	Sleeve Attach	2.5%

Both the volume at which economies of scale is reached as well as the eventual cost at scale is dependent on the specific processing decisions and conditions faced by an individual plant. In the analysis shown in Figure 3, testing occurs after six key intervals for the front end, after individual die isolation (bar cleave), and at five key locations during the back end processes. (See Appendix 1 for specific locations.) Final product yields achieved are 2.3% for the monolithically integrated device; final product yields achieved are 3.9% and 7.9% for the discrete laser and modulator, respectively, in a single package. Because data for the discretely packaged devices is derived directly from information collected on scenario 2, the yields for this scenario match those of the discrete device, single package case.

With yields in the single digits, even slight improvements or digressions within individual process steps can have significant consequences. The impact of small yield changes on final product cost can be seen for the mononlithic and discrete device cases as the shaded areas in Figure 29. The dominance of once case over the other is susceptible to the yields producers are actually able to achieve.

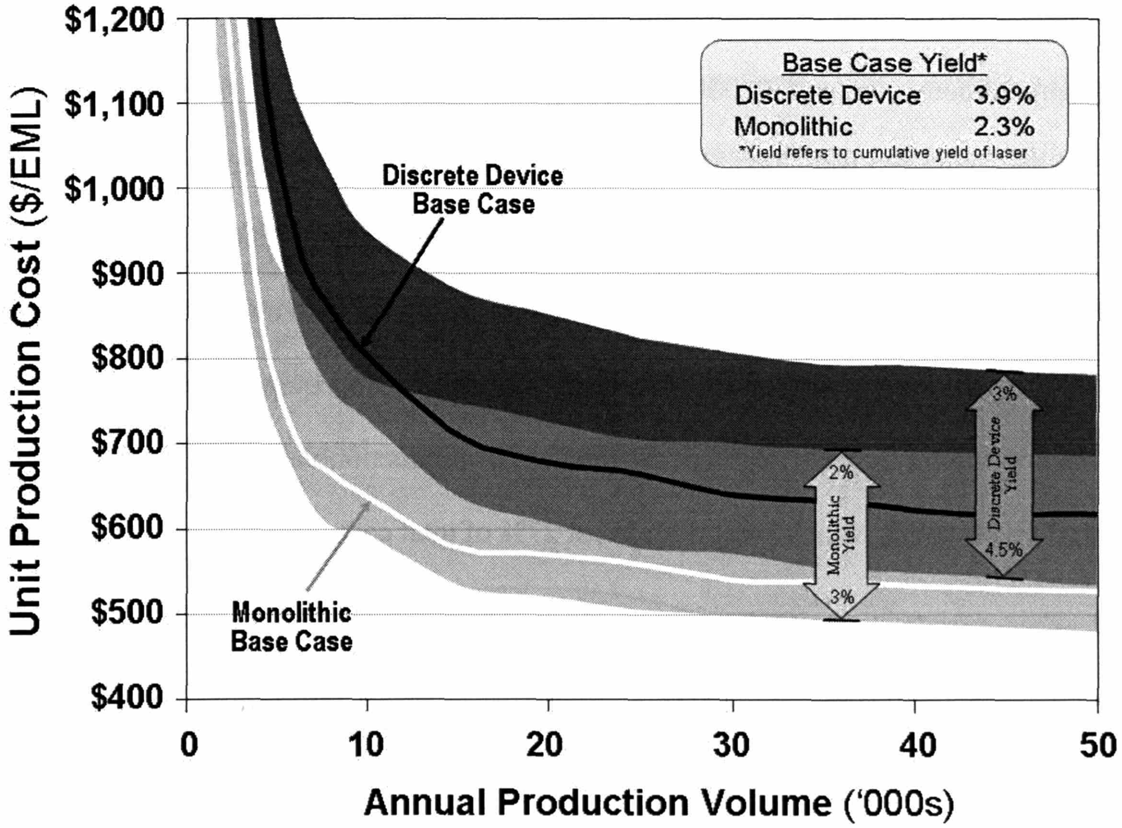
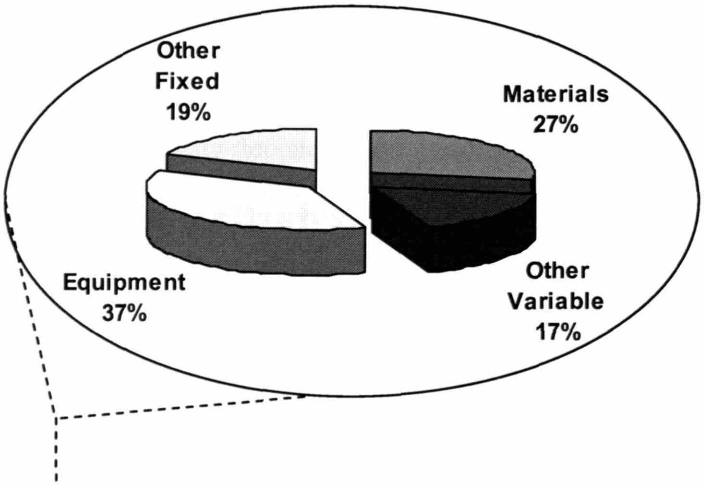


Figure 29: Cost Sensivity of Production Volume Analysis to Final Product Yield (For this analysis, the yield, Y_n, of the final step was varied to create the cumulative yields, $Y_{Cumulative}$, reported. In both of these process flows, the final step is a test.)

5.2.2 Identifying Cost Drivers

Although knowing the costs of alternative scenarios and how these costs vary with production scale is useful for strategic decision-making, more detailed information is required for informed operational decisions and firm-wide efforts to reduce cost. Process based cost modeling addresses this issue by providing the user with a wide variety of scenarios under which to observe the dominant drivers of production cost. Knowledge of cost drivers enables industry to focus scarce development resources on these dominant areas. The next five figures demonstrate the insights the CTR PBCM provides on the cost drivers in 1550nm InP Laser-Modulator production.

Figure 30 provides an aggregate breakdown of costs for the monolithically integrated device at a production volume of 30,000 units per year. In this and the four subsequent figures, costs are grouped into four headings: Materials (including purchased packaging components); Labor (direct and indirect, both with benefits, but not managerial costs); Energy; Equipment; and Other Fixed (comprising of Building, Maintenance, and Overhead, with overhead including managerial overhead costs). For the monolithically integrated case, equipment represents the largest cost, accounting for nearly 37% of the total at this production volume. Equipment costs are followed by Materials, which comprise almost 27% of total cost.



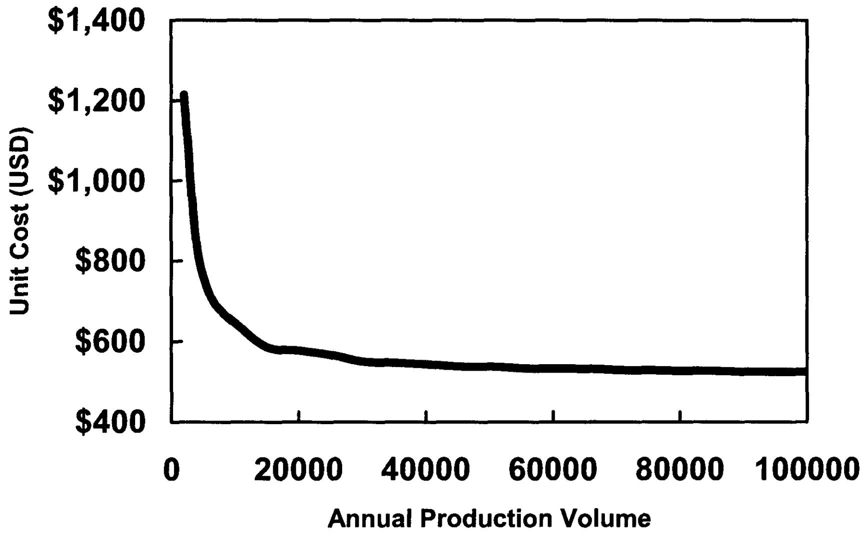


Figure 30: Monolithically Integrated Laser-Modulator Device Cost Breakdown at 30,000 Units Annually

Figure 31 shows how the cost breakdown by element differs for the three alternative designs studied. Notably, the relative contribution of both the fixed (equipment, fixtures, building, maintenance, and overhead) and the variable (material, labor, and energy) is remarkably similar across the different devices. Although material plays a slightly larger role and labor and equipment a slightly smaller role for the discrete devices in a single package, the top two costs – equipment followed by material – remain the same for all three options.

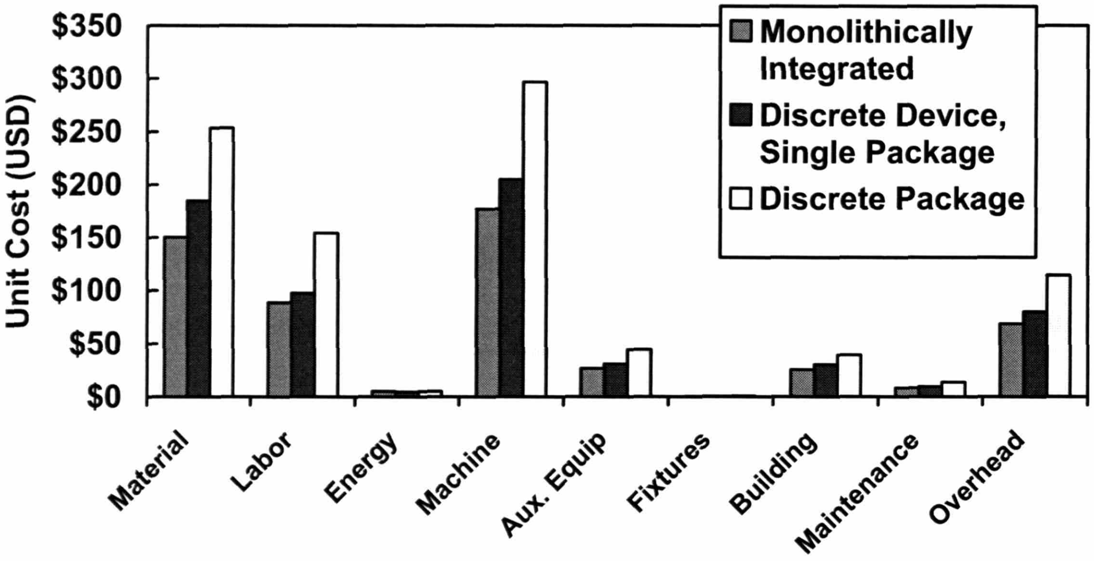


Figure 31: Cost Breakdown Comparison at 30,000 Units Annually for Different Levels of Integration

Although an aggregate breakdown begins to identify the cost drivers – in this case the cost of equipment – to truly focus research and development efforts it is necessary to further isolate the causes of cost. Figures 6 and 7 do this by showing the cost impact of particular groups of processes within the overall production of each product. In comparing the two figures, it is interesting to note that although equipment and material dominate aggregate costs across all three designs, this domination of equipment and materials is not true for all processes.

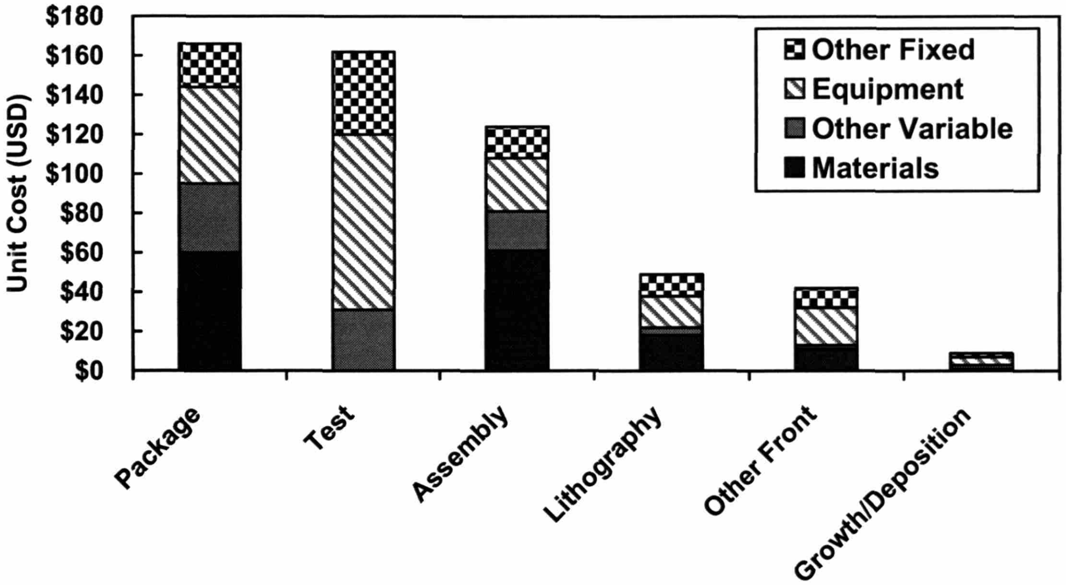


Figure 32: Monolithically Integrated Device Cost Breakdown by Process at an Annual Production Volume of 30,000 Units

Figure 32 shows that for the monolithically integrated EML, within-package assembly ("Package") and testing ("Test") make the largest contribution to production costs, followed by pre-package assembly (primarily the placement of the laser on the carrier). While testing is dominated by equipment costs; assembly, packaging, and lithography are dominated by material costs. Equipment costs dominate for testing due both to the expensive, specialized groupings of equipment required and to the long testing times for which this equipment must be committed. Equipment costs are much less dominant in assembly and packaging, where much of the work is often done by hand, requiring only microscopes with slight specialization. On the other hand, in these assembly and packaging stages, extensive parts from outside are required, which often come at high costs. Front end processes other than lithography (but including epitaxial growth) are dominated by equipment costs.

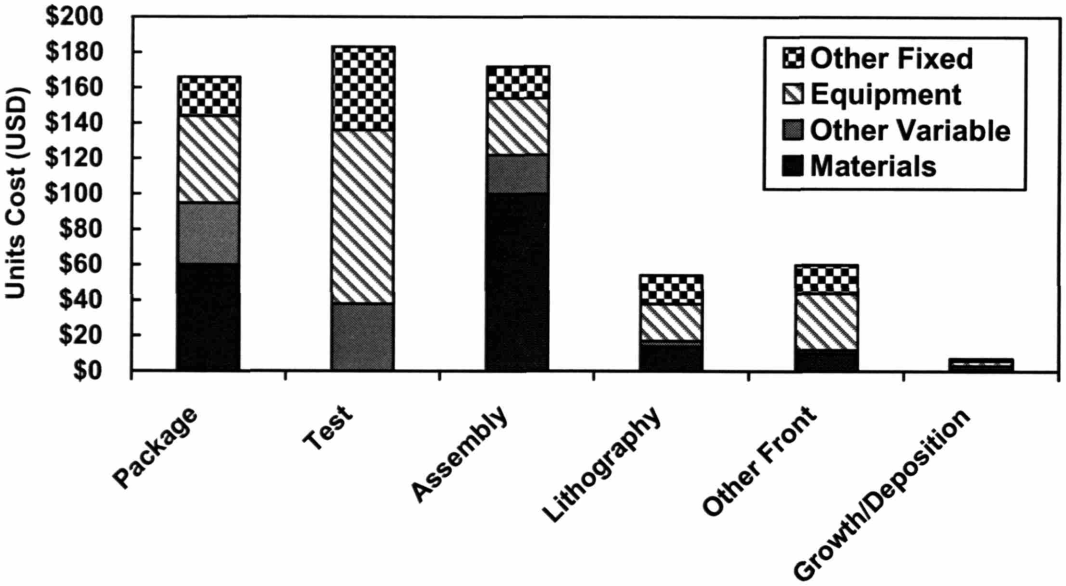


Figure 33: Discrete Device, Single Pacakge Product Cost Breakdown by Process at an Annual Production Volume of 30,000 Units

In contrast to the monolithically integrated device in which testing and packaging are close to equal in cost, testing is the largest cost driver for the discrete devices in a single package, followed by pre-package assembly ("Assembly"), and then within package assembly ("Package") (see Figure 33). Testing continues to be dominated by equipment costs, and materials costs continue to be the largest contributors to costs during packaging and assembly. Although the significance of material costs for assembly within the package remain the same, the significance of the material costs in pre-package assembly become 67% greater than they were for the monolithically integrated EML due to the assembly required on each separate device.

Because of the level of technical detail incorporated into the CTR-PBCM, it is possible to use the model to identify very detailed cost drivers. Figure 34 demonstrates this capability, identifying the drivers of laser-EML cost by individual processes. The top contributors to the overall costs for the monolithically integrated EML are, in decreasing order, alignment (i.e., micro-optical alignment including the addition of lenses into the package) , assembly-stage testing, isolated die testing after transfer to back-end facility, chip bonding, fiber attachment, bench assembly, visual testing, bench attach, wirebond, and cooler assembly. Together these ten processes account for 74% of total product cost. Obviously, developmental efforts focused on eliminating costs within these steps will have a significant effect on overall cost. It is also worth noting that there is great variety in the underlying causes of cost for each of these processes. Some processes are dominated by equipment costs (e.g., front to back testing, MOCVD), some by material costs (e.g., alignment, chip bond, fiber attach) and others by labor (e.g., assembly and visual test). Remarkably, these top ten cost drivers remain nearly the same across the differently integrated products.

Rankings of the top ten cost contributors for the discrete devices within a single package and for the discretely packaged device products can be seen in Table 17.

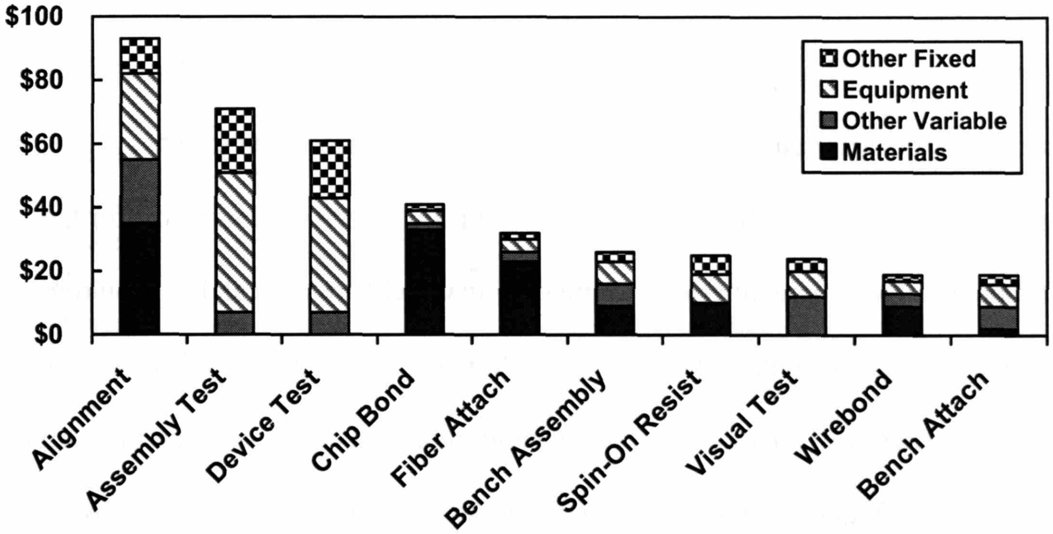


Figure 34: Monolithically Integrated EML Top 10 Processes Driving Costs at an Annual Production Volume of 30,000 Units

Table 17: Top Ten Drivers for Devices at Different Levels of Integration

	Monolith Integrated	Discrete Device	Discrete Package
Alignment[22]	1	1	1
Assembly Tests	2	3	2
Device Test	3	4	4
Chip Bond	4	2	3
Fiber Attach	5	5	5
Bench Assembly	6	8	6
Spin-On Resist	7	6	10
Visual Test	8	9	7
Wirebond	9	10	9
Bench Attach	10		8
EBeam Evaporation		7	

5.2.3 Quantifying Process Performance Targets

Because cost models build economic estimates up from the technical characteristics of a process, it is possible to use these models to investigate the impact of changing those characteristics. For the purposes of the optoelectronics industry, this capability can be particularly valuable in identifying processing performance targets (e.g., required yield, run rate, or materials consumption) and process steps on which to focus improvement efforts.

Along these lines, it is clear that per step yield is a primary driver of unit cost for the laser-modulator device. Development efforts to improve that yield are critical, but should be targeted to achieve the greatest return on investment. However, guiding these efforts can be difficult because the efficacy of a particular process yield improvement depends on the current yield of that process, the frequency with which that process is repeated in the overall process flow and on the specific positions in the process flow where that processing occurs. Nonetheless, despite the interrelationship of these effects, the operational detail of the MIT CTR model makes it possible to investigate the total cost effect of individual process yield changes.

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[22] Alignment refers to micro-optical alignment including the assembly of lenses into the package.

Figure 35 shows the direct impact of a change in selected process yields on unit cost for the monolithically integrated laser-modulator. A change in alignment yield, whether an improvement or a set back, has the largest impact on unit cost. An alignment yield of only 94.5% versus one of 95.5% (the range shown in Figure 35), adds over $10 to the final unit cost. MOCVD yield has the second largest impact on final unit cost – changing cost by $7 for a change in yield between 91.5% and 92.5%. Notably, for a process like wire bonding, a reduction in wire bonding yield has the second largest impact on cost – the steepness of the curve being second only to alignment – while an improvement in wire bonding yield has the smallest effect on final cost among the top ten the processes shown.

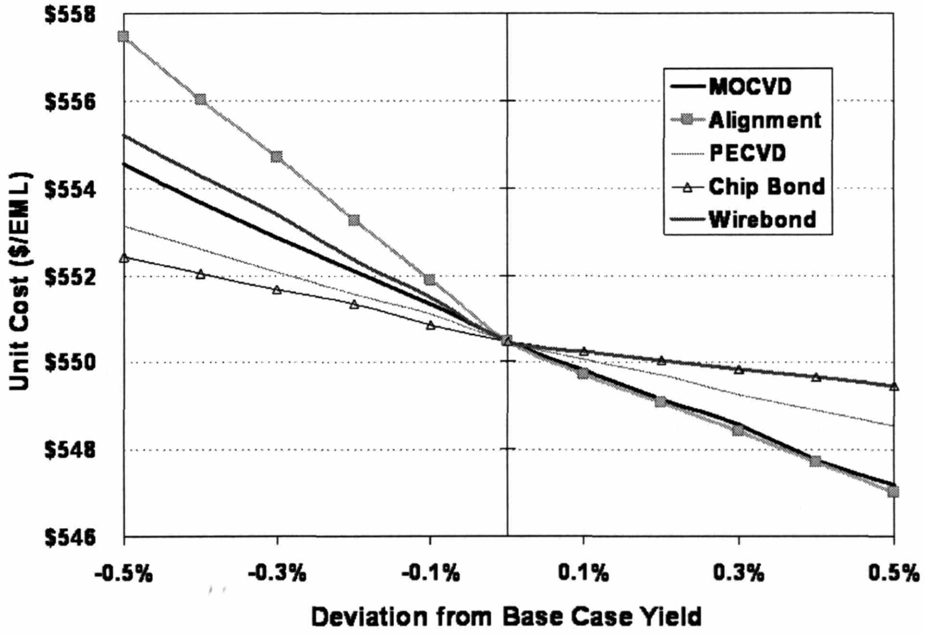

Figure 35: Monolithically Integrated EML Cost-Sensitivity to Changes in Process Yield (X-axis represents deviation from baseline modeled yield)

While informative, the analysis presented in Figure 35 suggests that improvement efforts be ranked solely by their impact on unit cost. While important, this metric sheds no light on the underlying difficulty of realizing the required change in yield. To gain insight on this tradeoff, a second measure – the reject rate elasticity of total unit cost, (ε_{r_j}), was calculated for each process in production of the 111-step monolithically integrated laser-modulator. The reject rate for each step (r_i) is calculated as follows:

$$r_i = (1 - Y_i) \qquad \textbf{Equation 30}$$

Since a process may be used at multiple steps in the production flow, the effective reject rate for process j (effr_j) was calculated as follows:

$$\mathit{effr}_j = \left(\prod_{q=1}^{Q_j} r_q\right)^{1/Q_j}, \ \forall \text{ steps } q_j\ [1, \ldots, Qj] \qquad \textbf{Equation 31}$$

such that step q_j uses process j, and Q_j is the total number of steps using process j. The reject rate elasticity of total unit cost (ε_{r_j}) can then be calculated as shown below:

$$\varepsilon_{r_j} = \frac{C' - C^o}{C^o} \Bigg/ \frac{\mathit{effr}_j' - \mathit{effr}_j^o}{\mathit{effr}_j^o} \qquad \textbf{Equation 32}$$

Where r_j^o is the original reject rate for process j, where $j \in [1, \ldots, J]$ and J is the total number of processes, r_j' is the perturbed reject rate for process j, C_o is the total unit cost with all reject rates at original values, and C' is the total unit cost at the perturbed state. By normalizing change in cost against the percent change in reject rate, this elasticity attempts to account for the relative difficulty of lowering the reject rate of a process. Implicitly, this figure of merit assumes that improvements in low yield processes should be easier to realize than for those processes with yields already at 98% or 99%, making them potentially better targets for improvement efforts.

Figure 36 shows such an analysis for the monolithically integrated device using a uniform 0.1% decrease in reject rate for all processes. The elasticity results also show that changes in alignment and MOCVD reject rates have the largest impact on total unit cost. A 0.1%

decrease in the reject rate (increase in the yield) of MOCVD generates savings at a rate 10 times that of some other processes. This importance of MOCVD yield is not identified in earlier work by Stirk et al, which provides instead a detailed analysis of the theoretical contributions of thermal, mechanical stress, and optical coupling to yield. Stirk et al's conclusions regarding thermal, mechanical stress, and optical coupling contributions to yield may be important, however, to improving process yields in alignment, which along with MOCVD, has one of the largest impacts on total unit cost (Stirk 1998).

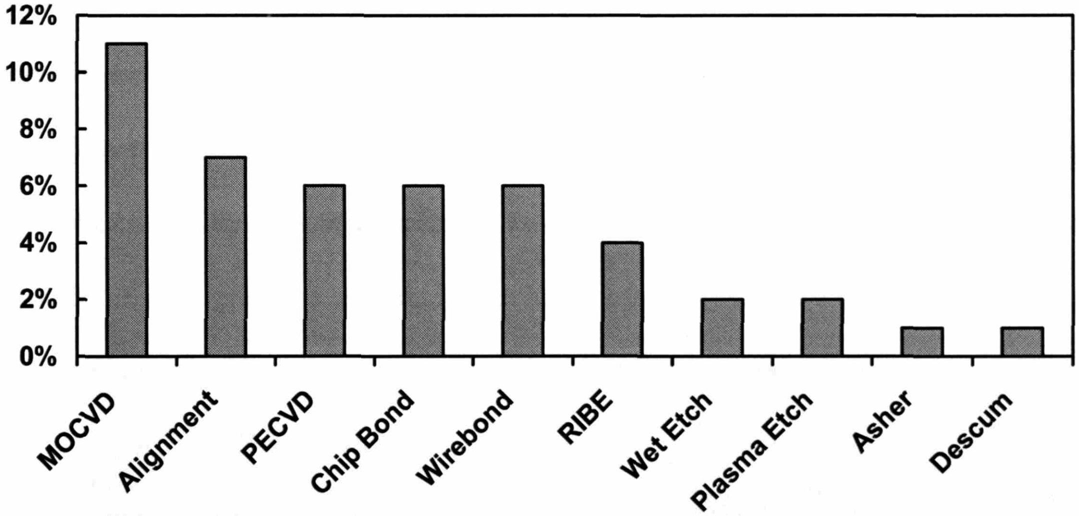

Figure 36: Unit Cost Elasticity to Reject Rates (ε_{r_j}) for Different Process Steps

Because processing defects are often difficult to detect until the final product is assembled, one of the largest yield hits is at the "Final Test." The Final Test represents the tests performed as the last step (step n) of the process. According to previous studies, thermal dissipation within the package, mechanical expansion and stress during both epitaxy and epoxy steps, and compound effects of component placement on optical coupling efficiency, play major roles in contributing to optical transceiver module yields experienced in this Final Test (Stirk 1998, Kim 2002). Previous studies also suggest that for an integrated EML, yield at the Final Test is mostly dependent on coupling constant (κL) and grating phase error (Kim 2002).Yields at the Final Test (Y_n) ranged from as low as 33% to 67% at observed facilities. Due to continual improvement observed in the process, this chapter assumes a "best practice" Final Test yield (Y_n) of 67%. In the model, the Final Test includes testing for laser light, current, and voltage; back facet monitor current, modulated power, line width, wavelength, alternating current extinction ratio, rise/fall time, side mode suppression ratio, mask margin, signal to noise ratio, and sensitivity and dispersion at one fiber length.

Figure 37, Figure 38, and Figure 39 present maps of the sensitivity of the final component cost to the yield experienced at the Final Test. The yield (Y_n) experienced at the Final Test, given that components have gone through over 100 steps to reach this stage, has an enormous impact on unit cost. A map of unit cost sensitivity to yield and production volume provides key insights on the Final Test yields necessary at different production volumes to achieve targeted unit costs.

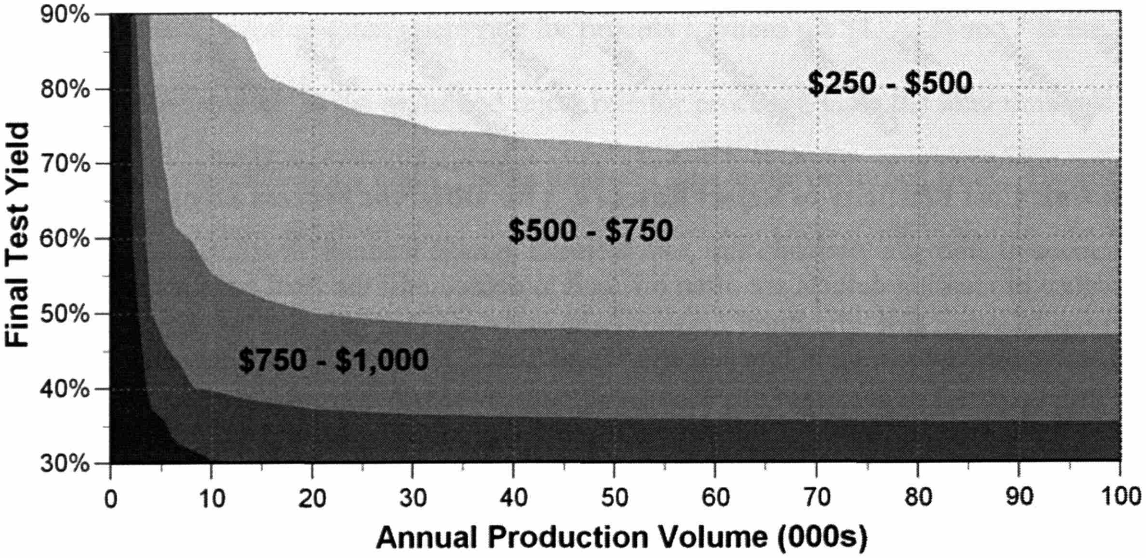

Figure 37: Monolithically Integrated Device Unit Cost Sensitivity to Final Test Yield

Unit costs under $1000 are essential to selling a laser-modulator on today's market. As Figure 37, Figure 38, and Figure 39 show, the monolithically integrated EML can be produced at much lower yields than its discrete device counterparts, and still achieve production costs under $1000, regardless of scale. For the base case yield of 67%, costs remain under $1000 up through production volumes above 2800 per year. In comparison, for the discretely produced device in a single package's production costs to fall under $1000, yields and production volumes must be higher. For the 67% Final Test yield base case, annual production volumes must be above 4800 annually for the single-package discrete laser and modulator production costs to fall under $1000. Yields must be significantly higher for the discretely packaged product's production costs to fall under $1000. Production volumes must be above 15,000 annual units for the discretely packaged product to cost under $1000.

Some estimates suggest it will be necessary for EML production costs to drop under $500 per unit within the next decade to remain competitive. Assuming that these products will at least monolithically integrate the laser and modulator, a set of Final Test yield and production demand objectives emerge. If production volumes rise to 100,000 units annually or more, Final Test yield must only rise around 3% beyond the current base case of 67%. If demand is expected to be such, however, that production volumes will remain below 100,000 units annually, the Final Test yields required become far more difficult to achieve. With the current process assumptions, production costs can not be brought under $500 for production volumes lower than 10,000. Notably, as pointed out by the earlier analysis of lidding yield, Final Test yield and annual production volumes, are not the only parameters available for companies to improve. Processing parameters can be changed to improve yield, new equipment can be bought with better yield performances, and testing positions can be moved earlier in the process to allow yield hits to be felt earlier in the process, to just name a few. Given the results shown below, further integration may have the most significant impact on lowering costs, despite resulting lower yields.

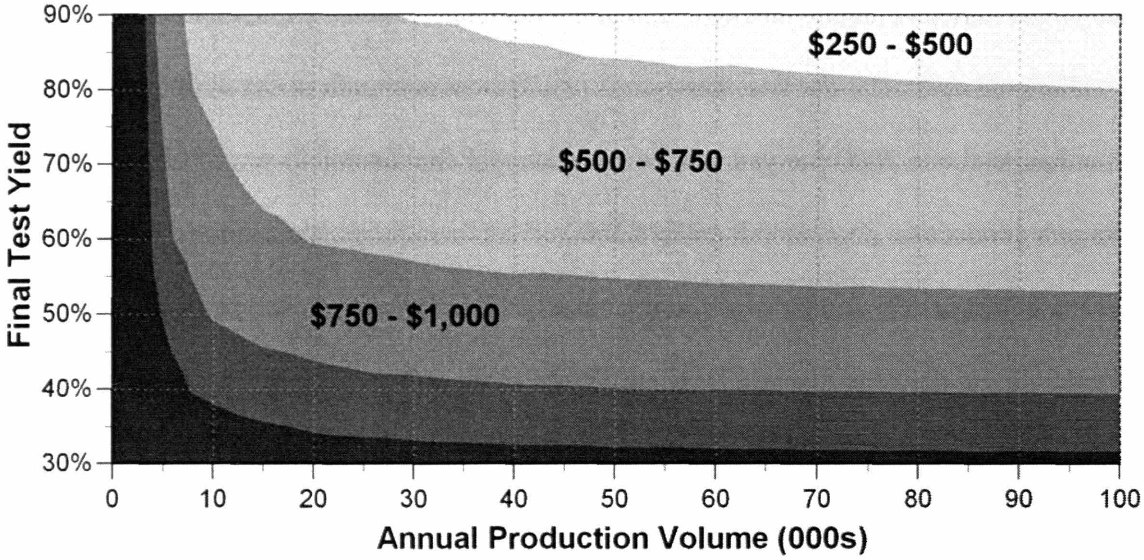

Figure 38: Discrete Laser and Modulator Devices in a Single Package Cost Sensitivity to Final Test Yield

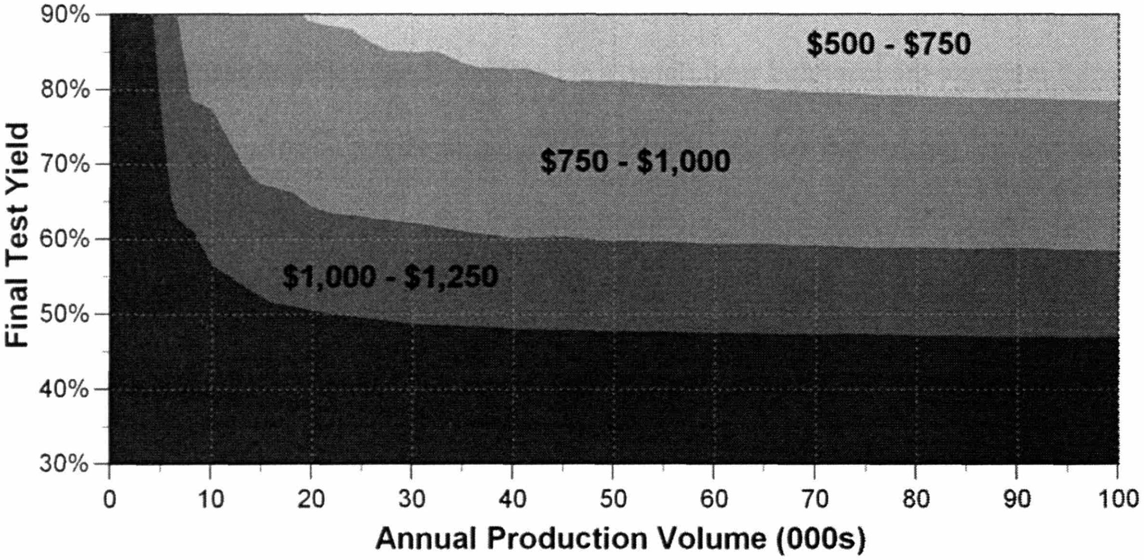

Figure 39: Discrete Laser and Modulator Devices in a Single Package Cost Sensitivity to Final Test Yield

The inherent lowering of Final Test yield caused by placing more steps in series during monolithic integration has previously often been overlooked. Instead, alternative reasons for monolithic integration lowering yields, such as extended processing time and increasingly structured wafer surfaces (Maerz 1996) often dominate discussions. The results shown above are particularly significant because they suggest that even though integration will lead to less favorable yields, these integrated devices can achieve the same cost targets with lower Final Test yields than a discrete device. Thus competency in other areas affecting yield discussed earlier – such as thermal dissipation within the package, mechanical expansion and stress during both epitaxy and epoxy steps, compound effects of component placement on optical coupling efficiency – may be able to remain the same or even be less in the monolithically integrated device and still achieve the same costs.

5.3 Analysis and Conclusions

Integration has been a singular driving force for the explosion of microelectronics-based devices and the infusion of electronic products into every aspect of life (Kimerling 2000). As such, it should come as no surprise that realizing integration is a focus for many segments of the optoelectronics industry. Integration eliminates packaging expenses, both by removing the physical artifact and the time consuming and error-prone processes required to assemble the packages. With integration, however, comes complexity; complexity in both design and processing. This complexity increases the incidence of performance and processing failures, which translates into higher costs. The pace of integration must therefore be measured, balancing packaging gains against processing losses.

For industry to effectively lower production costs, scarce development resources – in design, manufacturing, and tooling –must be carefully focused. Process-based cost models enable a targeted approach to cost reduction. This chapter shows the ability of the CTR-PBCM to assess the techno-economic characteristics of three integration strategies for high-performance laser-modulator pairs. For each of the products evaluated, the CTR-PBCM has provided the following key insights:

5.3.1 The Role of Production Scale

Production volumes above 30,000 units per year are critical to reaching economies of scale. The unit cost of one monolithically integrated EML is $1110 if only 2000 are produced annually, but is $550 if 30,000 are produced annually (and $520 if 250,000 are produced annually). Given that global markets for these products are currently not much higher than 30,000 units annually, the extreme cost-pressures being faced by the industry should come as no surprise. Discussions of an opto-fab or extreme industry mergers may become necessary solutions unless global production volumes rise significantly above economies of scale in the near future. The quick technological turnover of such optical devices, however, may make outsourcing to a single fab either too difficult or too dangerous towards losses of IP. An alternative solution for firms needing to increase productions volumes in order to reach economies of scale not evaluated in this chapter is platform sharing across products and increasing capability to run multiple products on a single line.

5.3.2 Cost Drivers / Cost Reduction Opportunities

In terms of categories of processes, the top three cost drivers for all of the integration levels analyzed were packaging, pre-package assembly, and testing. Alone, these three drivers comprise 82%, 81%, and 87% of total costs for the monolithically integrated laser and modulator, discrete laser and modulator with single package, and discretely packaged laser and modulator devices, respectively. Given this dominance of packaging and of the specific benefits of integration, it is not surprising that the monolithic design provides cost advantages over such a broad range of strategic and operational conditions. Notably, the unit costs per good device presented in this chapter include the direct costs of testing. Lost value added for rejected components is shown in the step where the expense is originally incurred. Testing is clearly key for delivering quality product. These results, however, show that both judicious application and technological development around testing, in particular, reducing the cycle times for testing, would have a strong impact on manufactured cost.

Improvements in the MOCVD and alignment process yields would have the largest consequences for unit cost reduction in a monolithically integrated laser-modulator device. A 0.1% improvement in the MOCVD yield would reduce final unit cost at a rate 10 times that of other processes. For devices with different process flows, MOCVD and alignment may or may not be the processes whose yield improvements would have the most significant impact on cost, however, analyses such as this one would readily identify effective targets for yield improvements.

5.3.3 The Role of Yield

Along with production volume, production yield is an essential part of manufacturing cost; improving that yield will be necessary to meeting long-term cost targets within the optoelectronics industry. Given the process assumptions made in this study, to reach cost targets of $500/monolithically integrated EML with production volumes of 100,000 units annually, yields at the final product test must be at or above 70%. If yields at the Final Test drop below 36%, costs cannot be brought below $1000/ monolithically integrated EML regardless of scale.

Achieving higher levels of integration requires more process steps in series. This manufacturing reality results in lower yields. For example, while the discretely processed laser and modulator in a single package have cumulative yields of 3.9% and 7.9%, respectively, the monolithically integrated EML's cumulative yield, using the same processing techniques, is only 2.3%. Despite these differences in cumulative yield, the monolithically integrated EML costs less than the discrete laser and modulator in a single package, regardless of scale. The complexity which comes with higher levels of integration leads to greater process difficulties and, therefore, lower process yields. However, the cost advantages of the integrated designs do not require as high yields to reach low price points. For the monolithically integrated EML, with annual production volumes of 100,000, only 70% of products produced must pass the Final Test for costs to reach $500/unit. In contrast, for the discrete laser and modulator in a single package, given annual production volumes of 100,000, 80% of products produced must pass the Final Test for costs to reach this low.

The benefits of integration are even more drastic when going from separately packaged devices to a single package. Given the processing assumptions in this study, the discretely packaged laser and modulator cannot meet cost targets of $500/unit (where one "unit" includes both the packaged laser and the packaged modulator), regardless of Final Test yield or production scale. Alone to meet cost targets of $1000/unit for the discretely packaged laser and modulator product, requires Final Test yields above 60% with annual production volumes of 100,000 products per year.

Ultimately, manufacturing cost reduction will be key to the long-term growth of optoelectronic component sales. Realizing this will require both organizational and technological changes throughout the industry. On the technological front, engineers have many design options – materials, processes, and architectures. Unfortunately, neither engineering nor traditional accounting methods are individually able to resolve the cost impact of novel technical changes. This chapter presents a method, process-based cost modeling, which incorporates strengths of both methods to provide those insights. As demonstrated in the case analysis, the model identifies both the strategic strengths of an integrated design as well as pinpointed specific development targets which will allow production economics to be improved effectively.

6 Changing Paths: The Impact of Manufacturing Offshore on Technology Development Incentives in the Optoelectronics Industry

This chapter explores the impact of manufacturing offshore on technology development incentives, and thereby the technology development path of firms in the optoelectronics industry. With the lowering of trade barriers over the past decade, today's firms have many new opportunities to choose where to manufacture and for what market. The implications of these new options for firm technology strategy are unclear. It is also uncertain whether U.S. firms will be able to learn the right lessons fast enough to survive global competition. For firms to compete in the global economy, they may need to take a new approach to technology and product development decisions.

This chapter looks at the implications of new global manufacturing opportunities for technology strategy in the optoelectronics industry. There are several important, distinguishing features of the optoelectronics case. As discussed in the section on Case Selection, Question Development in Chapter 2, the value chain in the optoelectronics industry tends to be global. At the start of this case, the firms manufactured the product of study in the U.S. and shipped it globally. At the end of this case, the most of the firms manufactured the product of study in developing East Asia and then shipped it globally. The market for the product of study is not differentiated by region. Further, the total size of the global market for the product of study is approximately three to five times the economies of scale for a single production facility. (See Chapter 2 Table 5.) Given this *market-technology match* and the large number of competing firms, existing optoelectronic firms are only able to have one manufacturing plant globally.[23]

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[23] The term "one manufacturing plant" is used here very loosely. Actually, optoelectronic firms are able to have one manufacturing plant *per function* globally. The plants performing these different functions are relatively dispersed. At the start of this study, most of the optoelectronic firms manufactured their chips in the U.S., did backend

Thus, these firms manufacture from one location for the global market. These same firms currently perform the majority of their R&D in their home country close to their international headquarters.

Through an innovative combination of engineering modeling and qualitative methods this chapter provides insight into the combination of cost incentives and knowledge diffusion constraints that can cause manufacturing location to influence the path of technology development. Given the complex dynamics to be studied and the lack of previous work in this subject, this chapter focuses on in-depth analysis of one case – emerging integrated designs in the optoelectronic industry (Glasner 1967, Eisenhardt 1989, Yin 1989). The chapter presents results based on data collected from 23 optoelectronics firms on how key process variables (yield, cycle times, downtimes, wage, materials) change with manufacturing location. The chapter then explores how those factors affect the cost-preferred design. Process-based cost modeling techniques (Kirchain 2000) are used to create a model of manufacturing based on the plant-level manufacturing data collected at firms. This model is used to evaluate the cost-competitiveness of emerging designs against the prevailing technology, and how this cost-competitiveness changes if production is in developing East Asia instead of in the U.S. The quantitative analysis is supplemented by information collected in semi-structured interviews. These semi-structured interviews are used to understand actual firm decisions, as compared with what the model might predict, as well as to understand the general product development environment. The chapter complements the model data and interview data with market data to provide a more holistic view of the firms' decision-making and product development

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assembly in the U.S., did packaging in developing East Asia, and then shipped the product globally. At the end of this study, most of the firms manufactured the chip in either the U.S. or developing East Asia, did backend assembly in developing East Asia, did packaging in developing East Asia, and then shipped the product globally. Chip production and backend assembly were sometimes but not always co-located. Packaging was mostly not co-located with the other functions.

environments (Jick 1979). Current optoelectronics research and development in the U.S. is aimed at addressing long-term market demands. Recent firm decisions, based on immediate cost pressures, have reduced the incentives for and the competitiveness of these research and development programs. The chapter uses this reduction in the competitiveness of U.S. research and development efforts to explore a potential shift in technology development paths of the firms and the industry.

In the case of the optoelectronics industry, the results suggest that the static economies of offshore manufacture create patterns of factor substitution that lead to dynamic diseconomies – specifically, disincentives for innovation. Given the burst of the telecom bubble, optoelectronics firms are being forced to decide between two alternatives to remain competitive: reducing materials, labor, and packaging costs (1) by adopting emerging integrated designs domestically or (2) by moving production to low-wage countries. Most firms are moving to mainland China, Taiwan, Malaysia, and Thailand, while few are pursuing the path of technology development and remaining in the U.S. Once in developing East Asia, a combination of non-transferable tacit knowledge in U.S. assembly line workers and implicit real-time on-the-line learning by design engineers is preventing firms from being able to cost-effectively manufacture the emerging design. Further, although the emerging design is cheaper than the prevailing design when both are manufactured in the U.S., the emerging design produced in the U.S. is not able to cost-compete with the prevailing design manufactured in developing East Asia.

The emerging integrated designs, however, do not only reduce costs. In the short term, integrated designs hold potential for improvements in communications network performance and speed. In the long term, integration in optoelectronics may be critical to bringing the information carrying capacity of photons to computers, and to surpassing the interconnect bottleneck challenging Moore's law. Although production in developing East Asia may be reducing short-term costs, the loss of cost-incentives for integration may in the long term be slowing down technological advancement. At the extreme, U.S. optoelectronics firms may through their current actions be giving up their ability for key innovations to further Moore's Law and continue driving the information economy.

The results of this case raise troublesome questions for economic theories on gains from trade (Krugman 1994, Rodrik 1997, Baghwati 2004, Samuelson 2004). Conventional trade theory predicts that the gains of the winners from trade will be more than sufficient to compensate the losers (Samuelson 2004). Yet, technological change has come to be generally accepted in economics to contribute as strongly to economic growth as traditional factors of production.24 If the static economies of offshore manufacture create patterns of factor substitution that encourage dynamic diseconomies – specifically, reduced innovation – gains from trade may be less than conventional trade theory predicts. This last issue can, however, of course, not be resolved through a single case study alone.

6.1 Background: The Optoelectronics Industry and Competitive Advantage

The Information Age, enabled through advances in computers, computer software, and digital transmission technologies, has revolutionized the way we do work. From the personal computer, to email, to cell phones and the Internet, our daily lives have changed irreversibly. These technological advances were originally based in electronics – which uses devices to control the flow of electrons to send, receive and process information. In the past 20 years, a new science, photonics, has begun to play a role in the sending and receiving of information.

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[24] Economists from Mill and Marx to Schumpeter and Solow argue for the critical contribution of technology to growth in the economy. In 1988, Robert Solow won the Nobel Prize for his famous "Solow residual" which ascribed the part of output growth that cannot be attributed to the accumulation of any input to technological progress. Solow, R. M. (1988). "Growth Theory and After." American Economic Review 78(3): 307-317.

With their higher information carrying capacity, photons (and the devices that generate and control them) have been critical to meeting consumer demand in telecommunications for increased communications bandwidth (Schabel 2005). Transatlantic telephone cable using optical fibers has created virtually lossless transmission, while innovations in land area networks and fiber-to-the-home have brought Ultra-High Speed Internet, telephone, and television services to users.

In the upcoming decade, a much greater challenge faces electronics, and a much greater opportunity faces optoelectronics. Intel's ability to exponentially increase the processing speed per chip, as predicted by Moore's Law, has driven not only the chip industry. Complementing the increased processing capabilities of Intel's chips, have been innovations in innumerous other industries covering both hardware and software (Gawer 2000). The continual advance in the capabilities of Intel's microprocessors plus the complementary innovations occurring in other industries have together been a key contributor to the revival and acceleration of productivity experienced since the 1990s by the U.S. economy (Feroli 2001). However, this continual advance in microprocessor speed is rapidly coming to an end. As more and more electronic transistors are squeezed on a chip, cross-talk problems arise between the wires connecting the transistors, limiting the possibility for the integration of more transistors to continue to improve performance. Photons have a higher information carrying capacity than and lack the cross-talk complications of electrons. Although copper wires and insulation have extended the lifetime of Moore's Law for electronics, if the information economy is to continue, a cure to what has come to be known in electronics as the "interconnect bottleneck" will be needed. (See Figure 40.) Optoelectronic devices, with their ability to communicate at the interface between electronics and photonics, are expected to be that cure (Kimerling 2000).

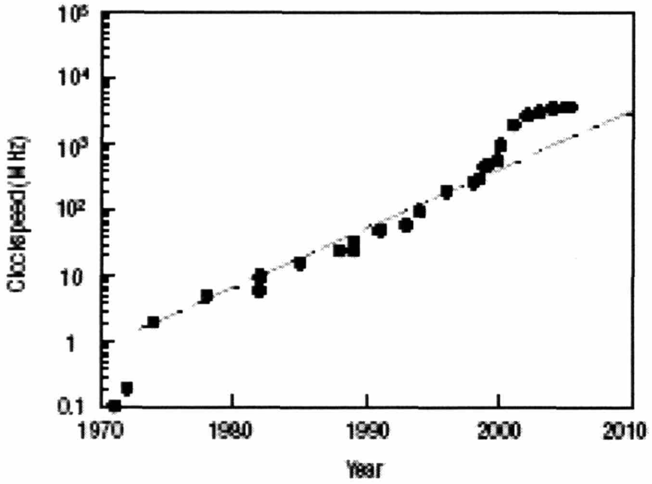

Figure 40: Will the "Interconnect Bottleneck" Challenge Moore's Law? (Source: (Muller 2005))

In order for optoelectronics to meet the demands of computer interconnects, cutting-edge researchers believe it will be necessary to develop a large-scale optoelectronic integrated circuit (Kimerling 2004, Ram 2004). This integrated circuit would consist of five critical components – a laser, modulator, waveguide, photodetector, and receiver. In order to bring all of these components together on a single chip, a sixth component – an isolator – will also need to be integrated. The integration[25] of components, however, is not elementary. Currently in optoelectronics, capabilities only exist for very simple integrated circuits. These circuits integrate two components – either a laser and a modulator or a detector and an amplifier.

Market forces may be getting in the way of the critical innovations necessary for large-scale optoelectronic integrated circuits which integrate many components onto a single chip. In the early 80s and 90s, as optoelectronics was revolutionizing telecommunications, a firm's

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[25] At present there are two main approaches to integration: hybrid and monolithic. Hybrid techniques involve combining optoelectronic components in the same package or substrate using bonding techniques such as flip-chip or bump integration. Monolithic techniques involve integrating multiple component functions through sequential deposition, growth, and pattern transfer on a single substrate. The ability to integrate devices made from different materials systems may make hybrid integration an advantage in the short to medium term, but as longer serially-integrated subsystems are fabricated, the elimination of device-to-device interfacing losses is expected to favor monolithic approaches. For the rest of this paper "integration" will be used to refer to monolithic integration. Fonstad, C. G. (2005). Optoelectronic Integrated Circuits. Research Laboratory for Electronics. Cambridge, MA, Massachusetts Institute of Technology, IntensePhotonics (2005). Photonic System On Chip Solutions: What's the Recipe?.

competitiveness was dependent on being fastest at bringing the latest innovation to market. Although the telecommunications market is small, technology development for that market used to push forward critical innovations in component integration necessary for the much larger computer market of the future. Since the burst of the telecommunications bubble in late 2000, however, firm survival has become a function of unit cost. (See

Figure 27 from Chapter 5.)

With costs threatening firm survival, firms may overlook innovations with long-term benefits to produce large-scale optoelectronic integrated circuits in favor of what appear to be the quick and easy cost reductions of moving manufacturing offshore. Materials, labor and packaging are the primary contributors to production costs for optoelectronic devices. The results of this work suggest that with the burst of the telecommunications bubble optoelectronic firms are being forced to choose between reducing materials, labor, and packaging costs (1) by continuing to develop integrated technologies at home or (2) by moving production to low-wage countries. Most firms are moving to developing East Asia, while a few are pursuing the path of technology development and remaining in the U.S. Although moving production to developing East Asia may in the short term reduce costs, in the long term, offshore production may have dire consequences. The results of this study suggest that moving production to developing East Asia may not only be reducing cost incentives for critical innovations toward large-scale optoelectronic integrated circuits, but also be taking away firms' very ability to make those innovations. The consequences may be disastrous for U.S. comparative advantage through the information economy.

6.2 Methods and Data Collection

This chapter presents a case study from which the researchers inductively build grounded theory (Glasner 1967, Eisenhardt 1989, Yin 1989). The chapter triangulates quantitative modeling data, qualitative interview data, and market data to provide a more holistic view on the drivers of technological change (Jick 1979). On the quantitative side, process-based cost modeling techniques are used to map technical design decisions to their manufacturing cost implications and thereby isolate cost incentives for technology development. The qualitative interviews and market data are used to develop a picture of the actual design and location choices being made by firms in the industry, and the short- versus long-term implications of those decisions for firms' technology development path, and ultimate competitiveness.

This work uses a 52 module process-based cost model to forecast the production and assembly of discrete versus integrated optoelectronic component designs. The details of the model can be found in Chapter 5. In extending this work to address the implications of manufacturing location on the relative economic competitiveness of the design alternatives, this work identifies a set of factors that would lead production costs for identical technologies to differ across two regions. (See Table 2 in Chapter 1.) The sections below discuss the product selection, company participation, model data collection, development of a generic production scenario, and interviews for this case.

6.2.1 Product Selection

Integration of III-V optical functions[26] is still in its relative infancy, with the current state-of-the-art being relatively simple optoelectronic integrated circuits which combine only two

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[26] Here, "III-V optical functions" refers to optical functions made from materials which combine elements from columns IIIA and VA of the periodic table. Research on creating optical functionality in other materials, such as silicon (which comes from column IVA), is in an even greater state of infancy. Clayton, R. a. T. D. (2005). Integration in III-V Materials. Microphotonics: Hardware for the Information Age. L. C. Kimerling. Cambridge, MA, M.I.T. Microphotonics Center. The integration studied in this paper is of III-V optical functions. Specifically, the devices in this study are made of Indium, an element from column IIIA of the periodic table, and Phosphide, an element from column VA of the periodic table.

components on a single substrate – such as laser/modulator or detector/amplifier combinations (IntensePhotonics 2005). The large-scale optoelectronic integrated circuits necessary to bring photonics into board-to-board and chip-to-chip applications in the computer will require the integration of many more than two components. A typical optical data bus for board-to-board or chip-to-chip applications would require five basic components – a transmitter, laser, waveguide, photodetector, and receiver. Critical to preventing unwanted feedback into the laser, and to enabling the integration of the other five components, is a sixth component – the optical (or Faraday) isolator.27

This chapter looks at the cost incentives for technology development in integration by modeling the cost-competitiveness of the integration of two components – a laser and a modulator – and then of three components – a laser, modulator, and isolator – against the prevailing, discrete component alternatives.

Integrated laser-modulator devices currently exist on the optoelectronic market, and compete against devices that provide approximately equivalent performance with discrete laser and modulator components. These devices are produced for the telecommunications market, where designers hope the integration of the two components will decrease production costs and increase network speed and reliability. This study looks in Part I at production of a 1550nm distributed feedback (DFB) laser and an electro-absorptive modulator on an InP platform. The researchers chose a product with these specifications due to the wide availability of data on its production, as well as their compatibility with the performance requirements eventually required to board-to-board and chip-to-chip computer interconnect applications. Two designs, imperfect

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[27] A seventh component whose integration may also be important to enabling the integration of the other five components is the thermoelectric cooler. This device acts to control the temperature, and hence wavelength, of the laser. Other designs are also being explored which may incorporate cooling functions into the transmitter with alternative methods, or may eliminate the need for cooling of the laser.

substitutes28 for each other in the current market place are compared: (1) a discrete 1550nm InP DFB laser & a discrete electro-absorptive modulator within a single package, and (2) a 1550nm InP DFB laser and an electro-absorptive modulator integrated on a single substrate.

Laser-modulator devices such as studied in Part I are assembled into optoelectronic transmitters. Transmitters perform the role of transmitting and receiving data signals in applications ranging from telecommunications networks to sensors to computer interconnects. A SONET telecommunications network transmitter, such as would hold the 1550nm DFB laser and an electro-absorptive modulator, is made up of two components in addition to the laser and modulator – an isolator and a thermoelectric cooler. These components are brought together during the back-end production processes known as optical subassembly. The ability to integrate an isolator may be critical to enabling large-scale optoelectronic integrated circuits for board-to-board and chip-to-chip computer interconnects (Ram 2004). Integrated isolators are not currently available on the market. Integrating the isolator onto the same substrate as the laser and modulator should, however, reduce both size and cost by eliminating the need to assemble yet another component during backend optical subassembly. In Part II, this study looks at whether extending integration to not only the laser and modulator but also the isolator provides diminishing or increasing savings in production costs. Two designs, imperfect substitutes29 for each other in the current market place, are compared: a 10G long wavelength XFP transmitter (1) with an integrated laser and modulator, but discrete isolator, and (2) with an integrated laser,

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[28] In today's market, discretely packaged lasers and modulators, discrete lasers and modulators in a single package, and integrated laser and modulator designs compete for the same market. In reality, the integrated design is smaller than the discrete design, and may already provide some additional reliability. These improved performance characteristics, although beneficial in future applications both in telecommunications networks and computing, are not yet required for today's applications.

[29] Extrapolating from the laser-modulator designs studied in Case I, we assume in Case II that the transmitter with the discrete isolator and the transmitter with the integrated isolator would initially compete for the same market. Similar to the laser-modulators in Case I, the integrated laser, modulator, and isolator design would be smaller than the discrete design, and would have the potential to provide additional reliability.

modulator and isolator30. Given the wide range of debate over the eventual design necessary to integrate an isolator with a laser and modulator, this study sets the cost of integrating the isolator to its theoretical minimum – $0. By setting the cost of the integrated isolator to $0, this study presents the most optimistic case possible for the cost-competitiveness of isolator integration.

6.2.2 Company Participation

Seven companies currently hold the majority share (65%) of the optoelectronics component market. These companies are Agilent Technologies, JDSUniphase, Bookham, Finisar, Infineon, Mitsubishi, and Sumitomo Electric/ExceLight. Agilent and JDSUniphase lead, each holding approximately 15% market share, while Bookham, Finisar, Infineon, Mitsubishi, and Sumito Electric/ExceLight each hold approximately 7% market share. The remaining 35% of the market is split up between 32 and 394 companies, depending on which source is used. Among these remaining players, Intel holds only 3% market share, but is keeping its eye on potential computer interconnect technologies. The other key players without significant market share are start-up companies whose venture-funded technologies hold the potential to swing optoelectronics into new application spaces, or to restructure competition in the industry. (Schabel 2005)

In carrying out this study, the researchers were engaged with over 23 companies up and down the supply chain in the industry. Participants from these companies were interviewed,

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[30] Transmitters are classified according to their transmission speed (Gigbits per second, or G), instead of the wavelength of their lasers. A 1550nm InP DFB laser is one type of laser which could be found in a 10G transmitter. Due to rapid changes in packaging (Schabel, M. J. (2005). Current State of the Photonics Industry. Microphotonics: Hardware for the Information Age. L. Kimerling. Cambridge, MA, M.I.T. Microphotonics Center.), this study looks at optical subassembly of a transmitter with an (uncooled) 1350nm DFB laser for SONET applications instead of a (cooled) 1550nm DFB laser for SONET applications. The 1350nm laser, by not requiring cooling, can be packaged in what is know in the industry as a "TO-can." TO-cans are rapidly becoming the packing standard for optoelectronic transmitters. Currently 1550nm DFB lasers are packaged in larger, butterfly packages, which are required to provide the extra space for a thermo-electric cooler. Advancements in cooling technologies (monolithic integration of thermoelectric coolers being one potential solution), may eventually enable all transmitter technologies to fit into the smaller TO-can-like packages.

totaling over 100 interviews. Sixteen of the 23 companies involved in the study were optoelectronic component suppliers. Together these 23 component companies hold over half of the total optoelectronic component market, and include five of the seven companies which together hold the majority share of the component market.[31] This study also involves several companies with a smaller market share but potentially critical insights to the future of the industry. These companies include Intel, Infinera (a start-up company with critical integration technology), Flextronics (a U.S.-owned contract manufacturer, traditionally in electronics but moving into the optoelectronics space), and two developing East Asia contract manufacturers used by a large cross-section of the industry. The authors were able to receive additional company insights and feedback through participation in three industry consortiums, namely the MIT Microphotonics Roadmapping Consortium, the MIT Center for Integrated Photonics Colloqium, and the MIT Communications Futures Program.

Different companies were willing to contribute different types of information, and different levels of detail on their production. In all cases, the researchers' data collection efforts were to two main ends (1) to have sufficient data to obscure individual company production information, and (2) to have model results representative of the industry as a whole, despite the range of design and production strategies followed by individual firms. Although different component manufacturers contributed to the "front-end" device manufacturing data and the "back-end" optical subassembly data, all nine of the component manufacturers providing direct production data had both front-end and back-end production capabilities internal to the company. Details on the data collection approach and company contributions to different aspects of the study are provided below.

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[31] Of the seven component companies which together hold the majority share (65%) of the market, this study does not include the two Japanese-owned companies – Mitsubishi, and Sumitomo Electric/ExceLight.

6.2.3 Process-Based Cost Model Data Collection

Process-based cost modeling methods provide a means to compare technologies outside of an individual firm's processing decisions. Data for the process-based cost model of front-end device fabrication used in Part I were collected from 10 firms across the optoelectronics supply chain. These firms included three end-users of laser-modulator devices, three device manufacturers, and four manufacturers of production-line equipment. The three device manufacturers were chosen to represent the different production approaches in the industry: high-volume automated manufacture, low-volume labor-dominated manufacture, and a middle-of-the-road approach. Discussions with device end-users and with equipment manufacturers were used to bolster and cross-check data from the device manufacturers.

Data for the process-based cost model of the back-end assembly of the transmitter studied in Part II were collected from six firms. Again, these firms were chosen to represent a cross-section of the industry – including a large firm with highly automated production facilities, three mid-sized U.S.-based firms with production sites in developing East Asia, and two developing East Asia contract manufacturers focused on providing rock-bottom costs.

At each firm, data collection was focused in three main areas: (1) design: (a) current design technology (material, process, and geometry) and (b) emerging design alternatives; (2) production: (a) production data for current manufacturing technology and processes and (b) new production requirements for emerging design alternatives; and (3) location: differences in production variables between the U.S. and the offshore manufacturing location.

(1) Design. Industry-wide component design standards do not yet exist for the optoelectronics industry. Roadmaps and workmanship guidelines have evolved in place of standards through industry associations such as NEMI, IPC, NIST, and IMAPS. Standards, called SONET and SDH, do exist to regulate data transmission rates over fiber optical networks.

Suppliers are also developing de facto standards through cooperative multi-source agreements (MSA), where component form factors, pin-outs, and control features are established as common features. MSA's are being used to drive a trend toward packaging and integration convergence between voice (Sonet/SDH) and data (Ethernet) based communications (Schabel 2005).

A SONET-compatible 1550nm InP system 10Gb/s distributed feedback (DFB) laser and electro-absorptive modulator (EA) was chosen for the laser-modulator device. Specification sheets and product information, as available publicly, were collected from each of the three device manufacturers on an integrated laser and modulator and a discrete laser and discrete modulator in a single package being manufactured to the above-described specifications. One device manufacturer also provided electronic copies of in-house design diagrams to aid the study.

Designs for transmitters meeting equivalent performance specifications vary widely by firm. For each firm, a SONET-compatible 10G long wavelength XFP small form factor (SFF) multi-source agreement compliant transmitter design with an uncooled, 1350nm isolated DFB laser was chosen. Again, specification sheets and product information, as available publicly, were collected at each firm. With four of the six firms, diagrams of the firm's particular design were collected on-site. Design options for an integrated isolator were discussed with M.I.T. Professor Rajeev Ram, based ongoing research projects within the Research Laboratory for Electronics (RLE). To avoid current debates over the design necessary to integrate an isolator with a laser and modulator (and the cost of manufacturing that design) this study sets the cost of integrating the isolator to its theoretical minimum – \$0.

(2) Process. Three types of data were collected at each company to create the "virtual fab" in the model. First, a process flow for each product was created with a representative

engineer. Internal production cost models, bill of material and material handling sheets, equipment investment files, and operations documents were then collected to fill in the 26 inputs necessary for each process step (see table 3). Notes were taken during a tour of the production facilities, and cross-checked to identify overlooked process steps, scrap and yield sources, downtimes, and cycle times. In the two cases where production facility visits (one front-end fabrication facility, and one optical subassembly facility) were not allowed, experiences at other firms were used to cross-check the process flow and other data for inconsistencies or missing items. The process flow and data were then aggregated into a table identifying the data for each process step, and confirmed with the engineering team.

(3) Location. All three of the firms which provided front-end fabrication data produced their laser and modulator components in the U.S. or in Europe. This trend to do front-end fabrication in the home country is currently true for all U.S. and European firms in the optoelectronics industry with the exception of Agilent, which moved its front-end manufacturing to Singapore in 1988 (Yao 2003).32,33 Contract manufacturers and Japanese-owned firms may be doing front-end fabrication in developing East Asia; however, it is unlikely that at this time any of this fabrication is of high-end laser-modulators such as the one modeled in this study. Actual plant data was therefore not available to the researchers on front-end production differences between the U.S. and developing East Asia at the time of the study. Future manufacturing location trends for front-end optoelectronic device fabrication are difficult to

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[32] Agilent's operations in Singapore go back to when Hewlett-Packard established its first assembly and test facility in Singapore in 1971.Yao, G. (2003). Mr. George Yao, Minister for Trade and Industry, at the Opening of Agilent Technologies Singapore New Building at Yishun on 25 February 2003, Singapore Ministry of Trade and Industry.

[33] Although Singapore can have lower wages than the U.S., Europe, or Japan, it is not considered in this paper to be in the same category as low-wage countries such as China, Thailand, and Malaysia. Singapore is listed as one of 29 "advanced economies" by the IMF and as one of 55 "high-income economies" by the World Bank Group. Singapore is not listed as one of 42 "Developed Regions" by the United Nations. http://www.imf.org/external/pubs/ft/weo/2005/01/data/groups.htm#1, http://www.worldbank.org/data/countryclass/classgroups.htm#High_income, http://unstats.un.org/unsd/mi/developed_new.htm.

postulate, and it is likely that at least some of front-end fabrication will move to developing East Asia, even if not through U.S.- or European-owned firms. This study therefore explores the cost-implications of laser-modulator fabrication in a developing East Asian production environment. Initial estimates for laser-modulator production differences between the U.S. and developing East Asia are based on production differences between the two regions observed for the back-end optical subassembly.

Of the six firms contributing to optical subassembly production data for the study, all six were either in the process of moving or were already performing optical subassembly operations in developing East Asia. Based on the variable mapping shown in Table 4, the authors chose seven variables for initial focus when working with firms to identify U.S. and European versus developing East Asia production differences. These seven variables, starred in Table 4, are wage, yield, downtime, cycle time, price of building space, price of electricity, and discount rate. Data collected on the process (see (2)) were used to document values for these variables in each location during visits with the six firms contributing to back-end optical subassembly data. Discussions with engineers were used to gain insights on the source of the observed production differences. The author did not, however, attempt to quantify the magnitudes of the different sources' contributions.

The data collected by the researchers show the impact of production in mainland China, Taiwan, Thailand, or Malaysia on transceiver subassembly production parameters to vary by firm. Although it took one firm six months to re-qualify its product after transfer from the U.S. to its plant in developing East Asia, the firm was eventually able to achieve equal or better cycle times and yields for each process step. Some firms expressed similar experiences with transfer times and improved assembly yields; however, other firms experienced worse yields in developing East Asia. Downtimes were longer in the developing country production environment for all firms due to a lack of local equipment expertise. With capital equipment developers and manufacturers still in the U.S. or Japan, time differences and lack of local expertise could often cause a machine to remain out of order for 1-3 days. Worker schedules also tended to be different in developing East Asia for all firms interviewed.

A more accurate portrayal of the impact of changing manufacturing location will require further data collection. A set of preliminary assumptions regarding differences in variables between a developed country and a developing country manufacturing facility therefore are used here. These preliminary variables chosen to represent the U.S. and developing country production are based on differences seen in all of the firms interviewed (see Table 18). These country-dependent variables are used to demonstrate the potential of process-based cost modeling methods for assessing the impact of manufacturing location on the relative economic position of technology alternatives. These preliminary production differences are also used as a base-point for exploring the sensitivity of results to these location-specific variables.

Table 18: Production Variable Differences for Initial U.S. vs. Developing East Asia Scenarios

	U.S.	Developing East Asia
Working Days per Year	240	360
Number of Shifts	3 x 8-hour shifts	2 x 12 hour shifts
Wage Incl. Benefits	$15 / hour	$2.60 / hour **
Discount Rate	10%	16%
Workers Unpaid Breaks	1 hour / day	1.5 hours / day
Downtime (Paid Breaks)	1.2 hours / day (5%)	1.8 hours / day (7.5%)

** The $2.60 hourly wage used for "developing East Asia" is an average of observed wages. While wages observed in mainland China were around $0.57 per hour with benefits, wages in Taiwan were on average $4.51 per hour with benefits.

6.2.4 Development of a Generic Production Scenario

Data were collected under non-disclosure agreements to encourage companies to provide the maximum amount of information. To increase incentives for participation and honesty, companies were encouraged to add products of interest specific to their individual company to the analyses. Analyses and recommendations were provided back to each company based on the products and information they provided. The author then developed a public, "generic production scenario" to represent common, industry-wide practice. For all companies, participants were asked to identify what of their processes they felt were non-generic. These confidential practices were excluded from the generic process flow. Mean values across the represented firms were then calculated for the 25 inputs for each process step in the generic process flow. Unit cost results for the generic process flow were cross-checked with unit cost results of individual companies to ensure the generic process flow results were representative.

6.2.4.1 On-Sight Interviews

A combination of semi-structured interviews and market reports were used to develop a picture of company decisions. The interviews focused on both (a) design (material, process, and geometry) decisions in the home-country versus the offshore manufacturing location, and (b) company explanations or logic behind those decisions. The interviews were primarily informal, occurring naturally during the process of product and process data collection. In four cases, when dealing with higher levels of management, actual times for interviews were arranged. All interviews were semi-structured, allowing interviewees to bring-out the most important points in their individual experience. Notes were taken throughout company visits during data collection, discussions, and interviews, and transcribed within 24 hours.

6.3 Results and Analyses: Changes in Cost Incentives with Location

6.3.1 Part I: Integration of Two Components

A SONET-compatible integrated InP 1550nm DFB laser and electro-absorptive modulator is available from many firms today for telecommunications applications. The emerging integrated design competes with prevailing discrete designs which provide the same functionality. Researchers have for a long time argued that integration will provide the same unparalleled gains in functionality and reductions in cost for optoelectronics that it did for electronics. Agreement is lacking in the industry on whether the current integrated optoelectronic designs, given their lower yields, are actually more cost effective. Since both the integrated and discrete designs are available on the market, this study is able to provide results based on real, plant-level production data – including material costs, downtimes, cycle times and yields. The competitiveness, based on the U.S. manufacturing data collected for this study, of an InP 1550nm DFB laser integrated with a electro-absorptive modulator against the discrete alternative can be seen in Figure 41.

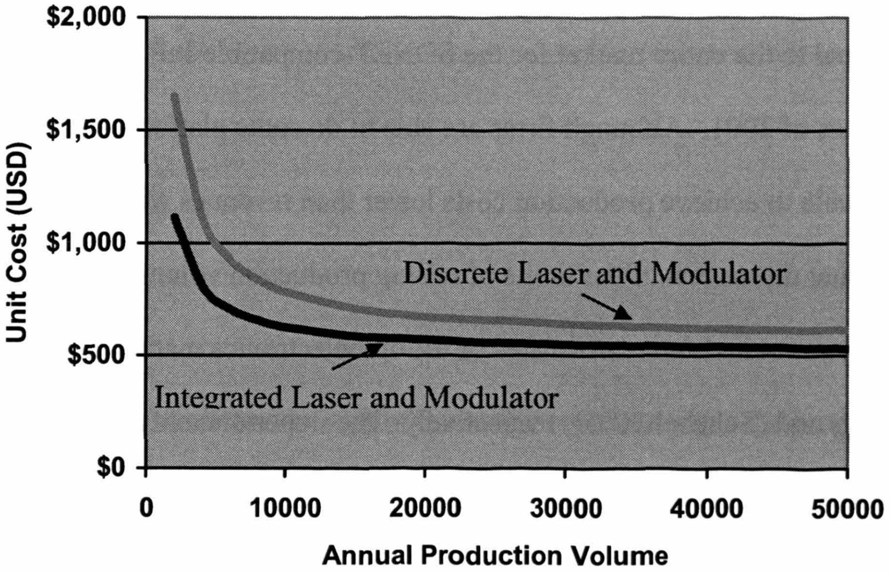

Figure 41: Laser-Modulator Device Cost Sensitivity to Annual Production Volume (APV)

As can be seen in Figure 41, according to the data collected in this study, the integrated design is cheaper than the discrete alternative regardless of production volume. At production volumes of 30,000 units annually, the integrated DFB laser and electro-adsorptive modulator device saves $92 per unit over the discrete laser and modulator, a 14% cost reduction. These savings are brought about by the streamlining of backend packaging, assembly, and testing allowed by integration. The cost savings occur despite a 41% and 71% decrease in yield (i.e., from 3.9% and 7.9% for the discrete laser and modulator, respectively, to 2.3% for the integrated laser-modulator). Of the integration cost savings, 17% are due to reduction in labor requirements. (Labor costs drop by $66, or 42%.) Of the integration cost savings, 28% are through reduction in material requirements. The remaining cost savings are through the reduction of backend equipment and their associated requirements (i.e. electricity, maintenance, and overhead). Notably, moving production to developing East Asia is attributed to providing cost savings in exactly the same areas – namely labor and material costs – as integration.

Before going on, it is important to note that economies of scale are achieved in Figure 41 at 30,000 units annually for both the integrated and the discrete design.34 This annual production volume is approximately equal to the entire market for the SONET-compatible InP 1550nm DFB laser and modulator devices as of 2001. Although firms are able to do some platform sharing across products, they are unable to achieve production costs lower than revenues with more than one production facility. Further discussion of the limits of raising production volumes in reducing costs as well as of current and future estimates of the optoelectronics market can be found in (Fuchs forthcoming) and (Schabel 2005), respectively. The importance of a constrained market to this case is discussed later in the document.

The primary argument used against integration is that it is unable to be cost-competitive against the conventional discrete technology due to its low production yields. The yields shown are the average (mean) yields of the three firms observed in the study, which were carefully chosen to represent the range of industry practice. It is possible to imagine, however, that other

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[34] The term "economies of scale" is more correctly used to describe the economic phenomenon where cost per unit reduces with increased production. Here, the term "economies of scale" is used more loosely to describe the area of the production curve where further increases in production volume no longer lead to dramatic reductions in cost. In Figure 2, the unit cost of the integrated laser and modulator drops 15% between 10,000 and 30,000 annual units, whereas it drops only 2% between 30,000 and 50,000 annual units, and similarly only 1% between 50,000 and 70,000 annual units.)

firms would have different yields. Figure 29 in Chapter 2 showed the sensitivity of the results from Figure 41 to changes in yield. As was shown in Figure 29, the cost-competitiveness of the integrated design against the prevailing discrete design (assuming U.S.-based production in both cases) is relatively robust. Even if cumulative yields for the discrete laser and modulator design can be brought up to 4.5%, the integrated design at current yields remains the most cost-competitive alternative. Only if cumulative yields for the integrated design fall below 2.3% does the discrete laser and modulator design have the chance in a U.S. production environment to cost-compete.

Figure 42 provides a breakdown of the major contributors to the production costs of the emerging integrated design. The left-hand side of

Figure 42 shows the contribution of fixed versus variable costs to the total unit cost of manufacturing the integrated design. “Other variable” costs in the figure below include both labor and energy, but labor, at $88, represents 90% of this category. “Other fixed” costs include maintenance, tooling, building space, and overhead. Given that materials and labor contribute to 43% of the total unit cost of producing the integrated design, incentives seem to still exist, to produce the integrated design in developing East Asia. As can be seen on the right hand side of Figure 42, production costs of the integrated laser-modulator are still, like the conventional discrete design, dominated by backend costs for packaging, assembly, and testing. The processes which fall under backend packaging, assembly, and testing can be seen in Table 13 in Chapter 5.

The dominant nature of the backend costs suggest that there may be cost advantages (or cost incentives) for further integration.

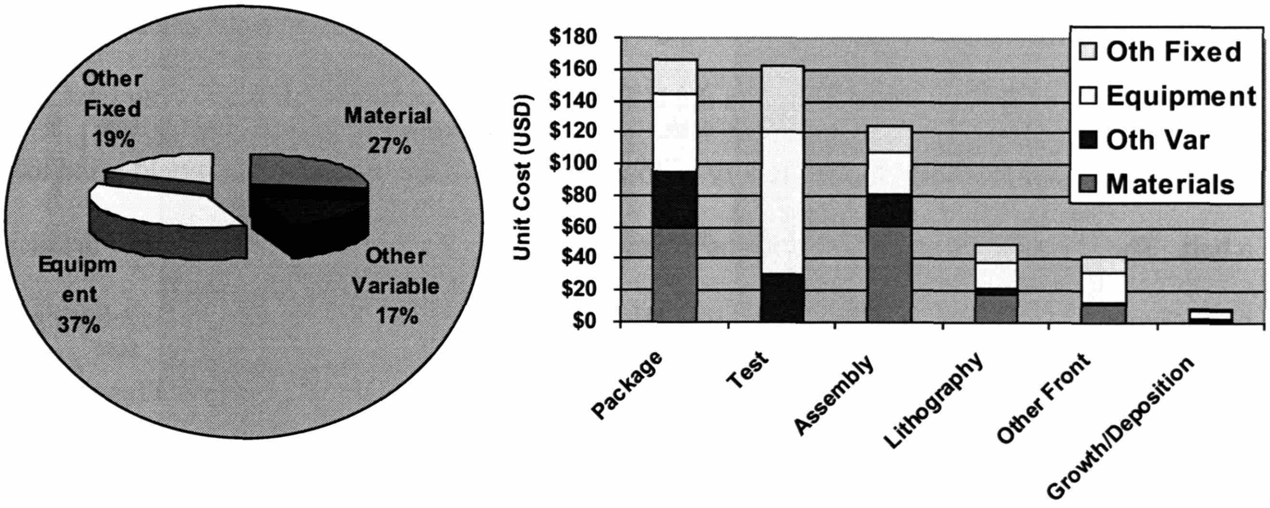

Figure 42: Integrated Device Cost Breakdown by Process (30,000 APV)

Although data was not available at the time of the study on production of an InP 1550nm DFB laser and electro-absorptive modulator in developing East Asia, several firms are exploring this option. The inputs in Table 18, showing the labor, plant operation, and downtime differences observed for the U.S. versus developing East Asia optical subassembly facilities, are used as an initial estimate of U.S. versus developing East Asia differences for laser-modulator manufacture. As can be seen in Figure 43, placing laser-modulator device fabrication in the low-wage environment depicted in Table 18 enables a significant cost reduction for both designs. At 30,000 units per year, the discrete laser and discrete modulator in a single package is $193 cheaper in the developing East Asia than in the U.S. production environment. According to these results, a firm can be more cost-competitive by producing the prevailing discrete design in a developing East Asian environment than by pursuing producing the emerging integrated technology in the U.S.

The integrated design's cost curve is shown as a dotted line since interviews with firms suggest that this technology could not currently be produced in developing East Asia. Production engineers expect that the extremely low yields (2.3% and lower) experienced during the production of the integrated design in the U.S. would drop even lower in developing East Asia, and without engineers in the vicinity to solve production line crises, output would grind to a halt. The ability to produce new designs in developing East Asia is discussed in greater detail in the section on "Difficulties Manufacturing High-Performance Optoelectronics in Developing East Asia" below. If the integrated design could be produced in developing East Asia (as defined in Table 18) at the same yields as it is produced in the U.S., the integrated design's unit cost curve would be equivalent to the dotted line shown in Figure 43.

Notably, even if the integrated design could be produced at similar (or even better yields) in developing East Asia, the incentives to integrate are less in the developing East Asia than in the U.S. While integration saves $92 over the prevailing discrete design in the U.S., it only would save $83 in the low-wage country environment.

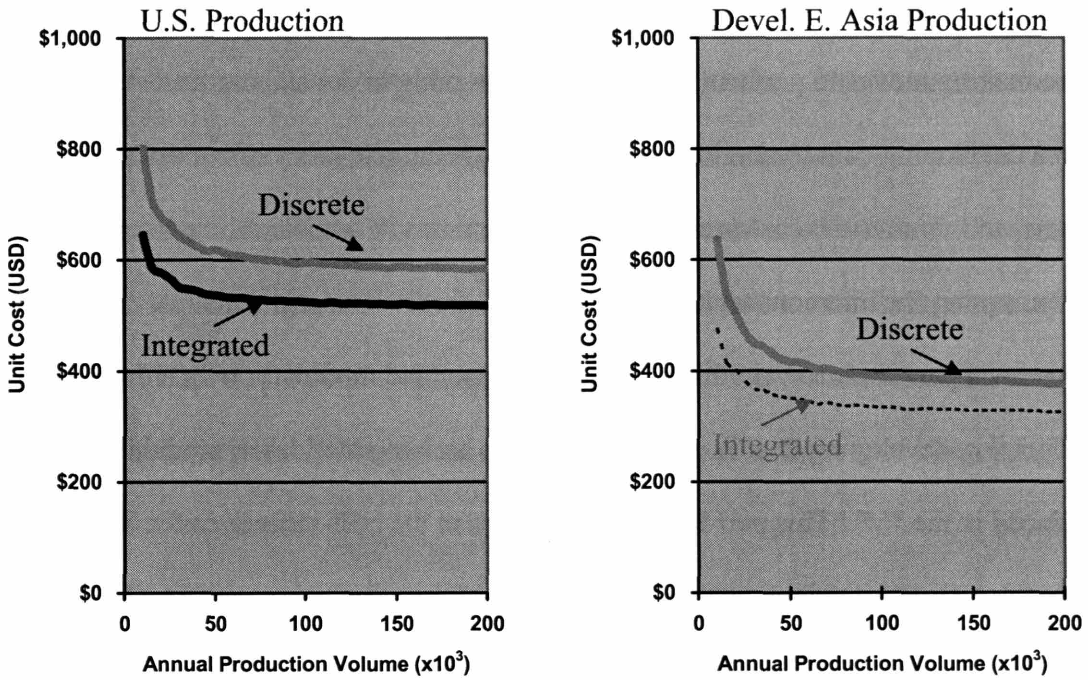

Figure 43: Cost-Competitiveness of U.S. Produced Integrated Laser and Modulator vs. Developing East Asia Produced Discrete Laser and Modulator Design

6.3.2 Part II: Integration of Three Components

Research and development efforts for further integration, and other technological advancements to reduce packaging costs, pervade the optoelectronics industry, including efforts to integrate MOSFET driver circuitry, photodetectors for on-chip optical clock signal distribution (Kimerling 2004), a magneto-optic waveguide isolator, on-chip heat flow controls, and on-chip thermal profiling for photonic integrated circuits (Ram 2004). Other research and development in the industry includes efforts to remove the need for an isolator, efforts to remove the need for a cooler, and efforts to locally hermetically seal devices using a polymer film (Ram 2004).

These research efforts have two items in common. They are all located in developed countries (specifically, the U.S., Europe, and Japan) and they all act to reduce back-end packaging and assembly costs – the major cost driver in U.S.-located optoelectronics production. Unlike laser-modulator fabrication, optical subassembly currently occurs in both developed countries and the developing world. With increased cost pressures in the industry, many producers are making moves to perform all optical subassembly in developing East Asia. This relocation to a developing country environment may reduce the relevancy of current packaging-focused efforts, and remove the cost-pressure for developments in optoelectronic integration critical to overcoming the interconnect bottleneck.

This second part explores whether an integrated laser and modulator with a discrete isolator produced in developing East Asia is cheaper than an integrated laser, modulator, and isolator produced in the U.S. This part looks, specifically, at the cost-incentives for integration of an optical isolator – a critical component for the large-scale optoelectronic integrated circuits necessary for board-to-board and chip-to-chip computer interconnects. Traditionally, for long-haul telecommunications applications a laser and a modulator, such as described in the first section, are assembled together with an isolator and a thermoelectric cooler into a transmitter, which is used to send and receive information along the network. Although integration of the isolator in addition to the laser and modulator may in the short term enable additional cost reductions in this telecommunications application, the capability to integrate the isolator is a critical step towards being able to integrate the other components necessary for large-scale optoelectronics integrated circuits for computer interconnects. [35]

Two designs, imperfect substitutes for each other in the current market place, are compared: a 10G long wavelength XFP transmitter (1) with an integrated laser and modulator, but discrete isolator, versus (2) with an integrated laser, modulator and isolator. Assembly of a 10G long wavelength small form factor XFP transmitter occurs in two phases. In the discussion which follows, the costs of these two phases are occasionally presented separately. The first set

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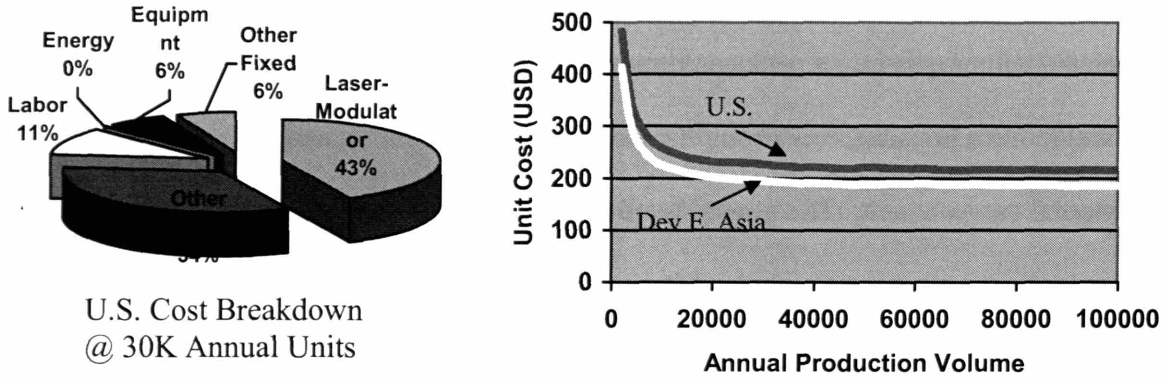
[35] Researchers are also exploring if alternative technologies exist such that the isolator and thermo-electric coolers would no longer be needed.

of steps are known as the TO-can build. Here the laser and modulator are assembled along with their associated submounts into a package known as the TO-can. This TO-can is then aligned and laser-welded to a housing, containing the isolator, a focusing lens, and a fiber receptacle out into the external environment. The assembly of the parts contained within the housing and the housings' subsequent alignment with the TO-can are known as the transmitter optical subassembly (TOSA). Given the wide range of debate over the eventual design necessary to integrate an isolator with a laser and modulator, this study sets the cost of integrating the isolator to its theoretical minimum – $0. By setting the cost of the integrated isolator to $0, this study presents the most optimistic case possible for the cost-competitiveness of isolator integration.

Figure 44 below shows the unit cost for the 10G DFB laser TO-Can build and TOSA in the U.S. versus developing East Asia. As can be seen in Figure 44, 19% of the US-produced transmitter units costs (not including the costs of the laser-modulator) are driven by labor costs. Given the labor, plant schedule, and downtime production characteristics shown in Table 18, companies are able to save $31 per unit by moving production to developing East Asia. Although not represented in Table 18, production engineers within companies repeatedly expressed expectations in the near term to begin to source materials (other than the laser-modulator) cheaper in developing East Asia. With labor (19%) and materials (59%) together 78% of total transmitter unit costs (not including the laser-modulator), it is easy to see the strong push for companies to move these operations to developing East Asia where labor and material costs are reduced.



U.S. Cost Breakdown
@ 30K Annual Units

Figure 44: 10G TO-Can Build and Transmitter Optical Subassembly in the U.S. vs. Developing East Asia

The transmitter optical subassembly, whether performed in the U.S. or in a developing East Asia environment, is dominated by the cost of isolator subassembly, as can be seen in Table 19.

Table 19: Isolator Costs (within the Transmitter Optical Subassembly) in the U.S. vs. Developing East Asia

	U.S.	Developing East Asia
Transmitter Optical Subassembly	$31.5	$29.5
Isolator Subassembly	$21.3	$20.9
Isolator Percent of TOSA	68%	71%

Of the $21.31 it costs to put together the isolator subassembly in the U.S., $20.55, or 96%, is the price of the isolator part itself. Similarly, for the low-wage TOSA production, of the $20.88 it costs to put together the isolator, $20.55, or 98%, is the cost of the isolator itself. In the interviews to-date, the isolator is included in the parts that companies plan to source cheaper in developing East Asia. Figure 45 shows the cost boundary at which an integrated isolator ceases to be cost-competitive against a product assembled with cheaper parts within the developing country. Given the lack of a completed model of integrated isolator production, U.S. integrated isolator production costs are set to $0 – the optimistic limit in possible cost savings through integration. With this assumption, at production volumes of 100,000 annually, local sourcing needs to save 35% in material costs to make it impossible for a U.S.- produced transmitter with an integrated isolator to compete on cost. The two interviewees (from different firms) who believed that they could achieve material cost savings by sourcing locally in developing East Asia, when asked, both believed it was not unreasonable to achieve materials cost-savings of this magnitude.

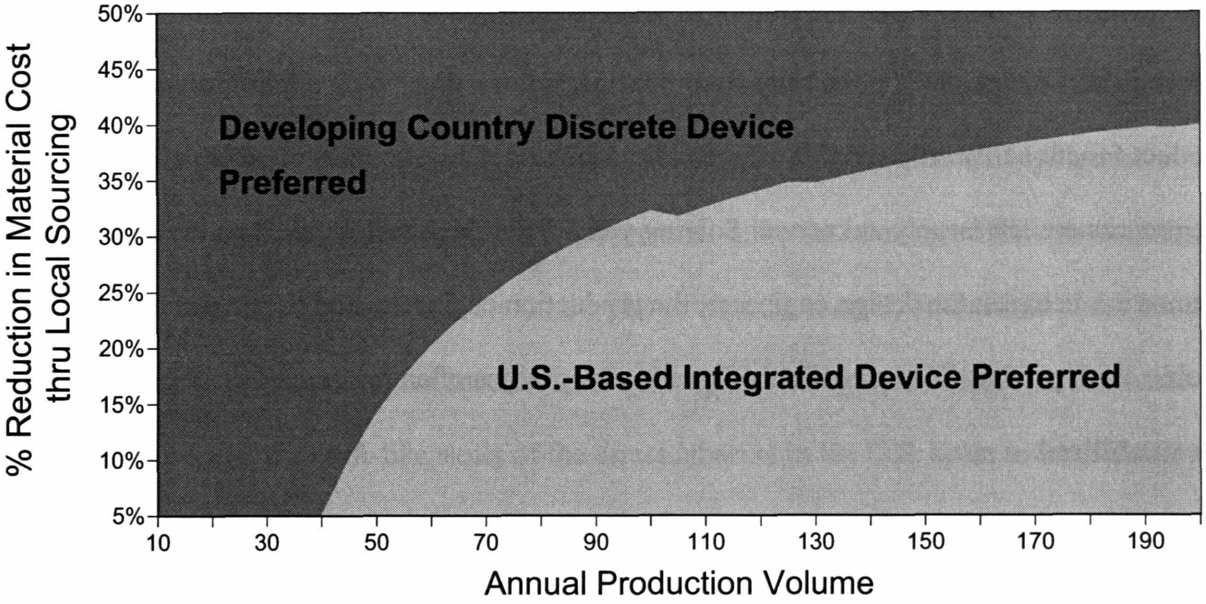


Figure 45: Discrete Isolator Transmitter Production in Developing East Asia -- Cost Savings Over Integrated Isolator Transmitter Production in the U.S.

6.3.3 Difficulties Manufacturing High-Performance Optoelectronic Components in Developing East Asia

Parts I and II compare manufacturing an integrated design in the U.S. with manufacturing a conventional, discrete design in developing East Asia. Production characteristics specific to the optoelectronics industry make it difficult to produce high-performance designs in a developing country environment.

Front-end fabrication techniques are necessary for integration and are dominant in laser-modulator production such as for the designs in Part I. Front-end fabrication techniques are currently almost exclusively implemented close to their research and development centers in developed country environments (primarily the U.S., U.K., Canada, and Japan). There are many indications as to why front-end optoelectronic device fabrication is still located close to research and development. For front-end fabrication, yields can fall below 10%, ranging as low as 1-3% for high-performance integrated devices. For a high-performance device such as the 1550nm InP laser-modulator, days can go by without yielding a single good device. Production, design, and test engineers are needed on the shop floor multiple times a day. With significant aspects of product functionality only testable after final product assembly, sources of yield problems within the process are left largely unknown. Solving yield difficulties thus requires an intimate connection between the design engineers, the production engineers, and the production process itself. With product lifetimes of only 3 years, new designs often replace old ones before yields have stabilized.

The need to locate front-end device fabrication near research and development may change over time. Despite the short product life of optoelectronic devices, the technology as a whole may mature, raising yields. Codification of currently non-standardized production techniques may also be expected to raise yields. Also, optoelectronics technology knowledge in mainland China, Malaysia, Thailand, and Taiwan, may increase, possibly allowing research and development to be located in these countries along with manufacturing. If optoelectronics production processes could mature and technical skills in optoelectronic factories could improve in the short term while wages, interest rates, and downtimes were to remain typical of a developing country environment, there could be cost-advantages to producing all optoelectronic designs in developing East Asia. Assuming this hypothetical case in which the same yields currently achieved in the U.S. could be achieved in developing East Asia, production costs would be similar to the dotted unit cost curve representing the integrated design in Figure 4.

Although firms are in the process of trying to move all backend assembly (such as the TO-Can build and transmitter optical assembly studied in Part II) to developing East Asia, many problems, again, are arising with high-performance designs. Multiple reasons are cited for the difficulty of transferring production to an alternative location, and for the location of high-end production facilities in developed country environments. Optoelectronic assembly continues to be non-standardized rather than designed for high-volume manufacture. Alignment of lasers with lenses and other devices, although machine-aided, is done manually. The more high-power a laser is, the more challenging its alignment requirements. Like for laser-modulator production, production, design, and test engineers are on the phone with the shop floor multiple times per day, and suit up to go into the clean room at least once a day. In the case of high-performance alignments, however, the craft-like skills of the direct laborers in the U.S. seem to be difficult to transfer to developing East Asia. Most firms sent one or two workers for several days to several weeks to pass along their skills. One firm sent an entire team of direct laborers for the backend processes over to developing East Asia for two weeks to teach their techniques to the workers at the new Asian facility, but with no success. At the time of study, the six researched firms were still primarily producing low-performance products in developing East Asia. The one firm with a slightly more advanced product – a 10G FP transmitter – being produced in developing East Asia expressed significant concern about being able to meet specifications three months after the product's introduction, and was considering bringing the product back to production in the U.S.

The requirements for interaction with engineering and the difficulty of transferring the tacit assembly knowledge suggest that firms will, in the short term, be forced to choose between designing advanced technology alternatives for production in the U.S., and designing low-technology alternatives for production in the developing world. This research suggests that by moving production to developing East Asia, the U.S. firms in this industry may be removing not only their incentives but also their ability to make the innovations necessary to continue to survive in optoelectronics, once the demands from the computer interconnect market become critical.

6.4 Conclusions

Current theories on technology trajectories and gains from trade overlook the possibility that manufacturing offshore changes firms' technology development paths. This paper provides in-depth analysis of a single case – emerging integrated designs in the optoelectronics industry. Photonics has been and is expected to continue replacing electronic applications – moving from transcontinental fiber-optic cables, to local land-area-networks, eventually into intra-computer applications. As the photonic-electronic interface moves nearer to the computer's core, the demand for optoelectronic devices – the devices that act at this photonic-electronic interface – grows. In the 80's and 90's, the most competitive optoelectronics firms were those quickest at bringing the latest innovation to market. A primary direction of these innovations was the integration of multiple devices on a single chip. In the short term, integrated devices are expected to increase network speed, improve network performance, reduce device size, and reduce device and network costs in telecommunications. In the long term, integrated designs are considered key to solving the interconnect bottleneck which threatens to prevent the advancement of Moore's Law, and for optoelectronics to access the much larger computer market.

However, since the burst of the telecom bubble in early 2000, competitiveness in the optoelectronics industry has become a function of cost. As a result, firms have been forced to choose between two options to reduce material, labor, and packaging costs – (1) to continue to develop new technologies at home (specifically, integrated designs) or (2) to move production to low-wage countries. Several factors constrain firms to the above two options: First, firms are currently unable produce integrated designs in their offshore production facilities due to a lack of local highly skilled design engineers and to problems transferring tacit backend assembly skills. Further, the constant attention of design engineers required on the production line makes it difficult to geographically separate design activities and production. Second, the size of the current telecommunications market does not support multiple production sites. As shown in the cost-results in this paper and supported by interviews, component manufacturers are unable to support two manufacturing facilities (one in the U.S. producing the emerging technology and one in developing East Asia producing low-cost products with the prevailing technology) without pricing under cost.

The cost results of this work show that although the emerging integrated design is cheaper than the prevailing design when both are manufactured in the U.S., the emerging design produced in the U.S. is not able to cost-compete with the prevailing design manufactured in developing East Asia. Almost all of the firms studied have chosen the path of relocating manufacturing offshore and continuing to produce the prevailing technology. Although in the short-term these firms are reducing production costs, they are also reducing cost incentives for research agendas in the U.S. focused on integration. The advance of integrated designs in the optoelectronics industry may be critical to continuing Moore's Law and driving the information economy. If shifting production to developing East Asia slows this advance, the negative effects are significant. Either no firms will advance Moore's Law and the information economy will slow globally, or U.S. firms will fall behind and lose the technological rents associated with driving the information economy. Such negative effects may more than offset any gains from lower labor and material costs. Further, this paper's principal finding that manufacturing offshore reduces incentives for innovation challenges conventional theories of trade, in particular their underlying assumptions about the long term dynamic effects which work through technological change. Although only one case, the optoelectronics case raises the troublesome question about whether these effects might be generally perverse and reduce or possibly eliminate the gains from trade over the long term.

6.4.1 Future Work

This paper demonstrates the potential of process-based cost modeling methods to show shifts in the relative economic position of emerging technologies due to manufacturing location. As research on these shifts develops, it will be important to assess implications for firm strategy. Important for the optoelectronics industry will be whether firms should be producing low-tech optoelectronic solutions in developing East Asia, pushing forward technology solutions in a developed country environment such as the U.S., or hedging bets by keeping manufacturing in both locations. Although firms pushing for high-tech solutions in the developed world could come out ahead, cost pressures could also put them out of business before technology can come to the rescue. Markets, technologies, and national comparative advantage (in the form of different wages, skills, material costs, etc.), however, all change over time. The relative rates of change of these variables could make the difference between a cost-effective versus a failed investment. For example, if the optoelectronics engineering knowledge in developing East Asia would develop to the point of being able to design and manufacture integrated devices in time to meet the demand for these emerging designs in the computer market, would investment in manufacturing facilities in developing East Asia still be a poor investment decision? Likewise, if optoelectronics production technology would standardize to the point that engineers were no longer required on the line to produce emerging integrated designs, would investment in manufacturing facilities in developing East Asia then not be a poor investment? Future work should include model development to illuminate how investment risks are affected by relative rates of change in markets, technologies, and national comparative advantage.

As shown in this paper, production and investment costs are not the whole story. Future work should continue to follow the story of the optoelectronics industry for insights on the impact of manufacturing offshore on technology advancement, firm competitive advantage, and economic competitiveness in the U.S. The lack of wide-spread product or process standards as well as the existence of primary competitors to the firms studied in this paper in a different country (Japan) under a very different industry and regulatory structure, makes the optoelectronics industry particularly interesting for further study. In terms of technology advancement, with industry standards in the early stages of development, one can imagine short-term cost pressures leading to standards that lock the industry in to a set of inferior technology solutions. In terms of the impact of manufacturing offshore on technology development paths, national competitiveness, and innovation, Japan is an important next case. In contrast to the U.S., Japan has long-term oriented firm structures, legislative incentives to manufacture onshore, and government initiatives aimed at providing critical financial support for optoelectronics R&D. Early discussions with U.S. firms suggest that their Japanese competitors may be significantly ahead in developing critical integrated design technology.

Although in-depth study of a single case provides critical insights not possible in broader studies, additional research will be required to understand the wider implications and applicability of the optoelectronics industry case. Given the lack of prior study on the impact of manufacturing offshore on the product development decisions of firms, future work should in the short term continue to be case-study based. Building on prior research in related areas, future industry cases should be chosen so as to explore the role of capital intensity, design-information intensity (Fujimoto 1998), industry clockspeed (Fine 1998), product incubation time, industry maturity (Vernon 1966), and geographic variance in market demand characteristics in influencing the impact of manufacturing location on the cost-competitiveness of emerging designs, and the technology development decisions of firms.

7 Cross-Case Conclusions

Current theories on technology development and innovation overlook that manufacturing offshore may change firms' paths of technology development. This dissertation asks the following question:

> *Are firms' manufacturing location decisions changing their technology development incentives, and thereby the technology development path of the firm and the industry?*

Given the lack of previous work on this subject, the dissertation analyzes two cases (Glasner 1967, Eisenhardt 1989, Yin 1989). These two cases are fiber-reinforced polymer bodies in automobiles and integrated designs in optoelectronic components. In the stand-alone analysis of each case, two types of methods were used: first, simulation modeling methods were used to understand the impact of manufacturing offshore on the most economic design alternative; second, qualitative social science methods are used to develop a picture of the design and location choices made by firms and to understand the environment in which those decisions occur.[36] This chapter moves beyond the stand-alone analyses of each case to compare both cases.

As will be seen in this chapter, the cross-case analysis reveals five similarities between the two cases. Two similarities emerge from the model analyses: (1) the relative economic positions of the emerging and the prevailing design[37] shift when production is transferred to

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[36] The stand-alone conclusions for the automotive case can be found at the end of Chapter 4. The stand-alone conclusions for the optoelectronics case can be found at the end of Chapter 6.

[37] As discussed in Chapter 1, the term *prevailing technology* refers to a mature technology used in a design (called the *prevailing design*) sold on today's market. The term *emerging technology* refers to an early stage technology, using an alternative design (called the *emerging design*), which provides a substitute for a prevailing design sold on today's market, and has physical properties associated with demand preferences expected in the long-term. (For more detail, see Chapter 1.)

developing East Asia; and (2) while the emerging design is more cost-competitive in the U.S. production structure, the prevailing design is more cost-competitive in the developing East Asia production structure. Three additional similarities arise from the qualitative data: (3) firms initially do not understand the implications of moving offshore for the competitiveness of their designs; (4) firms eventually chose to produce the prevailing design offshore; and (5) although the firms' decisions to produce the prevailing design offshore are rational in a static model, they fail to take into account dynamic diseconomies – specifically, disincentives and disadvantages for innovations critical to long-term markets.

The cross-case analysis also reveals important differences between the two cases. As shown in Chapters 4 and 6, manufacturing offshore does not have the same impact on technology development in the automotive and optoelectronics industries. Manufacturing offshore does not change the path of technology development in the automotive industry, but it does change the path of technology development in the optoelectronics industry. A firm's technology choices influence the feasibility of customizing products to different markets, of having multiple production facilities, of separating manufacturing from the targeted market, and of separating R&D from manufacturing. Depending on the technology alternatives that exist in a particular industry, a firm's location decisions can limit its technology options, and its technology decisions can limit its location options.

7.1 *Manufacturing Offshore Changes the Most Economic Design Alternative*

Following the format of Chapter 1, this chapter revisits each part of the dissertation question separately. The first half of the question posed by this dissertation asks,

> *Are firms' manufacturing location decisions changing their technology development incentives?*

The author makes seven propositions regarding this question (See Table 1.)

The results of both cases supported that *manufacturing offshore changes production variables (Proposition 1a).*[38] In both the automotive and optoelectronics cases, this research found that many of these production variables were, in fact, different offshore than in the U.S. In the case of automobile body production, this research found that 15 variables[39] were different offshore (see Table 11 in Chapter 4). In the case of optoelectronic component production, this research found that six variables[40] were different offshore in all of the firms (see Table 18 in Chapter 6). A seventh variable, yield, was also different offshore in some firms. Many of the firms believed that materials would be able to be sourced cheaper in developing East Asia in the near future. If materials are sourced in developing East Asia, an eighth variable, material price, would also be different offshore.

The results of both cases also supported that *changes in production variables lead to changes in manufacturing cost structure (Proposition 1b).* In both the automotive and the optoelectronics industries the differences in production variables lead to significantly different manufacturing cost structures offshore. This difference in manufacturing cost structure causes the production cost curves offshore to be different than those onshore for each of the technologies. Given their underlying technological differences, the production cost curves of the emerging and the prevailing design are not affected in the same way. As a consequence, *the relative economic positions of the emerging and the prevailing design shift when production is transferred to developing East Asia.*

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[38] See Table 1 in Chapter 1 for a proposed list of "production variables" which would differ if manufacturing were offshore.

[39] These 15 variables are direct wages including benefits, working days per year, number of shifts, paid breaks, capital recovery rate, installation cost, price of building space, building recovery life, average downtime, yield, scrap rate, machine costs, raw material costs, tool costs, and plant utilization.

[40] These six variables are direct wages including benefits, working days per year, number of shifts, paid breaks, capital recovery rate, and average downtime.

The results of this dissertation support that *if manufacturing offshore changes* both *the production variables and the targeted market, then the most economic design alternative will change (Proposition 2b).*

As discussed above, the author based Proposition 2b on the results in (Fuchs 2003). These results are updated and confirmed in the analyses in this dissertation. As shown in Chapter 4, in the automotive case the relative position of the emerging and prevailing designs' cost curves shift only slightly when production is transferred to China. This shift causes the emerging design to be slightly less competitive than the prevailing technology. The relative competitiveness of the prevailing design in China, however, increases significantly once market differences are taken into account.

The results of this dissertation do *not* support that proposition that *if manufacturing offshore changes* only *the production variables (and not also the targeted market), the most economic design alternative will not change (Proposition 2a).*

There is little to no differentiation in market preferences for optoelectronic components globally. Given the *market-technology match* for current optoelectronic component technology, the optoelectronic firms are only able to afford to have one manufacturing facility. Firms produce the same quantity of optoelectronic components for the same market, regardless of manufacturing location. Contrary to expectations, however, the impact of production differences offshore on the relative economic position of the emerging and prevailing component technologies is significant enough to shift the most cost-competitive design. Although the emerging technology is the most cost-competitive in the U.S. production cost structure, the emerging design could not be produced in developing East Asia.[41] Further, the prevailing design

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[41] Although the rest of the results summarized in relation to propositions 2c and 2d are based on the model results, the author learned of the companies' inability to produce the emerging technology offshore during the qualitative interviews.

can be produced cheaper in developing East Asia than the emerging design can be produced in the U.S.

Thus, in both the automotive and the optoelectronics case, the shift in the relative economic positions of the technologies offshore is significant enough to change the most cost-competitive design. In both cases, *while the emerging design is more cost-competitive in the U.S. production structure, the prevailing design is more cost-competitive in the developing East Asia production structure.*

As mentioned earlier, the results for propositions 2e and 3 derive from the qualitative data. The results of this dissertation do not support that *if manufacturing offshore changes a firm's most economic design alternative, it will also change the firm's technology development incentives (Proposition 2e).*

For proposition 2e to be true, firms must understand what is the most economic design alternative and must make technology development decisions based on this understanding. This is not a straightforward proposition. A large body of literature has explored firm decision-making processes and their departure from classic economic rationality (Simon 1959, Cyert 1963,1992, Sterman 1989, Eisenhardt 1992). It is unclear to what extent firms understand their internal cost structures. Nor do firms necessarily understand the impact of those structures on the competitiveness of their designs. Given internal organizational barriers, institutional barriers, and knowledge flow constraints, firms may particularly not understand the impact of manufacturing offshore on the competitiveness of their designs. Second, there is a large amount of uncertainty regarding what will be the most fruitful direction for technology development. The most economic design alternative today may not be the most economic design alternative in the long-term. Production environments and market preferences change over time. Network externalities can cause a dominant design to emerge that may not necessarily consist of the best performing technology (Cusumano 1992, Utterback 1994). New technologies can emerge that out-compete the existing options (Christensen 1997). Firm understanding of cost structure and design competitiveness is discussed below. The role of uncertainty in firm product development decisions is discussed later in this chapter.

The results from this dissertation suggest that, at least in the two cases studied, firms do not have a good idea of the impact of manufacturing offshore on the competitiveness of their design alternatives. In the automotive case, firms lacked an understanding both of the impact of manufacturing offshore on the cost-competitiveness of their design and of the Chinese market. At the beginning of the optoelectronics case, the firms did not know the unit cost of producing the emerging technology, and in particular, if the emerging technology would be cheaper than the prevailing technology (assuming both were manufactured onshore). Although there were proponents within the firms of moving manufacturing offshore, it is doubtful that these proponents knew that the prevailing design manufactured offshore would be cheaper than the emerging technology manufactured onshore. The firms definitely did not know that they would be unable to manufacture their more technologically advanced designs offshore.

In both the automotive and the optoelectronics cases, the firms clearly learn (Levitt 1988) through their offshore experiences. It is difficult, however, to know whether the firms learn the "right" lessons. In the automotive case, both DaimlerChrysler and General Motors attempt to bring a fiber-reinforced polymer vehicle body to the Chinese market. In both cases, when their prototype is poorly received by the Chinese consumers, the firms pull out. General Motors brings over, instead, a production facility to build steel-bodied vehicles. DaimlerChrysler, with the exception of Beijing Jeep (which already existed), is only re-entering the Chinese market now. In the optoelectronics case, two firms attempt to transfer more advanced products to developing East Asia, only to find that they can not achieve sufficient production yields offshore. Both of these firms bring manufacturing of the more advanced products back to the U.S. – one at the expense of having to re-open a recently closed manufacturing facility in California.

This section on technology development incentives discusses the results from this dissertation's two cases with respect to Propositions 1-2e, as presented in Chapter 1. In both cases, as shown in the simulation model, manufacturing offshore changes the most economic design alternative. The qualitative results suggest, however, that *firms, at least initially, do not understand the implications of moving offshore for the competitiveness of their designs.* Firms do appear to learn over the course of the study. It is difficult to know, however, if they are learning the "right" lessons. Additional qualitative research will be required to understand the relationship between the relative economic position as represented in the simulation models and the perceived technology development incentives within firms.

7.2 *Manufacturing Offshore Only Sometimes Changes the Path of Technology Development*

As suggested in Chapter 1, the second half of the question posed in this dissertation is equally important:

> Are firms' manufacturing location decisions changing their technology development incentives, *and thereby the technology development path of the firm and the industry?*

The results of this dissertation do not suggest that manufacturing offshore changes the path of technology development in the automotive industry, but do suggest that manufacturing offshore changes the path of technology development in the optoelectronics industry. These results are discussed in detail below.

As discussed in the previous section, the results of this dissertation do not support the proposition that *if manufacturing offshore changes a firm's most economic design alternative, it will also change the firm's technology development incentives (Proposition 2e).*

The results of this dissertation may, however, support the proposition that *if manufacturing offshore changes a firm's technology development incentives it will also change the firm's path of technology development (Proposition 3).*

In the automotive case, manufacturing offshore influenced firm design decisions, but in the end did *not* change the automotive firms' paths of technology development. The automotive firms initially expected the emerging design to be more competitive offshore (both from the standpoint of production costs and the preferences of the targeted market). These initial expectations turned out not to be true. First, as shown in the simulation model, the emerging design was less competitive offshore. It is doubtful DaimlerChrysler was aware of this model result, and unclear if General Motors was aware of this result. Both firms, however, found through prototype introductions that they had misjudged Chinese consumer preferences. Driven by market preferences, both firms pulled their fiber reinforced composite bodied vehicles out of China, and reverted to producing the prevailing design.

According to the simulation model, manufacturing offshore does change the automotive firms' most economic design alternative. Many aspects of this result from the simulation model, however, are unclear. Firms are not producing in the U.S. the design suggested to be most economic according to the simulation model. Thus, it is unclear what other aspects not included in the model (such as embedded capital and knowledge investments in steel) are determining the automotive firms' technology choices in the U.S. If the same factors which cause the firms to choose the prevailing design in the U.S. also exist in China, these firms' technology development incentives do not change. According to this analysis the automobile industry case does not support Proposition 2e but does support Proposition 3.

In the optoelectronics case, manufacturing offshore *does* appear to be changing the firms' paths of technology development. The market-technology match in the optoelectronics industry is such that firms are currently only able to support one manufacturing facility. With the burst of the telecom bubble, firms are faced with two options for reducing manufacturing costs. Firms can attempt to reduce manufacturing costs (1) by continuing to develop the emerging technology, or (2) by moving manufacturing offshore. Twenty-two of the 23 firms studied chose to move manufacturing offshore. Whereas many of those firms were previously pursuing being able to manufacture the emerging design in the U.S., all 23 of those firms chose to produce the prevailing design offshore. The one firm which stayed in the United States chose to produce the emerging technology. It is unclear if that firm will survive. Preliminary findings show that the firm that has been offshore the longest is the farthest behind in bringing the latest technology to market. Additional data collection will be required to discern if research efforts are declining in the other firms that have moved offshore.

Upon first glance, the optoelectronics case seems to support both Propositions 2e and 3. A closer look, however, again brings into question the validity of Proposition 2e. Managers in the optoelectronics industry may not have been aware that the prevailing design would be cheaper than the emerging technology offshore. Many managers in the optoelectronics firms were surprised when they found out that they couldn't produce designs with more high-end technology offshore. For a matter of fact, none of the managers seemed to consider that manufacturing offshore would change the competitiveness of their technology. More research will be required to understand the relationship between the most economic design decision, as represented in the model, and technology development incentives perceived by firms.

This section discusses the results from the automotive and optoelectronics cases in relation to the second half of this dissertation's question – specifically, are firm's manufacturing location decisions changing their technology development incentives, *and thereby the technology development path of the firm and the industry*. This section suggests that although manufacturing offshore changed the most economic design alternative according to the simulation model, it did not change the firms' technology development incentives. In addition, although manufacturing offshore initially impacted the automotive firms' technology development decisions, it did *not* in the end change their technology development path. In contrast, manufacturing offshore does appear to have changed the technology development path of the optoelectronic firms. Although firms' actions are in accordance with the results of the simulation model, the qualitative interviews suggest it is unlikely the approach used in the simulation model analysis is representative of the decision framework within the individual firms. Additional research will be required to understand the relationship between the most economic design alternative as represented in the simulation model, the technology development incentives perceived by firms, and the decision-making structures which determine firms' paths of technology development.

7.3 *Innovation Myopia*

In both the automotive and the optoelectronics cases, firms eventually choose to produce the prevailing design offshore. *Although the firms' decisions to produce the prevailing design offshore are rational in a static model, they may fail to take into account dynamic diseconomies – specifically, disincentives and disadvantages for innovations critical to long-term markets.*

The automotive industry currently faces two major trends – (1) increasing concerns over fuel consumption (for reasons of national security, resource scarcity and the environment), and (2) a radically expanding Chinese (and perhaps Indian) market in conjunction with minimal to no growth in developed world markets. Vehicle light weighting provides a fast, high-impact solution to both fuel consumption and emissions concerns in vehicles. Both DaimlerChrysler and General Motors experimented with developing a fiber-reinforced polymer bodied vehicle for local manufacture and sale in China. In both cases, the firms pulled out. General Motors replaced their fiber-reinforced polymer body component facility with a facility aimed at producing steel components. DaimlerChrysler is only considering re-entering the Chinese market now. The limited existence of oil resources, however, is becoming a market issue in the U.S. through the Iraq war and is expected to become more of an issue in the next 5-25 years. Meanwhile, the embedded capital infrastructure continues to create barriers to investing in new technologies. As such, Daimler Chrysler and General Motor's original hunch to experiment with fiber-reinforced polymer vehicles may have been a good idea.

In the case of the optoelectronics industry, the cutting edge of innovation in optoelectronic component integration is currently aimed at products for the telecom market. This same direction of innovation, however, has long-term implications for a second, much bigger market – specifically, computers. The simulation results show that although the emerging integrated design is cheaper than the prevailing design when both are manufactured in the U.S., the emerging design produced in the U.S. is not able to cost-compete with the prevailing design manufactured in developing East Asia. Almost all of the firms studied in this dissertation choose to relocate manufacturing offshore and continue to produce the prevailing technology. Although in the short-term these firms are reducing production costs, they are also reducing cost incentives for research agendas in the U.S. focused on integration. The advance of integrated designs in the optoelectronics industry may be critical to continuing Moore's Law and driving the information economy. According to Intel's roadmap, to continue Moore's Law, computer optical buses integrating seven components will be required within 10 years. Given this looming demand for integration, the optoelectronics firms may have been better off staying in the U.S. and pushing forward the emerging (integrated) technology.

Time will be required to see how dynamics in the automotive and optoelectronics industries play out for the firms studied in this dissertation. Many papers support the idea that the firms studied in this dissertation would have been better off pursuing the emerging technology. A body of literature argues for "first mover advantage" – the idea that a firm can gain competitive advantage through technological leadership, preemption of assets and buyer switching costs (Lieberman and Montgomery). Christiansen, Suarez and Utterback suggest that there exists a "window of opportunity" just before the establishment of a dominant design during which firms with architectural innovations have the greatest change of survival (Christiansen, Suarez, Utterback). There exists, however, a large amount of uncertainty in technology development. Disadvantages for firms taking a first-mover strategy include free-rider effects, lack of resolution of technological or market uncertainty, and shifts in technological or customer needs (Lieberman and Montgomery). Cusumano shows that even given the existence of a superior product, network effects can lead to market dominance by a less suitable alternative (Cusumano 1992). Without knowing the future, it is difficult to know if the firms studied in this dissertation have made a fatal error by not choosing to produce the emerging technology.

Although much uncertainty exists in choosing winning technologies, the results of this dissertation suggest that simulation modeling methods may help firms better inform their technology investment decisions. Particularly important for firms may be to consider relative rates of change in market, technology, and national comparative advantage into their manufacturing location and product development decisions. Markets, technologies, and national comparative advantage (in the form of different wages, skills, material costs, etc.) all change over time. The relative rates of change of these variables will alter whether an offshore investment is successful, not to mention cost-effective. For example, Daimler Chrysler and General Motors both attempted to manufacture and sell a low-cost vehicle with a fiber-reinforced polymer composite body design in China. After putting significant funds and multiple years into developing their product, however, both companies' prototypes were rejected in tests with Chinese consumers. Did Daimler Chrysler's and General Motors' market analysts misconstrue the demand preferences of the Chinese market in their initial assessments, or did they originally interpret the Chinese demand preferences correctly but fail to recognize the speed at which Chinese demographics were changing? In the optoelectronics industry case studied in my dissertation, offshore manufacturing created both disincentives and disadvantages for new integrated device innovations critical to long-term market success. Two factors currently make it difficult to produce advanced optoelectronics designs offshore – a lack of optoelectronics simulation knowledge in developing East Asia and the lack of standardized production processes. Investing in manufacturing facilities in developing East Asia may only be a poor decision if neither of these factors can improve quickly enough for firms to meet market demand for emerging integrated designs with the offshore manufacturing facilities.

8 Theory-Building: Towards a Generalizable Framework

The previous chapter related the results from this dissertation's two cases the original propositions of this dissertation. This chapter builds on these results from the two cases studied in this dissertation to propose a general framework from which to approach future work. This framework focuses on how the impact of manufacturing offshore on technology trajectories varies by firm and industry, and subsequently how firms should be incorporating manufacturing location into their technology development decisions.

Chapter 1 proposes that three variables – market differentiation, market-technology match, and product transportability – moderate the influence of manufacturing offshore on the targeted market. These variables represent three corresponding phenomena – the demand for product differentiation, the feasibility of product differentiation, and the feasibility of separating manufacturing from the target market. The results from the optoelectronics case suggest that another phenomenon is particularly important – specifically, the feasibility of separating R&D from manufacturing.

Multiple factors can affect this feasibility. As discussed in Chapter 1, a long history of work has explored the role of geography in constraining knowledge flows (Polanyi 1958, Arrow 1969, Rosenberg 1976, Teece 1977, Manfield 1982, VonHippel 1994). Mansfield and Teece find wide variation in the costs of transferring knowledge over distance (Teece 1977, Manfield 1982). VonHippel suggests that some information – specifically, "sticky information" – is more difficult to transfer over distance than other information (VonHippel 1994). Allen emphasizes the important role physical proximity plays in enabling knowledge flows (Allen 1984). Arguments by Vernon and Cohen suggest that, regardless of the underlying reason, critical information will be lost if manufacturing is separated from R&D (Vernon 1966, Cohen 1987).

Several authors have suggested that design and process modularity may enable the separation of manufacturing from R&D (Sturgeon 2002, Fuller 2005). Others have pointed out that the partitioning which occurs in modular designs may hinder capabilities within R&D for radical (or architecture-changing) innovation (Henderson 1990, Chesbrough 2001, Chesbrough 2003).

In the optoelectronics case studied in this dissertation, two factors prevent firms from being able to manufacture high-end products offshore: the difficulty of transferring tacit backend assembly skills, and a lack of local highly-skilled design engineers offshore. The first factor brings out the challenge of transferring the tacit knowledge of line workers in one location to line workers in another. The second factor brings out the need for engineers to creatively interact with production activities in real-time to improve product and process design. This real-time learning is particularly important when, as is the case in optoelectronics, design is tightly linked to process, and the process is non-standardized. Early indications suggest that research and development efforts may be declining and innovation slowing down in the optoelectronic firms that have chosen to manufacture the prevailing technology offshore. Based on this study, it is difficult to tell if this decline in research and development efforts is because the prevailing design can be produced cheaper offshore than the emerging one, or because engineers find it difficult to innovate without local manufacturing facilities.

Table 20 below presents the four previously described phenomena which determine the proximity of manufacturing to R&D and the targeted market. Each of these phenomena is inevitably influenced by multiple variables. The initial set of influencing variables shown in Table 20 is by no means meant to be complete. Additional research will be required to create more complex mathematical functions that represent the relationship between the phenomena and their influencing variables. As proposed in Table 3 in Chapter 1, the author continues to assume below that market differentiation, market-technology match, and product transportability will affect the influence of manufacturing offshore on the targeted market. In addition, the author proposes that product standardization, process standardization, and product modularity contribute to the feasibility of separating manufacturing from R&D.

Table 20: Determinants of Organizational Footprint

Phenomenon	Influencing Variable(s)	Variable Definition
Demand for product differentiation	Market Differentiation	Global extent of variance in market preferences.
Feasibility of product differentiation	Market-Technology Match	(Global Market Size) / (Economies of Scale) The number of production facilities efficiently sustained by the global market.
Feasibility of separating manufacturing from target market	Product Transportability	Ease of transporting the final product (as a function of size, weight, shelf life, etc.)
Feasibility of separating manufacturing from R&D	Product Standardization Process Standardization Modularity	Extent to which design parameters are already set prior to product development Extent to which processing procedures can be codified Extent to which complex products are made up of smaller subsystems that can be designed independently yet function together as a whole (Baldwin 2000)

Building on Table 20, different scenarios can be imagined based on a firms' positioning relative to the four phenomena. In Table 21 which follows, the influencing variables are used as a proxy for the phenomenon they influence. In the case of the feasibility of separating manufacturing from research and development, process standardization is used as the proxy variable. Table 21 represents a revised proposition for the impact of manufacturing offshore on the most economic design alternative.

Table 21: Impact of Manufacturing Offshore on the Most Economic Design Alternative

Scenario	Market Differentiation	Market-Technology Match	Transportability	Process Standardization	Outcome
1	Low	Low	Low	Low	(?) Economically infeasible
2	Low	Low	High	Low	Global commodity produced in home country for the global market
3	Low	Low	Low	High	(?) Economically infeasible
4	Low	Low	High	High	Global commodity produced offshore for the global market
5	Low	High	Low	Low	(?) Global commodity produced locally where local R&D exists
6	Low	High	High	Low	(?) Global commodity produced for the global market where R&D exists
7	Low	High	Low	High	(?) Global commodity produced locally for local market using global R&D
8	Low	High	High	High	Global commodity produced offshore for global market using global R&D
9	High	Low	Low	Low	(?) Economically infeasible
10	High	Low	High	Low	(?) Regionally customized product produced in home country for global market, extensive platforming
11	High	Low	Low	High	(?) Economically infeasible
12	High	Low	High	High	(?) Regionally customized products produced offshore for global market with extensive platforming
13	High	High	Low	Low	Regionally customized product produced in the home country for the home market
14	High	High	High	Low	Regionally customized product produced in the home country for the global market
15	High	High	Low	High	Regionally customized product produced locally for the local market using global R&D
16	High	High	High	High	Regionally customized products produced locally, (generally) for the local market using global R&D

While some of the variable combinations in Table 21 seem to suggest clear outcomes, it is unclear what the outcomes would be for other variable combinations, or if, in the real world, these variable combinations would survive in the market. Scenarios with less clear outcomes are marked in Table 21 above with a question mark. More research will be required to understand the outcomes for the scenarios proposed in Table 21 and which variable combinations can survive the market.

Notably, of the variables described in Table 20, *market-technology match*, *product transportability*, and *process standardization* are all influenced by technology choice. For example, in the automotive case, the emerging technology has a higher market-technology match than the prevailing technology. In the optoelectronics case, the emerging technology has lower process standardization than the prevailing technology. Table 22 shows how the cases in this dissertation fit into the scenarios described in Table 21. Using the scenario numbers from the table, scenario (15) is representative of both the emerging and the prevailing technologies studied in the automotive industry case. The optoelectronics industry case, however, shows that a firm can use technology choice to change its location options, or, in other words, the geographic footprint of the organization. Specifically, the optoelectronics firms were initially positioned to be in scenario number (2) from Table 21. By reverting, however, to the prevailing technology, the firms were able to switch themselves into scenario (4). (See Table 22.) The results from this dissertation, thus, suggest that firms are able to use technology to choose the scenario they are facing. For firms to effectively manage technology in today's global environment, it may be critical for them to recognize this impact of their technology decisions on the geographic footprint of their organization.

Table 22: Using Technology to Change the Geographic Footprint of the Organization

Dissertation Case	Scenario	Market Differentiation	Market-Technology Match	Process Standardization
Automotive	(15)	High	High	High
Optoelectronic	(2) → (4)	Low	Low	Low → High

Technology choice does not only have implications for a firm's footprint. The influencing variables described in Table 21, determine the extent to which a firm's manufacturing, market, and R&D location decisions are constrained. Although market-technology match, product transportability, and process standardization can be influenced by technology choice, a technology may not exist which provides the desired footprint scenario and matches market preferences. Often, the existing technology alternatives in a particular industry may not change the firm's rating on a particular influencing variable. For example, in the automotive industry case both the emerging and prevailing technology had high market-technology match. In the optoelectronics industry, both the emerging and the prevailing technology had low market-technology match. The extent to which existing technology alternatives shift the value of a firm's technology-determined influencing variables should tell a lot about the impact manufacturing offshore will have on a firms' path of technology development. A firm's rating for each technology-determined influencing variable changes the extent to which a firm's footprint options are constrained. For all four variables the "low" end of the range represents the situation in which the firms' options are most constrained. The "high" end of the range represents the situation in which firms' options are least constrained. The implications of the limits of each variable's range for a firm's footprint are shown below in Table 23.

Table 23: Implications of the Limits of Each Influencing Variable's Range for a Firm's Footprint

Influencing Variable	**Low** ⟵	⟶ **High**
Market-Technology Match	Market only able to support one production facility	Market able to support infinite production facilities
Product Transportability	Manufacturing must be close to market	Manufacturing can be significantly separated from the market
Process Standardization	Manufacturing requires extensive knowledge-workers (line workers *and* engineers)	Manufacturing does not require knowledge-workers on the line or in close proximity

What are the implications of Table 23 for the impact of manufacturing offshore on technology development? Imagine a firm in the most constrained scenario – with low market-technology match, low product transportability, and low process standardization. Imagine for the moment that all demand globally is concentrated in the home country. According to Table 22, a firm facing this scenario would be forced to manufacture at home for the home market. Next release one of the constraints, and move product transportability from low to high. Releasing this constraint creates low market-technology match, high product transportability, and low process standardization – the scenario faced by the optoelectronics firms at the start of the study. According to the proposition in Table 22, firms facing this scenario would manufacture at home for the global market. This dissertation suggests that the three influencing variables discussed above are technology determined. As such, a firm can create the option to move offshore by changing its technology so as to increase process standardization. Presuming, as was true in the optoelectronics case, that the market-technology match is low for all technology alternatives facing the firm, the firm is unable to continue to manufacture the other technology after moving offshore. Thus, in scenarios with low market-technology match and either low product transportability or low process standardization, a firm is likely to have to change its path of technology development in order to move manufacturing offshore. If the market-technology match and the other two technology-determined influencing variables are all high, a firm is presented with a very different set of options. Specifically, rather than having only one manufacturing facility and being forced to chose between technology alternatives depending on the chosen manufacturing location, a firm in the least constrained scenario has the option to have multiple manufacturing facilities in multiple locations. A firm in this situation could benefit significantly by diversifying its global product development portfolio so as to leverage different market and production characteristics in different locations.

It is helpful to use the influencing variables to illustrate the points made in the previous paragraph – a.k.a. the role technology can play in influencing organizational footprint. It is important, however, to return to the fact that the influencing variables may not fully capture the phenomenon in Table 20. Given this fact, even if, for example, process standardization is high, other factors could cause the feasibility of separating manufacturing from R&D to be low. Although the variable-based scenarios presented in Table 21 provide some initial insights, the most constrained scenario is actually the scenario where there is low feasibility of product differentiation, low feasibility of separating manufacturing from market, and low feasibility of separating manufacturing from R&D. The least constrained scenario is the scenario where there is high feasibility of product differentiation, high feasibility of separating manufacturing from market, and high feasibility of separating manufacturing from R&D. More research will be necessary to fully understand the factors leading to low versus high ratings for each of these phenomenon. The implications of the most constrained versus least constrained scenarios for technology development are proposed in Figure 46 and Figure 47 below.

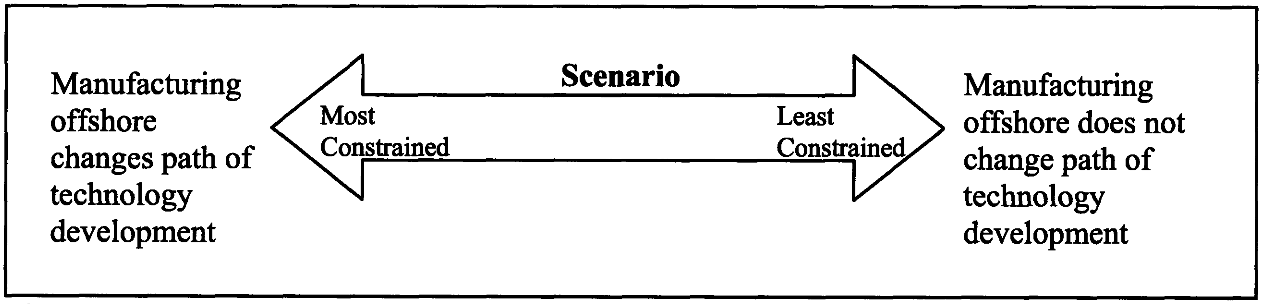

Figure 46: Impact of Manufacturing Offshore on the Path of Technology Development: The Role of Technology Constraints

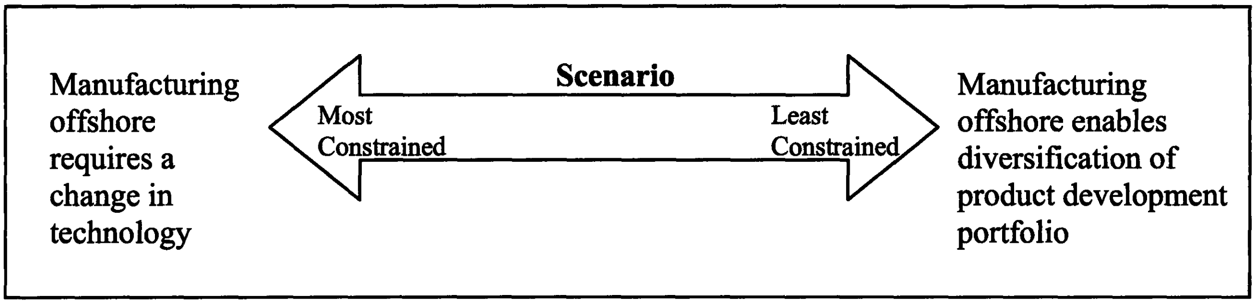

Figure 47: The Implications of Manufacturing Offshore for Firms Strategy: Incorporating Technology Constraints

This chapter compares the results from the two cases in this dissertation to gain new insights on the impact of manufacturing offshore on the technology development path of the firm and the industry. In both cases, the simulation modeling shows that manufacturing offshore changes the most economic design alternative. The relationship between the most economic design alternative, as represented in the simulation model, and the technology development incentives perceived by the firms is less clear. In the automotive case, although manufacturing offshore changes the most economic design alternative, it does not change the path of technology development. In the optoelectronics case, manufacturing offshore does change the path of technology development. In both cases, the firms choose to produce the prevailing design offshore. These results are compared below in Table 7-6 to the original propositions from Chapter 1.

Table 24: Summary of Cross-Case Implications for Chapter 1 Propositions

	Proposition	Case Supports?
P1a	Manufacturing offshore changes production variables.	Yes
P1b	These changes in production variables lead to changes in manufacturing cost structure.	Yes
P2a	Manufacturing offshore does not always change the targeted market.	(Yes)*
P2b	The impact of manufacturing offshore on the targeted market is influenced by market differentiation, market-technology match, and product transportability.	(Yes)
P2c	If manufacturing offshore changes only the production variables, the most economic design alternative will not change.	No
P2d	If manufacturing offshore changes both the production variables and the targeted market, then the most economic design alternative will change.	Yes
P2e	If manufacturing offshore changes a firm's most economic design alternative, it will also change the firm's technology development incentives.	(No)
P3	If manufacturing offshore changes a firm's technology development incentives, it will also change the firm's path of technology development.	(Yes)

* The implications of the cases studied in this dissertation for propositions 2a, 2b, 2e, and 3 are unclear. Early indications are suggested in Table 24 within parentheses.

Building on these results, this chapter proposes a new framework by which to understand the impact of manufacturing offshore on technology development incentives and thereby the technology development path of the firm and the industry. Drawing from the optoelectronics case, the author proposes a fourth phenomenon critical in influencing the global footprint of a firm – specifically, the feasibility of separating manufacturing from R&D. Representing each of the four phenomenon with a proxy "influencing variable," the author then demonstrates how a firm's global footprint options can be influenced by technology choice. The chapter ends by pointing out that the existing technology alternatives in a given industry in turn create limits for a firm in its footprint choices. As shown in this dissertation, depending on how a firm's technology options position it in relation to the four phenomena critical to a firm's global footprint, manufacturing offshore can hold back technology development or create new opportunities for a firm to expand its global product development portfolio.

9 Future Work

As discussed in Chapter 1 of this dissertation, current theories on technology innovation management fail to incorporate geography – in the form of institutions, resources, and regulations – as a critical parameter in design, product development, and innovation. This dissertation studies the impact of manufacturing offshore on the technology development path of the firm and the industry. Several areas for future research are discussed below.

9.1 The Impact of Manufacturing Offshore on Technology Development Incentives

As discussed in Chapter 7, it is unlikely that the simulation model's results for the most economic design alternative are representative of the technology development incentives perceived by the firms. It is unclear to what extent firms understand their internal cost structures. Nor do firms necessarily understand the impact of those structures on the competitiveness of their designs. Further, even if firms would be fully aware of the results of the model, they may involve factors not represented in the model into their decision frameworks and may or may not follow classical rational economic behavior. Additional research will be necessary to clarify the relationship between the most economic design alternative, as shown in the simulation model, technology development incentives as perceived by the firms, and the actual decisions firms make. Particularly important for this work may be to focus on the mental models and decision-making frameworks with which the firms are currently approaching both manufacturing location and technology development decisions.

9.2 The Impact of Manufacturing Offshore on Technology Development Path: Cross-Case Framework

As discussed in Chapter 7, manufacturing offshore does not change the path of technology development in the automotive industry, but does change the path of technology development in the optoelectronics industry. Drawing on the results from both cases, Chapter 7 develops a preliminary framework by which to understand the impact manufacturing offshore will have on the technology development path of a firm and an industry. This framework gives technology an active role in determining the global footprint constraints faced by a firm. Specifically, a firm's technological choices influence the feasibility of customizing products to different markets, the feasibility of have multiple production facilities, the feasibility of separating manufacturing from the targeted market, and the feasibility of separating R&D from manufacturing. Depending on the technology alternatives that exist in a particular industry, a firm's footprint decisions can limit it's technology options, and it's technology decisions can in turn limit it's footprint options. Additional research will be necessary to determine the relevance of the phenomenon and influencing variables developed in Chapter 7. Although future work should explore all of the proposed scenarios, it will be particularly useful in the short term to study additional examples representing the most and least constrained scenarios. In studying additional cases of the most and least constrained scenarios, this future work should seek to further confirm (or disconfirm) the propositions in Table 7-3 as well as to explore the existence and importance of other influencing variables. Additional research will also be required to understand the implications of the interaction between technology choice and organizational footprint for firm strategy. Particularly important will be understanding how firms should be changing their current decision frameworks.

9.2.1 Automotive Case: Global Product Development Portfolios

The conclusions in Chapter 7 suggest that firms facing the least-constrained scenarios (high feasibility of product differentiation, high feasibility of separating manufacturing from the targeted market, and high feasibility of separating R&D from manufacturing) will not necessarily change their technology development paths by moving manufacturing offshore. Instead, firms facing such scenarios have the possibility of leveraging different regions' production environments and market characteristics to broaden their global product development portfolios. These firms will need to balance the trade-offs between customizing designs to regional manufacturing economics and having higher product development costs due to an increased number of designs. Future work should build on Johnson's analysis of the product development costs for not-yet-existing designs (Johnson 2004). Future work should also recent work on platforming strategy (MacDuffie 1996, Krishnan 2001, de Weck 2005, Suh 2005). Finally, the relevancy of recent work on portfolio management for new products (Cooper 2001) should also be explored.

9.2.2 Optoelectronics Case: Technology Development Path

The qualitative interviews for the optoelectronics case studied in this dissertation find that the firm that has been offshore the longest (for historical reasons) is the farthest behind in bringing the latest technology to market. Additional interviews suggest that other optoelectronics firms may also be hollowing out their R&D since moving offshore. Future work should test the theory built in this dissertation that manufacturing offshore is changing the technology development path of optoelectronics firms. In testing this theory, future work should gather data on how the quantity and subject-area of research and development funds, the quantity and subject-area of patents, and the quantity and subject-area of publications have or have not changed over the past ten years. This same research should gather data on when firms moved which products offshore, and the extent of manufacturing offshore at different points over the same time period. These two streams of data should be compared to explore the impact of manufacturing offshore on technology development in the optoelectronic firms. It will be important to distinguish between changes in total R&D expenditures and changes in the percentage of R&D funds allocated to different subject areas. It will also be important to discriminate between impacts on R&D caused by the internet bubble and seen in all firms, versus those impacts seen only in firms which have moved offshore.

9.2.3 Decision Tool Development: Incorporating Relative Rates of Change in Technology, Market, and National Comparative Advantage into Global Product Development Portfolios

Markets, technologies, and national comparative advantage (in the form of different wages, skills, material costs, etc.) all change over time. As discussed in Chapter 7, the relative rates of change of these variables will alter whether an offshore investment is successful, not to mention cost-effective. Future work should include model development to illuminate how global product development portfolios should take into consideration relative rates of change in markets, technologies, and national comparative advantage. Initial work should leverage the existing proceed-based cost models from the automotive and optoelectronics cases. Many of the variables of interest already exist in these models. Among other variables, yield and downtimes are key variables influenced by changes in process standardization, and wage and material prices are key variables most likely influenced by changes in national comparative advantage. After exploring the impact of relative rates of change in the existing, trusted models, a major contribution would be for this research to develop a simpler, more elegant approach. For the automotive case, and other cases where firms have the ability to have multiple plant locations, this work should build on the global product development portfolio research discussed above. This research should also explore the relevancy of previous work on applying options thinking to R&D valuation (Faulkner 1996).

9.2.4 Decision-Tool Development: Optimizing the Timing of the Manufacturing Location Decision in the Product Development Process

Traditional economic and business models expect firms to move manufacturing offshore as their technology matures (Vernon 1966). In today's economy, firms face the question of whether of not to manufacture offshore at the inception of a new product. This need to make manufacturing location decisions at the same time as product development decisions raises many questions on how decision-making in these two areas should be interlinked. Previous work on optimizing the product development process has explored the benefits of "stage gate" versus "spiral" product development processes for different product and industry types (McConnel 1996, Ulrich 2000). Stage gate and spiral processes aim to minimize product development time and cost by balancing the tension between design flexibility and design rigidity at different stages of the development process (Unger 2003). Like other decisions in the product development process, choosing the manufacturing location can limit flexibility in design. Future work should explore where the manufacturing location decision should occur in the product development process to minimize time and costs. This work should include how the timing of the manufacturing location decision will change with industry clockspeed (Fine 1998), capital intensity, knowledge intensity, and coupling of product and process development (Pisano 1997).

9.3 Generalizability of Findings: Manufacturing Offshore Changes the Most Economic Design Alternative

In both the automotive and the optoelectronics cases in this dissertation, production characteristics offshore shift the relative competitiveness of alternative designs. Additional research will be required to understand whether production offshore generally changes which design alternative is most cost-competitive. Given a lack of prior research in this area, short-term future work on how manufacturing location should be incorporated into design decisions should continue to be case-study based. An interesting next case would be one where product development, rather than manufacturing, dominates costs and decision-making; for example, pharmaceuticals. Despite the dominance of product development in the pharmaceutical industry, work by Gary Pisano suggests that processing decisions are critical to competitiveness (Pisano 1997). With the recent economic slowdown, U.S. pharmaceutical companies are increasingly exploring lowering costs and avoiding regulation by manufacturing their products offshore (Katsnelson 2005, PRNewswire 2006). If offshore manufacturing is a success, will it change the most competitive designs in pharmaceuticals, and thereby the direction of this industry? By lowering manufacturing costs offshore, are pharmaceutical firms postponing product development and failing to push forward critical alternative designs?

9.4 Generalizability of Findings: Manufacturing Offshore Reinforces the Viability of the Prevailing Design

Technological change has come to be generally accepted in economics to contribute as strongly to economic growth as traditional factors of production (Solow 1988).[42] In both cases in this dissertation, the economics associated with offshore manufacturing reinforce the stronghold of the prevailing design. The cases studied in this dissertation represent two of the most common reasons for firms moving manufacturing offshore – market access and cost reduction. In the automotive case, firms moved offshore for market access, and market preferences reinforced the prevailing design. In the optoelectronics case firms moved offshore to reduce cost, and the reduced-cost production environment reinforced the viability of the prevailing design. Future work should explore whether the effects of offshore manufacturing on innovation are generally perverse. Cases may exist where offshore manufacturing instead spurs the development of new technologies. For example, why in cell phones does the Chinese market seem to be leading

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[42] Economists from Mill and Marx to Schumpeter and Solow argue for the critical contribution of technology to growth in the economy. In 1988, Robert Solow won the Nobel Prize for his famous "Solow residual" which ascribed the part of output growth that cannot be attributed to the accumulation of any input to technological progress. Solow, R. M. (1988). "Growth Theory and After." American Economic Review **78**(3): 307-317.1988.

global preferences? Alternatively, are firms with standardized processes (such as electronics) able to continue the same rate of innovation whether manufacturing is offshore or onshore?

9.5 Innovation Myopia?

Time may be the best indicator of whether firms current decisions are myopic. Inevitably, it will remain impossible to know what the outcome for technology innovation may have been if firms had made other decisions. As discussed earlier in this chapter, some insights into how firms should be approaching these decisions may be found in the literature on decision-making under uncertainty, in the literature on portfolio development in R&D, and by exploring tools for incorporating relative rates of change in technology, markets, and national comparative advantage into decision-making. Additional insights may also come, however, by examining the implications of existing organizational and institutional structures. Some research has suggested that networked small and medium sized enterprises can react more quickly to changing business environments, and are on the whole more innovative than their larger, slower-moving counterparts (Piore 1984, Pavitt 1987, Powell 1990, Acs 1991, Feigenbaum 1991, Rothwell 1994). Recent work has encouraged strategies whereby large firms outsource their innovation needs to these smaller firms through technology alliances or acquisitions (Cohen 1990, Lamb 1997, Chesbrough 2003). My dissertation work in the optoelectronics industry suggests that the low-resource, short-horizon perspective of small and medium sized firms may have distinct disadvantages. Specifically, in focusing on strategic plans practical for their individual firms, such firms choose to forego technology development critical to long-term markets. Firms such as Intel, whose open innovation strategies have left them dependent on these small firms' innovations, may under these conditions find themselves without sources for key innovations. In contrast to the U.S., institutions in Japan have led to vertically integrated firms with longer term foci, and government initiatives to support internal research and development for critical long-term markets. Initial interviews suggest that the optoelectronics firms in Japan such as NEC and NTT may be ahead of U.S. firms, including Intel, in critical emerging technologies necessary to continue Moore's Law in the computer. In a global market-place where offshore cost reductions allow companies to postpone technology-based cost initiatives, is the Japanese model of vertically integrated firms with longer term strategy horizons the preferable model?

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