Beating the System: Accelerating Commercialization of New Materials

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 Technology, Management, and Policy
at the
Massachusetts Institute of Technology
February 2005

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Abstract

Over the past century, materials have faced notoriously long delays between invention and commercialization. These delays make private investment very difficult, and can prevent good materials from reaching markets. A systematic exploration of the commercial histories of major commodity thermoplastics was performed, which showed that these delays were attributable to technical deficiencies in materials and obstacles in the application value chains. Contrary to popular wisdom, material costs, competitive materials, and serendipity were much smaller factors in commercialization delay. The factors that led to insertion of plastics into applications were different from the factors that led to post-insertion growth.

The major plastics showed a characteristic pattern of commercialization. First, they entered simple, small applications in which they solved new problems. They then progressed to achieve insertion in a single major application, which they continue to dominate today. Having established themselves with this application, they found insertion in a wide range of large applications.

The commercialization pattern can be explained in large part by the concept of switching costs. As knowledge of a material increases, switching costs are reduced; as value chain complexity increases, switching costs increase. The earliest applications required little understanding of plastics and had simple value chains, so switching costs were low, corresponding to fast commercialization. Later applications had more complex value chains and required much more detailed understanding of the failure modes and processing parameters of the material, corresponding to high switching costs and slow commercialization.

Materials can be deployed into many markets. By strategically selecting application markets, materials producers can significantly improve the probability that new materials will be adopted and can shorten the period of commercialization. Early markets should be selected based on the ability of the material to solve unique problems and the simplicity of the application value chain. When market selection is not an option, materials producers can integrate forward in the value chain to shorten commercialization times, but capital requirements are very high.

Once integrated into an application, the safest competitive position for materials is to be the lowest cost option that meets the exact needs of the application.

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Acknowledgements

I feel that a cadre of people has surrounded me to help me through this process, and I find myself in awe of their commitment.

I would like to thank the Mika family and Dick Maloney of ADM Cocoa for making this endeavor possible. It would have been irresponsible for me to continue my studies without their help.

I have been blessed with an extraordinary thesis committee. I believe them to be the best in the world at what they do, and some of the smartest people I have ever met. They have all been remarkably supportive of my work, and have encouraged me when necessary. I thank Clayton Christensen for his wonderful ability to teach—he has shown me the path to solving the problem and has taught me to carefully frame it. I thank Joel Cutcher-Gershenfield for his encouragement and wonderful understanding of data and methods. I don't know what I would have done without him. I thank David Mindell for his clarity and articulation—he has forced me to tell the story better, implicitly asking me to learn the material at a deeper level. I also thank Dr. Hammer, the honorary member of my committee. He is incredibly quick to understand, and has given me great insight.

Monty Alger of GE Advanced Materials has been an instrumental mentor for my thesis work. He is the first person that has tried to apply the theory, and his feedback has been invaluable. I look forward to maintaining our relationship. I also thank the engineering team at Special Metals, for being my first receptive audience.

The insights of the experts and industry friends whom I interviewed gave me great insight. Each one has earned my gratitude: Chris Magee, Paul Lagace, Chris Scott, Darran Cairns, Larry Bell, Eric Mayes, Tom Ricciardelli, Grant Bennett, and Stan Abkowitz, as well as the rest of Monty's team at GE and the team at Special Metals.

My friends have been a great support. Joel Williams, Murray Duff, Doug Cannon, Brian Bowers, Lou Rassey, Rick Johnson, and Josh Halverson have acted as sounding boards and counselors to force me to refine my ideas.

The Welding and Joining Group has been an extraordinary organization to be part of. Jeri Hill, Don Galler, Harold Larson, Burke Hunsaker, Raymundo Arroyave, Neil Jenkins, Mikal Balmforth and the other members of the group have been the best colleagues I can imagine, and have also been fantastic friends.

Tom Eagar took a chance in helping me get admitted to MIT, and has been a peerless mentor. He has helped me grow in every way, has pushed me to improve when necessary and humbled me when needed, and has been incredibly supportive. If there has been a single turning point in my professional life, it was Tom's decision to let me work with him. I will be forever grateful for his generosity and spirit.

I am eternally grateful for my family. My wonderful wife has never complained about the workload that has been required to complete this project, and has supported every

professional move I have made. She is my greatest cheerleader--truly a woman without guile, and I love her for it. Her kindness and intelligence have sustained me. I am also thankful for our two sons, Matthew (who was born a week before my generals) and William (who was born a month before my defense). Along with my wife, they have brought me greater joy than I thought possible.

My parents have always wanted the best for me and have encouraged me to be the most I can be. Like Tom and my wife, they have always believed more in me than I do. I am thankful for their love and support. My dad has wanted me to do the doctorate from day one. I am happy to report that it is done.

Chapter 1: Beating the System

Motivation

The early history of man has been classified by archaeologists into three chronological ages: the Stone Age, the Bronze Age, and the Iron Age[1]. Each of the Ages is named according to the materials technology that was possessed by society. This is recognition of the impact of materials on the welfare, economies, and technologies of societies. Materials are the basis of manufactured good and the basis of construction. In fact, they are the basis of most technological progress.

Because of the impact of materials on technology and society, there is a great deal of research focused on creating innovative new materials. However, the track record of commercialization of these materials is quite poor. Materials experts have asserted that materials breakthroughs in the twentieth century required nearly 20 years from the time of invention to gain widespread market acceptance[2]. Some applications, such as the use of aluminum in automobile bodies, have taken much longer, despite clear advantages in materials properties. This lag can be caused by many factors, ranging from poor market education to technical obstacles to political roadblocks to financial infeasibility.

No matter the cause, a 20 year commercialization horizon is simply too long for private investment. Capitalism has proven to be the most effective means of diffusing new materials into widespread use, but it works only if entrepreneurs and corporations are willing to take the risk of commercialization[3]. A long commercialization period increases this risk significantly, and also causes the present value of expected earnings to become very small. Shortening the commercialization period can be the difference between a successful new material and one that is dropped in the development stage.

The research presented here is designed to respond to a simple question: how can materials be commercialized faster? This is a broad question, and the methods used to answer it have also been broad. This thesis is not designed to test a simple hypothesis, but rather to provide a roadmap for commercialization of new materials. Extensive research has been performed to create this roadmap. More than 50 key papers from business innovation literature were reviewed; over 250 contemporaneous articles from the plastics industry were used as sources, including 65 years of annual technical, marketing, and price reviews[4,5]. Formal interviews or in-depth discussions were held with over 25 industry experts[6].

These sources provided data for several different analyses. A core set of time series data from the history of the most successful plastics was created to identify commercialization patterns. This data was analyzed using quantitative statistical techniques such as multivariate regression, and qualitative techniques such as expert scoring. In addition, more than 15 case studies were created (many of which are reported in this thesis) to reinforce the qualitative and quantitative analyses.

These complimentary analysis techniques combine to show that strategies exist to simplify the commercialization challenges of new materials. This thesis will show that all of the most successful plastics followed a characteristic pattern of commercialization which is counterintuitive to the traditional attitudes toward materials marketing. Most materials marketing literature has been focused on materials substitution in situations where both the attacker and the incumbent are well-understood[7]. In these cases, the most important factor is the value proposition (often expressed as multi-attribute utility), which allows deep penetration into existing markets[8].

This theory breaks down when applied to many new materials, where value proposition alone is not enough[9]. New materials are not well-understood—their design capabilities and failure modes are not fully developed. Furthermore, application manufacturers don't have experience processing them, and processing techniques are often nascent. Many parts of the value chain have to be adapted to adopt new materials; the costs and risks of these adaptations are unknown in the case of new materials, and provide rational disincentives for adoption. These disincentives limit the speed of insertion of new materials to the market, and must be overcome no matter how appealing the value proposition of a material.

The core contribution of this thesis is quite simple: traditional materials marketing wisdom is incomplete, and mindsets must be amended to deal with commercialization of new materials. Because new materials are not well-understood, the adoption conditions they face are different from the conditions faced by existing materials. New materials will succeed much more quickly if mindsets are changed to focus on value chain management in addition to value proposition. By doing this, materials producers can reduce the uncertainty and expense faced by applications manufacturers in adopting new materials. This assertion is as applicable to today's materials as it was to the plastics of the twentieth century, and several value chain management strategies will be presented that lead to shorter commercialization.

It is hoped that this research will be useful to materials researchers, innovators, and entrepreneurs. This thesis represents the most comprehensive analysis of commercialization of new materials to date, but is by no means complete. It is designed to provide strategies which will be operationalized very differently in different organizations. Within the operationalization lies opportunity for competitive advantage.

While this research is directly applicable to the materials industry, it also adds to the general body of innovation theory by revealing and explaining anomalies to existing models. In addition to explaining these anomalies, it uncovers several new questions for future work.

Materials are Special

Research in other major industries has shown strategies and business models that can significantly reduce commercialization periods of new technologies. Some of these strategies and models are applicable to many industries, but many of them are industry-specific. Although some tools have been developed for understanding the introduction of new materials, there is currently no comprehensive framework for the business of the materials industry, and the existing general frameworks offer, at best, limited applicability.

Part of the problem is that the "materials industry", per se, is a very broad classification. Many definitions exist for the word "material", ranging from "anything for which an engineering drawing does not exist"[10] to "The substance or substances out of which a thing is or can be made"[11]. Both of these definitions could include the chemicals, textiles, mining, basic metals, polymers, ceramics, and composites industries, to name a few. This thesis will deal with the basic materials sector, which includes a group of industries that dwell at the same point in the value chain and share many common challenges. This group includes those industries which process raw substances, such as chemicals and ores, into commercial materials which can then be converted by manufacturers into useful products which can be sold to customers. Under these boundaries, the mining and basic chemical industries are excluded, and the basic metals, polymers, ceramics, and composites industries remain.

It will be shown in this thesis that all of the basic materials in this group share some common elements, which make them unique as a group and profoundly impact the business conditions they face.

1. *Materials come early in the value chain*: As the basis of most products, materials are the first point of competitive differentiation in the product manufacturing value chain. They interact with every step in the manufacturing, distribution, maintenance, distribution, and disposal processes. Their position in the value chain facilitates commoditization, and makes introduction of major innovation very difficult.

2. *Materials are difficult to change:* Materials are highly complex products. Their properties are affected by raw materials (such as chemicals, ores,etc), production techniques, and secondary processes. Because of the interdependence of these factors on the properties of materials, they are very difficult to change compared to assembled products, software, or services.

3. *Materials are versatile*: most materials can be used in a wide variety of applications, and the properties of materials rarely "lock-in" users.

4. *Materials are functionally fungible:* Processing steps in the value chain disguise materials, and in most cases, end users neither know nor care what a product is made of, as long as it works. Market pull is for functions, not for specific materials. Funtional fungibility is related to versatility, but is slightly different in that it is caused by end users, whereas versatility is caused by the properties of a material.

While other industries have some of these factors, none has all. Because these factors have such impact on the business conditions that materials face and can be isolated, they make materials an interesting case study for other industries in which the factors are present but less prevalent. It may be possible to generalize the insights that emerge from the study of materials by recognizing and reintegrating these factors into the fabric of innovation theory. Each of these factors will now be discussed.

Materials Come Early in the Value Chain

Materials, *per se*, have very little value. They are worth little unless formed into a useful product and sold. In most cases, materials are produced and then sold to product manufacturers who process them and integrate them into saleable components, parts, and systems. Understanding the activities of the product manufacturers, and the interactions of materials with those activities, is an important part of understanding the uniqueness of the materials business for two reasons. First, product manufacturers are the direct customers of the materials business. Second, product manufacturers add value to materials so that they can be adopted by end users. Porter's value chain model is a useful tool for gaining this understanding.

The value chain model was introduced in 1985 as a tool for analyzing the competitive structure of industries and the competitive position of firms within that structure. According to Porter, "the value chain provides a systematic way to divide a firm into its discrete activities . . . to examine how the activities are grouped"[12]. The model contends that there exists a generic set of value adding activities (each with a corresponding set of knowledge and equipment) that every firm undertakes in order to deliver a useful product to its customer, shown in figure 1.1:

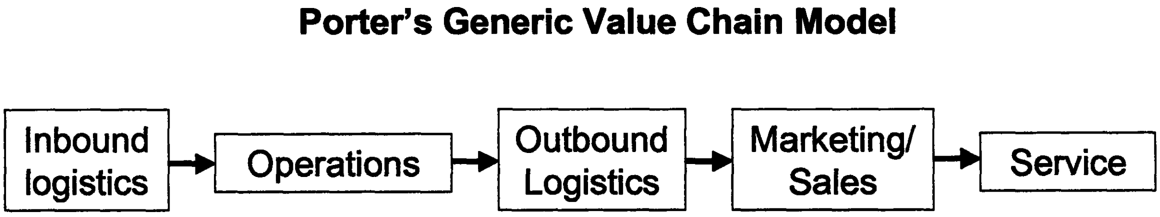

Figure 1.1: Generic value chain. Each box (node) corresponds to a set of activities.

The generic model becomes more useful when adapted to describe a generic materials value chain, as shown in figure 1.2:

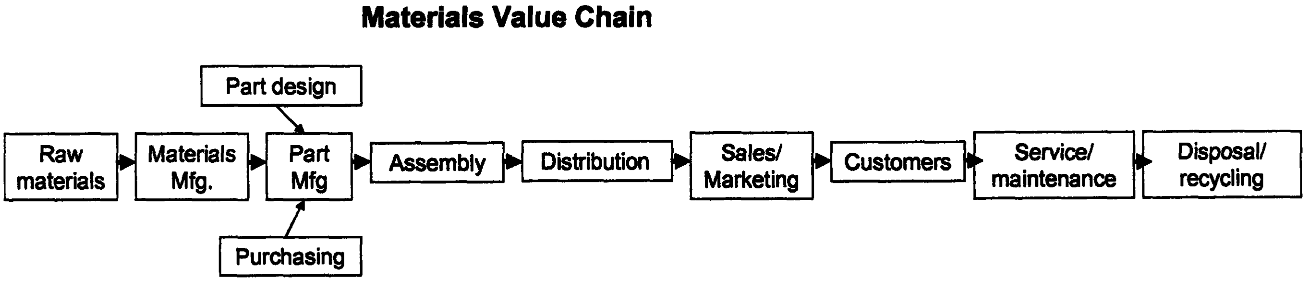

Figure 1.2: Generic materials value chain. Each box (node) corresponds to a set of activities.

Inspection of the materials value chain shows that materials manufacturing is the first of a series of value added activities, and is the first point of competitive product differentiation (since raw materials are almost always commodity products). Although purchasing and supply techniques for raw materials can create lower costs for materials manufacturers, their lack of differentiability makes them of little consequence to other nodes of the value chain. For this reason, they will not be considered here.

Value chains are systemically interdependent but functionally independent. Each node has specific functions to perform, which require different knowledge and equipment than other nodes, yet each node is affected by decisions and activities in other nodes. The nodes are also sequential, so that the effects of the activities and decisions of early nodes cascade into later nodes. Similarly, inter-node compatibility can force decisions in later nodes to have the effect of constraining flexibility in earlier nodes. Since materials are the first point of competitive differentiation in the value chain, they play an important role in determining the structure of the other nodes. Materials form the basis for end products, and interact with all of the value creating activities—and the corresponding knowledge and capital equipment—in the chain. Once a material is chosen, each subsequent node must be designed or adapted to accommodate it, as well as to meet the needs of the end customer. As a result, two vastly different products made of the same material may have nearly identical value chains. Table 1.1 shows some of the equipment, supplies, techniques, and knowledge that are required to produce two different parts of the same material.

Value Chain Activity	**HDPE Hair Comb**	**HDPE Bucket**
Material	HDPE	HDPE
Part manufacturing	Injection Molding	Injection molding
Assembly	none	none
Distribution	Truck/boat	Truck/boat
Sales and marketing	Retail (Wal Mart)	Retail (Wal Mart)
Customer	Household	Household
Maintenance	none	none

Table 1.1: Two different products, nearly identical value chains

Likewise, two very similar products made of different materials can have vastly different value chains (as shown in table1.2).

Value Chain Activity	**Wood Picnic table**	**PVC Picnic table**
Material	Wood	PVC
Part manufacturing	Sawing, sanding	Injection molding
Assembly	bolts, glue, nails	snap together
Distribution	Truck	Truck/boat
Sales and marketing	Retail (Wal Mart)	Retail (Wal Mart)
Customer	Household	Household
Maintenance	Stain, etc	none

Table 1.2: Two similar products, vastly different value chains.

The position of materials in the value chain as the first point of product differentiation is unique. It has important implications for the materials business: it creates disincentives for major innovation, increases the risk associated with failure, and facilitates commoditization. The interdependence of the value chain elements also raises the bar for switching materials, since significant costs must be incurred to change from one material to another. These switching costs will be shown to be very important factors in materials.

Materials are Difficult to Change

The relationship of materials to application value chains is not one-sided; the activities of the value chain have a profound effect on the end state of a material. This is because the properties of materials are intimately connected to the processing techniques used by application manufacturers to form them. The relationship of materials properties to processing is one of several important relationships that comprise a useful material. The performance of a material is also affected by the internal structure of the material, the quality of its raw materials, and the application itself. Figure 1.3 shows a diagram created by the Materials Advisory Board of the National Academy of Engineering which displays the factors that must be considered when developing a material.

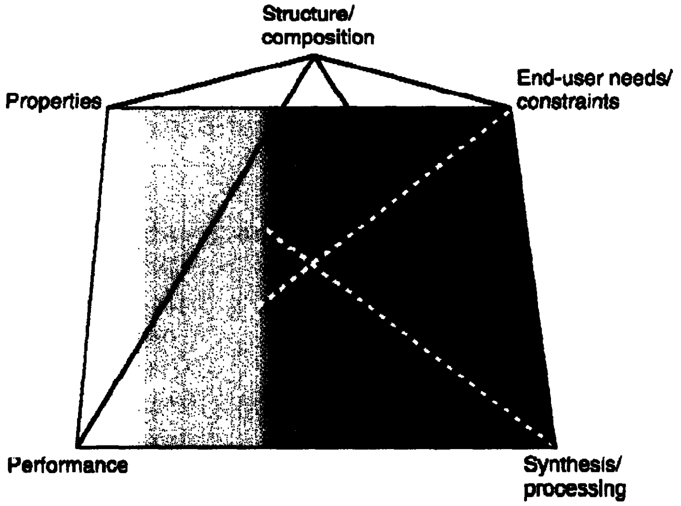

Figure 1.3: NAE materials polyhedron

The interconnected corners of the NAE polyhedron convey a subtle but important message: materials are very complex.

Because of the complexity of materials, materials science has always been an interdisciplinary field. Materials science has traditionally drawn on such diverse disciplines as chemistry, physics, and mechanical engineering[13]. It still draws on all of these fields today, but now has a much larger pool, including biology, manufacturing engineering, and even economics[14]. This breadth of disciplines gives insight into the complex interactions that take place when one (or many) of the corners of the polyhedron is altered. These complex interactions make sweeping changes of the properties of materials very difficult.

The net effect of complexity in materials is simple: it slows change. But slow change is only part of the story. There are fundamental constraints on many properties imposed by the chemistry and thermodynamics of the constituent elements of materials. These constraints have an effect that is at least as powerful as that of complexity: they limit the envelope of properties that can be attained with a given material. Materials scientists have developed tools to understand and manipulate fundamental constraints, and have created wider ranges of properties than could be imagined decades ago, but the constraints still exist. These constraints prevent materials from being all things to all applications.

Thus, materials are difficult to change and have fundamental limits on their properties. Materials do not have the luxury of being easily reconfigured to meet the needs of customers, meaning that market pull for introduction is an option only when the properties of a material coincide with needs of an application. This makes them very different from the assembled products which have been studied in the development of innovation theory, because assembled products can be rearranged to meet new needs[15,16,17]. This difference is significant, and can be expected to cause materials to follow different patterns of commercialization than other products.

Materials are Versatile

Luckily (since they are difficult to change), most materials are quite versatile. All but the most specialized materials have properties that make them applicable to a wide range (from dozens to millions) of applications. Although product redesigns are usually required to take full advantage of materials properties, examples of materials versatility abound. Car bodies are made of steel, ABS plastic, and fiberglass. Bicycles are made of steel, carbon fiber composites, and aluminum. Even jewelry is made from many materials, including gold, silver, titanium, and tungsten carbide. This does not mean that every material is right for every application, but most materials can be right for many applications.

The versatility of materials creates some interesting challenges in the materials business. First, there is a high degree of cross-product competition—materials may face challenges not only from other grades of the same material, but from completely different materials. This means that attacks can come from all sides: better grades of similar materials can attack by reducing cost; cheaper grades of similar materials can attack by improving properties; different materials can attack from lateral markets.

Market positions can also shift quite easily, according to changes in technology, new design specifications, or even the whims of consumers. This means that materials producers must be constantly vigilant to maintain markets. Versatility also facilitates commoditization. If two materials can easily fill the needs of an application, the application manufacturer will naturally select the lowest cost material. The easiest way for producers to compete in this situation is to lower the price of the materials. As competitors respond, a downward spiral ensues until one competitor becomes unprofitable. When many materials can fill the needs of an application, this pull toward the bottom becomes especially strong.

Materials are Functionally Fungible

The effects of materials versatility are exacerbated by another aspect of the materials business: functional fungibility. Most consumers neither know nor care about the exact material a part is made from, as long as that material performs its intended function within expectations of cost and reliability; thus, materials are "functionally fungible" in the eyes of consumers[18]. The distance in the value chain between materials and end users is quite long, and several of the intermediate nodes employ process technologies that add value to the material while simultaneously disguising its identity to the end user. This makes it very difficult for end use consumers to identify the exact materials used in a product, and parts are commonly described simply as "metal", "plastic", "wood", or "cement".

This long-value-chain induced ignorance is a key element of the materials industry: it makes consumers insensitive to small switches in material grade and manufacturer. Free from demands of end user loyalty, application manufacturers are free to switch materials (as long as the new material offers enough value to overcome switching costs). This freedom creates a rational incentive for materials producers to make clusters of nearly interchangeable products—wide varieties of similar grades from a wide variety of manufacturers—to compete for existing business. The same long, highly interdependent value chain that creates a rational disincentive to major materials changes creates a rational incentive for commodity competition.

The materials for which switching barriers between grades or manufacturers are very low are considered commodities. Almost every family of materials has commodity grades, and those grades generally account for the bulk of annual sales poundage. Because commodities are easily switched, and because they account for the most sales, it follows that the majority of materials changes occur in the commodity regime. Switches between grades or manufacturers often carry very low switching costs—ranging from no costs at all to small transaction or adaptation costs in a few nodes—because they are drop-in replacements for existing products. The switches may offer slightly more utility to consumers, may lower purchase costs of materials, or may reduce costs somewhere else in the value chain.

Conclusion

Materials are probably the most ubiquitous manufactured products in the world, and are the basis of almost all other manufactured products. They are several unique factors about the materials business that make it interesting to study. By recognizing and isolating these factors, it may also be possible to isolate their effects, so that insights from the materials industry can be generalized into other industries.

Materials are the first point of competitive differentiation in the value chain of most products, and have a large impact on the structure of value chains. Value chains can be expensive to change, and provide a rational incentive for applications manufacturers to stay with incumbent materials. Materials themselves are hard to change, because they are very complex and are fundamentally limited by their structures and chemistry. They aren't easily reconfigured to meet the needs of customers. Despite being hard to change, the properties of most materials lend themselves to a wide variety of uses. This creates an extremely competitive landscape between materials. This competition is worsened by the fact that, in most applications, end users neither know nor care about the material that is used in an application, as long as it works[19].

While each of these factors is interesting on its own, the interaction effects of the factors are more interesting. The position of materials in the value chain and the difficulty of change in materials interact to create very high barriers for materials innovation. Novel materials often require expensive changes in value chains, and the switching costs can be insurmountable. Since materials are difficult to change, technical deficiencies of new materials can require significant resources and long periods of time to overcome—barriers that can preclude the use of a material.

On the other hand, the versatility of materials interacts with functional fungibility to create markets that are ripe for commoditization. When the properties of multiple materials can fill the needs of an application, and consumers don't care about the material in the product, switching costs in the value chain are the only barriers preventing application manufacturers from switching materials. By creating materials that are interchangeable with incumbents within value chains, low-cost producers can force a downward commoditization spiral.

Perhaps the most interesting interaction is between the versatility of materials and the difficulty to change them. This interaction requires that the primary tools of innovators be changed. Innovators in industries such as assembled products and software often find themselves in a *market pull* situation, where properties are selected to match markets. These innovators must have an acute sense of market needs—and their primary tool is to configure their products to meet those needs[20]. Since most materials are both versatile and difficult to change, reconfiguration of materials to fit market needs is rarely a viable option. This puts materials innovators in the opposite situation of other innovators--they are faced with *technology push*, in which the primary tool is market selection. Markets must be selected to match the appealing properties of a material[21]. If one also considers the position of materials early in the value chain, and the fact that end users often don't care about their identity, it becomes obvious that materials commercialization may be an excellent field in which to learn about the behavior of technologies in a push situation.

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Chapter 2: Review and Commentary of Relevant Literature on Materials Commercialization

Introduction

Chapter 1 discussed the some of the unique features of the materials business, with a special focus on the interaction effects of those features. This chapter will review prior work with respect to materials commercialization in order to establish a baseline for further work. It will explain traditional materials marketing wisdom and will discuss some barriers to introducing new materials, most of which are related to value chain challenges. It will also discuss some of the limitations of general innovation with respect to materials.

The principle driver for materials advancements has been the desire to build profits, and the principle diffusion mechanism has been free market capitalism. It is doubtful that much research and development would be performed without the promise of competitive advantage--either military or commercial--and the associated spoils: most materials advancements would be of little value to anyone without commercialization.

Given the importance of profits in materials development, there are remarkably few papers in the technical literature about early commercialization of new materials. Most of the references that pertain directly to new materials reflect the opinions and experience of materials experts. However, a fairly strong body of work has been built around substitution between existing materials[1]. While some efforts have been made to apply the general substitution frameworks to new materials, they have met limited success. There is no prior work that shows a systematic exploration of historical successes and failures in materials commercialization.

In general, the opinions and experiences of experts and materials substitution models can be distilled to four important foundation points. First, there is a need for materials engineers, scientists, and entrepreneurs to improve their understanding of the business realities of materials propositions. Second, a traditional materials marketing mindset exists: new materials should be launched into large-market applications where they offer a superior value proposition to incumbent materials. Third, there is a series of systematic barriers that compound the difficulties of materials commercialization. Fourth, materials don't seem to follow the same rules as other innovations: existing innovation strategy frameworks do not completely describe them.

The purpose of this review is to reveal and expand the strengths and weaknesses of the underlying principles of the foundation points in order to provide a basis for a systematic investigation of the fundamentals of materials commercialization.

Understanding the Business Side of Materials Commercialization

The Technology Transfer Model

Most materials development in the United States is performed in government research labs, universities, or pure commercial research labs. It is often performed as basic research, or is targeted directly toward the aerospace industry, where cost is secondary to performance[2]. Because of the uncertain nature of materials research, it is often funded by the federal government or with commercial research (not product) budgets. The business of materials research could be the subject of another thesis, and will not be treated here. Instead, this scope of this chapter will begin at the point at which lab-scale prototypes of materials advancements have been built, and commercial development of the material is being determined. This is a very common situation, usually called technology transfer from research to product development. Technology transfers happen not only from government labs and universities to businesses, but also between businesses and within businesses, from research departments to product departments.

The business implications of technology transfer are substantial. Technology transfers allow businesses to broaden their research portfolios by purchasing research at a cost that is usually much lower than the actual research cost of the material, and to share potential risk with the seller by paying future—and uncertain—royalties. Furthermore, businesses have a much better idea of what they are buying in this situation; they can be reasonably confident that their material is not a technological loser. Both of these factors make technology transfer seem to be an attractive entry point.

Unfortunately, this model is not perfect. Materials research labs are generally concerned with materials research; they seek high performance solutions and have little incentive to develop processing methods for anything larger or better than lab scale[3], and tend to suboptimize. These factors can result in materials that are polished only enough for testing and which carry learning costs that make them far too expensive to be commercially viable, regardless of their properties. They are often well understood technically, but not ready for "prime-time" markets. Materials businesses and product manufacturers must undertake the difficult and expensive tasks of reducing manufacturing costs and refining the materials to meet practical market needs. Once these tasks are complete, materials ventures face a risky future, since there is no guarantee that their products will be accepted by the market[4].

Risk Factors in New Materials

In a recent report, the National Research Council declared that: "two sets of perceptions—the desire for timely incorporation of change, and caution in the face of its possible effects—create a significant tension between those charged with the development of new technology capabilities and those who feel accountable for the consequences of such technology incorporation"[5]. This statement reflects a belief that materials researchers must grasp the dozens of sources of risk faced by materials businesses if they are to succeed with commercialization. Most of these risks apply to both large and small companies, although they may have different effects. They can be generally classified into five categories, each of which will be briefly discussed.

Market/Product Risk[6]

There is an axiom in the business world that says market and sales forecasts are *always* wrong. This problem is particularly acute in the materials world, where the "technical community, in a wave of enthusiasm, systematically overestimates the value of its discovery", and almost always overprojects the size of a potential market. Materials depend on filling needs in products, and there is no guarantee to investors that materials will find product acceptance. In order to minimize risk, "materials must find applications quickly or else lose user interest".

Even if a new material is fortunate enough to be integrated into a product, there is significant risk that the product itself will not succeed. Because materials are embedded in products, any risks that exist in the product market are amplified in the materials market. This risk can be mitigated by integrating the material into a wide range of products, which is very expensive and difficult to do in the early stages of the life of the material.

Latent Liability Risk[7]

Materials almost always play "mission critical" roles in applications. If a material fails, the part that is made of it will fail. Furthermore, materials issues are often very difficult or impossible to fix, requiring part replacement in the event of their failure. In many cases, such as flight critical aerospace or automotive applications, material failure can cause injury or death to users. This means that investors in a new material assume significant latent liability and warranty risk that could emerge at any time in the life of the material.

The example of an automobile fender, shown in table 2.1, is useful to illustrate the possible latent warranty costs in a material failure. Note the extent to which costs rise (and blame shifts) as the damage extends deeper into the system. Note also that a problem such as grain boundary corrosion would most likely not be limited to a single vehicle.

Damage	Correction Procedure	Estimated Cost ($)	Who Pays?
Scratch	Polish	15	Customer
Deep scratch	Touch up, polish	50	Customer
Dent	Dent pull, polish	150	Customer/At fault
Dent with crack	Dent pull, sand, weld, repaint, polish	300	Customer/At fault
Grain boundary corrosion	Remove, scrap, replace, repaint, polish	600	Manufacturer

Table 2.1: Damage to an automobile fender.

Table 2.1 also offers a hint of the unknown costs that high volume manufacturers face, and why they would be reluctant to integrate unproven materials into their products.

Manufacturing Risk

Economies of scale are definitely present in materials manufacture. In fact, very few materials can be cost-effective without large-scale production. Since most materials are developed to lab scale first, there is significant risk that they will not be economically producible. Technical cost models can offer "best guess" predictions of the manufacturing costs, but it is impossible to foresee the magnitude of learning costs that occur during manufacturing scale-up. This problem is aggravated by market risk, because it is very difficult to project the proper manufacturing capacity to build. Because of the cost of building materials processing capacity, manufacturing will be considered as a barrier later in this chapter.

Time to Market Risk

Perhaps the biggest risk that new materials face is the "20-year barrier". Most materials advancements of the 20th century required 20 years to move from research stage to full commercialization[8]. This period is much longer than that faced by consumer products, electronics, and biomedical devices, to say nothing of software[9].

The anticipation of waiting 20 years to receive payback on an investment is not appetizing to investors because it introduces several sources of risk and severely retards the present value of cash flows. Given the pace of technology, there is significant risk that another, better solution will be introduced during that period that will displace a new material altogether[10]. That solution need not be a material, but could be a paradigm shifting design. There is also risk that market tastes will be different--imagine releasing in 1995 a new, more vibrant polyester for leisure suits that investors in 1975 thought would be a big seller!

There is also general economic and government regulation risk[11]. Wars, recessions, regulatory changes, and even demographic changes can occur in 20 years, all of which could eliminate the potential sales of a new material.

Capital Implications of the 20 Year Challenge

Experts have found it useful to educate engineers about the economics of a 20 year lag time using present value calculations. In order to justify the risk of doing business over the diversified risk of investing in the stock market, most large companies require an internal rate of return (IRR) of at least 5% over the historical return of the S&P 500[12], 15.55% over the past 10 years[13]. The equation for the required return on investment is

$$x=P(1+r)^t$$

where x=dollars required, P=principle invested, r=IRR (required percentage return), and t= time, in years[14]. Performing this calculation shows that each dollar invested today must return $42 in 20 years. However, if the period were shortened to 5 years, only $2.54 would be required from every dollar invested.

Many engineers have wondered why, given the enormous upside potential of new materials, venture capitalists don't take more interest in new materials enterprises. The IRR calculation quickly shows the reason. Because venture capital is invested in risky ventures, a premium of more than 10% is required over the S&P 500[15]. Furthermore, venture capitalists expect that 75% of their ventures will fail to make money, so they must bet on enterprises that have solid business plans and the potential to return *four times their required IRR*. Potential must exist to create annual returns of at least 100%[16]! This means that every venture capital dollar invested in the first stage of a new materials venture would need to return $1.05 million in 20 years! Shortening this period to 5 years has the dramatic effect of reducing the required return to $32/dollar invested.

Executives at materials companies have stated that development costs for new materials start at $10 million, and can be much higher if a material is very novel[17]. Most of this investment is made before a material is ever sold. The risk and capital implications of long commercialization periods create rational disincentives for investment. Shortening the commercialization period of new materials would significantly reduce the risk involved with introduction, and would also increase the net present value of materials investments.

Traditional Materials Marketing Wisdom

The materials industry is quite old, and a general set of ideas has been developed that seems to govern business behavior; it can be "traditional materials marketing wisdom". The 20-year barrier is an example of traditional wisdom—many experts believe that it simply takes a long time to commercialize new materials. The causes of the 20 year barrier will be considered in the next section. Some other tenets of traditional materials marketing wisdom will be discussed in this section.

Large Initial Markets

The first tenet of traditional materials marketing wisdom is simple and straightforward: initial markets must be large. Because of the size of investment needed to develop new materials, business principles dictate that returns be generated as soon as possible after commercialization. In a 1988 study, the Congressional Office of Technology Assessment showed that most producers required "a (projected) initial sales volume of $5 million to $50 million per year to justify production investment"[18]. If potential markets don't meet this criterion, the risk becomes very high.

While it may be possible to identify completely new markets that reach the volumes necessary for investment, they are difficult to assess and can be very risky. If new market risk is to be avoided, the large initial market investment requirement places an interesting constraint on new materials—it practically forces them to attempt to replace incumbent materials in existing markets. In this situation, unproven materials must offer enough value to overcome the cost and risk of switching from existing materials (which already work). This sets a very high bar, because switching to uncertain materials can be very expensive. Switching costs will be considered more deeply in chapters 4-6 of this thesis.

Substitution Based on Superior Value

Most materials substitution occurs between two existing materials that are well understood. Examples of this type of substitution would be aluminum body panels for steel ones in automobiles, ABS for polycarbonate in computer housings, and OSB for plywood in houses. Research has shown that superior value proposition is key to substitution between existing materials[19]. The importance of value proposition has become a tenet of traditional materials marketing wisdom.

Two major tools have been developed to assess the value proposition of materials, and both tools work best with established materials for which the properties are well-known. The first tool is technical cost modeling, in which manufacturing, market, and technical scenarios are analyzed using spreadsheet techniques[20]. Good technical cost models are very effective, because they take into account all known manufacturing costs and allow sensitivity analysis of many different scenarios. Their output is a comprehensive projection of material production costs over a range of production volumes, cycle time estimates, capital costs, and other uncertainties. They can be manipulated and used as an effective communication tool between business and materials people.

The cost data from technical cost models makes it possible to execute the second tool: multiattribute utility analysis (MAUA). MAUA is a tool designed to measure the overall value of a product to a certain set of users, and to group those users into potentially profitable market segments[21]. It is based on the concept that each feature of a product provides utility to a user. Each feature can be separately coded and assessed using lottery equivalent techniques, in which potential users are asked to identify the probabilistic tipping point at which they might be willing to switch between features[22]. Once preferences are established, all factors can be added together with scaling factors to identify the true sources of a value proposition.

The concept is rather easy to see when expressed mathematically[23]. For any given attribute, X_i, there exists a utility $U(X_i)$. Since materials have many potentially useful attributes, $(X_1,X_2,X_3\ldots)$, their value must be defined in terms of multiattribute utility. Once assessed, the different attributes can be combined into a weighted sum using scaling factors (k), such that

$$KU(X)+1=\prod_{i=1}^{N}(Kk(X_i)U(X_i)+1)$$

where K "is a normalizing parameter used to ensure consistency between the definitions of $U(X)$ and $U(X_i)$"[24].

Cost is considered an attribute in MAUA, so it is nominally possible to assess the cost at which a material becomes a viable alternative. When coupled to a cost model, one can obtain a rather wide prediction of the substitution potential between materials.

There are two important caveats that must be considered when applying MAUA. The first is that substitution analysis almost always requires consideration of an incumbent material and an entrant. This being the case, the utility functions are most often compared on the *attributes of the incumbent*. While this is a realistic comparison for most existing materials, it leaves little room for assessment of unique properties that a new material might offer since it systematically defines the new material in terms of the incumbent. Chapter 3 will show that this can be dangerous if a materials producer is aiming to commercialize a new material quickly, since the basis of commercialization for most new materials is some unique combination of properties that enables new products.

The second caveat is more fundamental. MAUA is built on an intuitive, yet false, premise: that cheaper, higher performing new materials will always be accepted over incumbent competitors. While the converse--that more expensive, lower performing materials will not be accepted over incumbent competitors—is almost certainly true, it is important to remember that risks and switching costs must be overcome for adoption, and that credible competition can come from many sources. The chapters that follow will show that switching costs and risks are particularly high for new materials, and that value chain elements must be managed to allow fast commercialization.

It should also be noted that proponents of MAUA do not explicitly claim that materials which appear promising will be commercialized quickly, although that indication is implicit.

A Special Focus on Lower Cost

The analytical assessment of value in multiattribute utility analysis was an important step in the understanding of materials substitution, because it explicitly recognizes the importance of utility, not just cost. While it is likely that other experts understand that a value proposition is comprised of both utility and cost, there appears to be an underlying belief with the materials community that the best path to substitution is to offer a lower cost material. It seems that most reviews of new materials state that market insertion will come as cost drops[25,26,27,28,29].

Cost clearly has an effect on the both the value proposition and the range of applications in which a material can be used (see figure 2.1), but it must be considered in context with utility. While the correlation between low cost, utility, and eventual sales volume seems clear, the correlation between low cost and quick substitution (which is implied by the clamor for lower cost) is dubious.

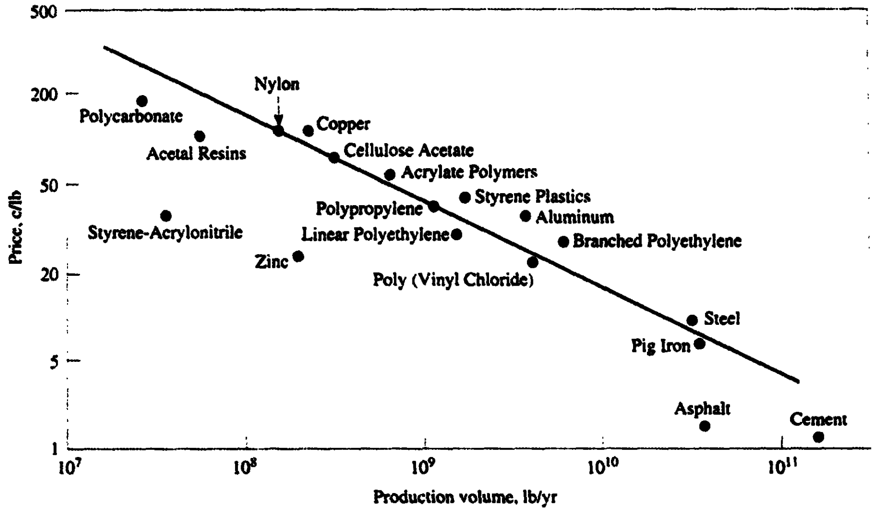

Figure 2.1: Graph of production volume v. cost. Note that this graph does not take into account the relative density of materials.

We thus see that traditional materials marketing wisdom is comprised of a few core ideas. Many materials experts believe that materials simply take a long time to commercialize. When they are commercialized, they must enter large initial markets, and these markets must be conquered by replacing existing materials. The basis of replacement is superior value proposition, usually through incremental improvements of the same properties that are valued in the incumbent material. Lower cost is considered by many to be the most powerful of these properties.

The IMM: An Excellent Application of Traditional Materials Marketing Wisdom

Maine and Ashby of the University of Cambridge have developed a methodology based on technical cost modeling and multiattribute utility analysis to help materials scientists and potential commercializers make a first attempt at assessing the value of a material innovation. This tool, called the Investment Methodology for Materials (IMM), integrates common business and innovation concepts to create what could be titled "Business Plan 101 for New Materials"[30]. The IMM is extremely broad, and its novelty lies in its specific application of the concepts to materials applications. It is divided into three parts:

1. Viability Assessment
2. Market Forecasting
3. Value Capture

IMM: Viability Assessment[31]

The strongest section of the IMM is the viability assessment. The viability assessment uses quantitative methods to assess the technical feasibility, projected manufacturing cost, and customer utility of a material. It is essentially a tool to describe known switching costs and to compare them with expected costs and revenues of adoption.

The IMM technical feasibility approach is to compare the properties of a material with those of other materials. Since many new material properties are measured, the analysis usually begins with the most remarkable properties (i.e. specific strength of CFRP or specific energy absorption of Al foams), and progresses to other properties. This step can act as a research filter: unless a new material will be dramatically less expensive than comparable solutions, its properties must demonstrate clear superiority to overcome switching costs and thus warrant further development.

Once technical feasibility is established, the next IMM step is to build a technical cost model. As in the applications cited earlier, the purpose of the technical cost model is to identify the range of materials costs that might be feasible given different market and manufacturing scenarios.

Knowing the technical properties and projected costs of a new material allows the application of multiattribute utility analysis. This analysis acts as a filter to identify potential opportunities in a known market. It does not help to identify new markets, unless multiple iterations are performed. Multiple iterations can help reveal markets, but technical and marketing intuition is still required because the market analysis tool depends on the results of the utility analysis and the utility analysis fails without a clear market.

IMM Market Assessment

The IMM Market assessment presents two complementary strategies for identifying markets for new materials: substitution and unmet needs. Both use the results of the viability assessment stage to find potential markets in which better or cheaper products could be created from the new material. No guidelines are given for executing the unmet needs strategy, but the examples indicate that niche specialty materials (such as Gore-Tex and Co-Sm magnets for headphones) are best suited for it.

The IMM substitution method is an excellent reflection of traditional materials marketing wisdom. Like the viability assessment, the market assessment recommends that producers of new materials survey the applications of materials with comparable properties in search of areas in which the material can offer value, either through lower cost or higher performance. It involves more detailed utility analysis than the viability assessment for prediction of premium profits, and attempts to predict the penetration rate of the new material by examining the histories of comparable products in the same industry. The history required by the IMM market assessment makes it best suited to large, established applications. While is superficially quantitative and robust, it ignores switching costs and risks. For this reason, it is almost, but not quite, limited to the simplest of drop-in application substitutions.

IMM Value Capture Assessment

It is well known in the business world that inventions have little value unless they can be leveraged to make money. Maine-Ashby is one of the few of the papers to acknowledge the importance of appropriability (protectability of intellectual property) in materials development. The IMM uses very general and basic business tools, such as Porter's Fiver Forces Analysis and Teece's model of appropriability to assess the attractiveness of products and industry[32,33]. These are useful as first filters of markets, and provide a basis for further investigation.

The IMM also addresses organizational structure of the materials developing company. However, it is largely useless in this application because it doesn't include business factors such as capital cost, existing assets (supply chain, distribution network, engineering, etc.), and organizational capability.

Overall, the IMM is most useful as a no-go filter for further investigation into the commercialization. If the IMM shows glaring flaws, such as high cost, low industry attractiveness, inferior technical properties, or extremely long likely time to market, commercialization of the material in present form is very unlikely.

The IMM accurately conveys the traditional wisdom of materials marketing, in which decisions of market selection are based on incremental value to be added to existing large market applications. It also accurately conveys the shortcomings of traditional wisdom: passing through the IMM filters is not enough for an investment grade business plan because it doesn't provide a realistic assessment of risk, which, along with upside potential, is one of the two most important factors in venture and commercialization decisions[34]. Furthermore, it lacks a framework for identifying market opportunities outside of copying existing material. A framework that provides guidelines for market identification in consideration of risk and value chain challenges would be very useful.

Obstacles to Commercialization of Materials

The 20-year barrier a product of traditional materials marketing wisdom that is generally well-accepted within the materials community. However, it is not a single, inherent barrier; it should be considered as a composite barrier—one that is made up of many smaller obstacles.

In a paper describing the application of the IMM to aluminum foams, Maine and Ashby provide a useful description of the steps a material must take on the road from development to commercialization[35]. Stepping through this paper, in combination with others, allows the creation of a map of the obstacles that are faced by materials. These obstacles are all contributors to the 20 Year Challenge. This map is not meant to be an exhaustive list of obstacles, but does convey the types of commercialization challenges faced by new materials.

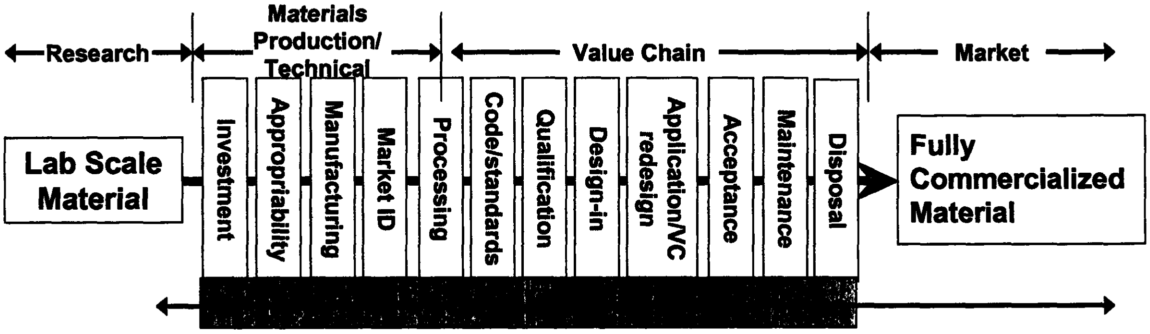

Figure 2.2: Commercialization map showing obstacles faced by materials developments. Time spent overcoming any obstacles increases the risk of competitive displacement.

The timeline on top of the map shows that obstacles tend to be grouped in phases. Assuming that the research produces an acceptable lab scale material, the first obstacles of commercialization arise in establishing the business and production capabilities. They range from highly technical manufacturing and materials development challenges to legal obstacles in obtaining intellectual property rights. The next set of obstacles comes from elements of the value chain, which are resistant to change because of switching costs, inertia, and risk. Only after research, materials production, and value chain obstacles are solved does a material have a fair chance in the market.

It is clear that any of these obstacles can represent significant threats to commercialization. In the best case, each obstacle will add to the time to commercialization. In the worst case, progress and commercialization will be altogether stopped. Each obstacle will be discussed, except for investment, which was discussed as a risk in the preceding section.

Materials Production/Technical Obstacles

Appropriability

Appropriability is the ability of a firm to protect the intellectual property of its invention. There are many protection strategies, ranging from trade secrets to patents to high entry barriers. Most materials producers will choose to patent new advancements. Many technology transfer materials will come with patents, but these patents often need to be extended to cover specific markets. The quickest patents are granted in several months, but the process often takes many years.

Building Production Capacity

Manufacturing risk has already been discussed, but the magnitude of the challenge of building production capacity is hard to overstate. Most novel materials require advanced processes, and usually require new tooling and machinery[36]. Supply chains, distribution networks, and production systems must be built or purchased. Due to the high cost of creating capacity, most materials production systems start with pilot plants. Since the cost of producing most materials is so sensitive to scale, it is very difficult for these materials to compete economically with incumbent materials. Since they can't compete economically, their adoption is limited, and it is very difficult to justify the construction of a larger scale facility in order to be cost competitive[37].

Specialty materials, which solve specific, high value problems, can often sidestep the scale challenge. Large manufacturers, who have existing distribution networks and supply chains, are also more likely to be able to handle the production capacity problem.

Market Identification

Because materials are both highly complex and highly interdependent with the processes that make them, they are not easily changed. They cannot be quickly reconfigured to conform to market needs after they are launched. Furthermore, markets can be very unforgiving with materials failures. For these reasons, it is crucial that the proper launch markets be selected.

Market identification is a significant barrier for new materials. In most cases, target markets are identified prior to investment but change over the course of manufacturing development. Changes in target market can stem from many factors including identification of new markets, shifts in needs of target markets, and even whims of executives. Continuous identification of new markets is often necessary to create the economies of scale necessary to compete.

Subsequent chapters will show that market selection is *the* most important factor in speeding the commercialization of new materials.

Value Chain Obstacles

A generic materials value chain was shown in chapter 1, and challenges can arise from any node therein. This section describes some of the more common obstacles that new materials face in the value chain.

Secondary Processing

Many new materials require completely different forming processes than existing materials, forcing the development of new equipment and supplies. Developing these forming processes can be a formidable task, and can range in scope from fundamental, scientific research funded by materials producers to practical, applied knowledge funded by product manufacturers. When processing techniques require the generation of new knowledge by science, they should be considered technical barriers. When they are solved with creative applications of common knowledge, they should be considered value chain obstacles.

Whether processing challenges are solved by basic science or common knowledge, process development effectively slows adoption of the material because new equipment suppliers, designs, and processing parameters have to emerge. Users of new materials must be willing to internalize the expenditures necessary for new processes; once expenditures are made, the processes must be refined to compete in quality with existing ones.

Codes and Standards

Codes and standards are written by government and professional organizations to ensure that products meet certain specifications. They are most often related to safety, and are explicit acknowledgements of familiarity with a material. Because they are designed as watchdogs, they are inherently inflexible and almost always favor incumbent ways of doing things. Changing codes and standards can be prohibitively expensive, and there is little incentive for alteration unless the new material is extremely pervasive or offers properties that are far superior to those of the incumbent. The challenge to change standards is further exacerbated by another chicken and egg problem. Many materials qualifications tests cannot be performed without changes to the standard, and the standard cannot be changed without qualification testing[38]!

It is important to recognize that emerging standards and codes can be influenced by new materials, and that skillful lobbying by new materials advocates can actually create captive markets that are protected from competitors[39,40]. This is discussed in chapter 8.

Qualification

The qualification barrier is very similar to the codes and standards barrier. Qualification processes are in-house corporate testing procedures designed to ensure that materials meet corporate specifications for quality and safety. They test supplier claims, examine compatibility, and test for unintended failure modes. They are designed to reduce unknown costs and learning costs in the value chain for product manufacturers.

Because the costs of in-field materials failures are very high (see table 2.1), most companies are very cautious with materials qualification. Intel, a company known for its fast introduction of new products, requires a qualification period of 12-18 months for new materials[41]. Other industries, whose products last longer and have larger failure consequences (such as injury or death to users), require a proportionally longer qualification period[42].

In cases where codes or standards and qualification apply, failing to meet code will preclude qualification. However, passing code requirements does not ensure passing qualification, although it is usually a good indication.

Design-In

Once a material is qualified, design-in begins. Designers rarely understand the properties and usefulness of new materials and tend to be "gun shy" when using them. One expert pointed out that drop-in replacement is seldom optimal for the use of new materials, and often leads to premature field failure[43].

Design-in is the first point at which a new material begins to merge with its application. If the difference between the incumbent material and the entrant material is at all significant, the application design will change from its previous state. This change will cause significant ripples throughout the application's value chain, ranging from changes in purchasing habits to overhauled supply chains to new production processes to different assembly and distribution methods. An executive from Ford Motor Company estimated the true cost of a material switch to be at least 10 times the apparent cost (the part design and integration costs) because of value chain reverberations[44].

Product Manufacturer Acceptance

Materials are generally integrated into one specific application first, and then transition into other applications based on performance; they rarely take their target market by storm. The period from first application to full market penetration (in which a new material is seen by product manufacturers as a viable, acceptable substitute for others) can be called the product manufacturer acceptance period. It is determined by several factors, including product acceptance (acceptance of the product into which a material is built), economic climate, etc. Obviously, this period varies greatly; Maine and Ashby noted that it is useful to look at similar products in similar industries when forecasting acceptance periods[45]. For example, cell phone base station materials are accepted more quickly (~5years)[46] than automotive body materials (~12-18 years)[47].

Maintenance

New materials often require different maintenance than previous materials. Developing maintenance procedures and techniques can be an obstacle. If field maintenance is to be done, as with pipe or automobiles, a significant period can pass before the maintenance processes are fully disseminated. Even if the processes are known, time elapses while maintenance organization commit to the product. When BMW introduced its first aluminum bodied car, the Z8, it was not available through all dealers. BMW would sell it only through dealers who were willing to make the investment necessary to develop the capability to weld and form aluminum, in case any Z8 customers were in accidents[48].

Disposal/Recycling

New materials often require new methods of disposal. As environmental regulations become more stringent, it is increasingly important that disposal and recycling issues be addressed during design and commercialization of new materials. This fact is particularly acute in Europe, where new regulations require automakers and other major manufacturers to take back their products at the end of life[49].

Recycling has always been a difficult challenge for thermoplastics, but creative applications of regrind have made it surmountable. In contrast, recycling concerns have nearly destroyed the development of bismuth based solder (bismuth attacks grain boundaries in steel and causes cracking)[50] and have severely limited the application of long-fiber composites in automobiles[51].

Applicable General Innovation Theories

There are many streams of theory in the general innovation literature, some of which are more applicable to materials than others. This section is not meant to be a comprehensive review of every theory of innovation which might be applicable, but rather to give the reader a basis for the chapters that follow. There are three streams of innovation thought that seem most applicable to the present work: Utterback's dominant design model, the economics of standards, and Christensen's disruptive technologies model. Although these models are interrelated, they are easiest to understand if considered alone.

The Dominant Design Model

The charter of business innovation as a field of study was written by Joseph Schumpeter in 1943[52], in which he described the process of Creative Destruction—displacement by new innovations of existing companies and industries. Framed in this way, innovation was a competitive tool, both defensively and offensively. Once the tool was identified, studies began to examine the emergence and displacement of products in the free market, and forces of innovation began to be identified.

The first major descriptive model of the forces of competition and innovation in industries was created in 1975 by William Abernathy (Harvard Business School) and James Utterback (MIT Center for Policy Alternatives)[53]. It has since been named the "dominant design" model, and remains one of the most popular descriptive tools in innovation. This model has several points, the most important being the observation of three distinct stages in the development of innovation-based industries. Those stages have since been named, and are as follows:

Fluid Phase:	Firms compete on product innovation in market Focus on finding the right product attributes to please market Uncoordinated processes (general equipment, specialized labor) Significant entry of many firms with fluctuating market share
Transitional Phase:	Product innovation slows down, starts to be technology stimulated Basic feature set emerges (dominant design), technology matters Islands of automation begin to form Mass exodus of firms begins
Specific Phase:	Innovation is process based Customer needs shift to price, quality, and convenience Rigid processes minimize production cost Small number of remaining firms compete for market share

The most important event in this cycle is the emergence of a dominant design, which embodies the basic needs of the customer and creates a paradigm into which new products must fit. It effectively reduces the number of performance requirements because products are simply expected to have them in order to meet the design paradigm. It also marks the end of major product variation, and shifts the competitive base to incremental innovations and process-based innovations. This results in a major shakeout of the players, with only the best ones emerging. It is important to note that the dominant design model applies to *individual innovations* and is a *cycle*, not an event. These facts mean that incumbent products and companies are not exempt from the shakeout.

A central tenet of the dominant design model is that products can be reconfigured during the fluid phase while manufacturers search for the most attractive set of features. During this phase, competitive advantage can be based on innovation in individual components without significant impact on the rest of the system, and completely new designs can be built around the reconfiguration of parts. Changes can be made easily, quickly, and with little cost.

The tenet of reconfigurability limits the direct applicability of the dominant design model to the materials industry, because the properties of materials are highly complex, and are interdependent with many factors, including raw materials, forming processes, and even applications themselves. Instead of being quickly reconfigured to meet market needs, materials must either find markets that can take them as they are, or delay commercialization in markets while value chain obstacles and technical deficiencies of the materials are worked out. However, materials seem to follow an analog of the dominant design model in which they are initially placed in many markets, and then are shaken out of the markets in which the don't work, eventually being placed in "dominant applications" that they fit best. Understanding this pattern would be a significant contribution to the dominant design school of thought, since the creators of dominant designs have explicitly stated that the model is inapplicable to process industries[54].

Standards and Externalities

Dominant designs can emerge for many reasons, including customer preference, strategic maneuvering, or government regulation[55]. Standards are a particularly powerful way to influence the outcome of dominant designs. In the materials world, standards are usually associated with building codes or engineering specifications, and they allow materials to grow because application manufacturers can tap multiple suppliers to make materials that meet the same standards.

The concept of standards can be applied at a deeper level to materials by considering externalities. Externalities can be defined as a "change in benefit that an agent derives from a good when the number of other agents consuming the same kind of good increases"[56]. Examples of products with strong externalities are fax machines, VHS video tapes, credit card networks, and (generally) materials. These products are of little use unless more than one person has them, and their utility increases as more people get them[57].

In addition to age, there are two major differences between new materials and old materials: new materials are less well understood than old materials, and a smaller installed processing base exists for new materials than for old materials. The bases of understanding and processing create externalities for materials. As knowledge of the behavior and failure mechanisms of a material grow, and as more processors learn to fabricate it into useful shapes, the material becomes more appealing to broad range of customers. However, in order to be used in applications, sufficient knowledge and processing bases must be in place.

Thus, even if a new material is inherently lower in cost and offers superior properties than an incumbent, it may not be adopted unless the knowledge and processing bases are sufficiently developed. This situation has been called "market failure" by economists, since superior solutions exist but are not adopted by markets because of external factors[58]. When externalities are strong, then significant costs must be incurred to overcome them. If these costs are greater than the perceived value of the switch, it is rational not to switch. So if the value provided by a new material is lower than the costs required to develop a processing base or than the latent liability costs imposed by unfamiliarity with the material, then it is rational for application manufacturers to continue using the incumbent material, regardless of the presence of a technically superior solution.

This line of reasoning suggests that early applications of materials should be selected to generate knowledge for both materials producers and application manufacturers and to create capability within the processing base. By doing this, materials producers can increase acceptance of a material and can more effectively generate further learning and processing capability. Early applications should generate the *credibility* of knowledge, *capability* within the processing base, and *visibility* with potential customers in order to increase future use.

Disruptive Technologies

The concept of disruptive technologies, developed by Christensen in the 1990s, builds upon the dominant design model and others to create a compelling framework for understanding innovation. It is particularly focused on the competitive aspects of innovation.

A key aspect of the framework is the separation of the concepts of sustaining and disruptive innovations. Sustaining innovations can be radical or incremental, but share the common thread of creating products that "help manufacturers to sustain the rate of historical performance that their customers have come to expect"[59]. They allow companies to create higher quality, higher performance, and higher margin products for their best customers. Incumbent firms usually fare better than entrant firms at designing and introducing sustaining technologies, because they have tremendous resources, development and manufacturing experience, and direct lines of communication with their customers. In fact, the theory asserts that the companies will make any technological jump, no matter how hard it is, in order to defend their best markets in the face of sustaining innovations.

Disruptive theory argues that, ironically, listening to the voice of the best (highest margin) mainstream customers causes firms to fail in the face of disruptive innovations. Disruptive innovations are those that move up from less attractive markets to attack the underbelly of an industry, causing redefinition of performance criteria and fundamental modification of business models. There are several telltale signs of potential disruptive technologies[60]:

- Their attributes do not appeal (initially) to mainstream customers.
- They are less expensive, more convenient, and more reliable than mainstream products.
- They are built to cater to smaller, lower margin markets than mainstream products.
- They have a steeper performance improvement trajectory than the mainstream market requires, such that they intersect the mainstream market over time.

Technologies that show these signs tend to displace mainstream technologies by increasing performance to meet the needs of mainstream customers. They are rarely better than the products they displace when measured by the original performance criteria, but they cause a value shift in the mainstream market once they are "good enough"[61]. Mainstream customers in many industries that have been invaded by disruptive technology base purchases on new criteria, such as reliability, price, or convenience instead of traditional performance measures.

The failure of established firms in the face of disruptive competitors is caused by "asymmetric motivations" on the part of incumbents: they have established successful value propositions and are unwilling to respond to attacks on low-margin businesses, but will ferociously defend high-margin businesses[62]. Christensen has shown that companies follow pattern of natural drift toward providing higher value products for their best customers, and that their cost base also follows this pattern. This drift causes disruptive technologies to intersect mainstream markets from below and causes an upheaval among incumbents whose value networks are structured to meet even higher performance and profit margin markets. It is extremely difficult for firms to move their value networks downward because it requires the unlearning and upending of all the things that caused the success of the firm in the first place.

Like other innovation models, the disruptive technology framework works best when products are easily reconfigured to meet consumer needs. It also works best if products are sold directly to consumers. Materials don't fit either criterion. They are difficult to change and dwell deep in the value chain, so they can be expected to show behavior that doesn't agree with the disruptive technology framework.

This does not mean that the framework is useless for materials. At its broadest level, the disruptive technology model encompasses any situation in which a product improves and overtakes a higher-end market. If this definition is used, then materials may well fit the model—there are many examples of new materials improving over time and displacing incumbents (plastics being the most obvious). However, this observation provides little strategic insight; it is better used as a historical observation. A more strategic insight from the disruptive model is the recommendation that materials be launched into simple, low margin markets in order to avoid competitive response from incumbent materials. This insight is a step toward recognition that market selection is a key tool in the innovator's arsenal. The research that follows will build on this insight by showing that simple markets are indeed the best entry point for new materials, but that the reason for this entry is not competition. If early markets are selected correctly, they generate a great deal of knowledge and credibility that is very important later in the life of a material.

This research will also show that there are limits to the ability of materials producers to make technological jumps into vastly different materials. There are few examples of this occurring outside of materials, but observance of the phenomenon will provide a platform for future work.

Conclusion

History shows that materials developments can have major positive impact on society when properly commercialized. Future materials advances will probably also improve the quality of life of users. It is well known that research costs of new materials are growing as scientists search for more advanced designs (although new computational tools promise to minimize this trend)[63]. Commercialization costs will most likely also continue to increase due to heightened competition as more materials flood the marketplace.

Experience in other industries has shown that construction of industry-specific predictive, descriptive commercialization frameworks can significantly reduce costs, increase profitability, and improve probability of success. The foundations for understanding the technical and business aspects of materials development are available through conventional channels, and the IMM offers a good framework of traditional materials marketing techniques for first-pass analysis.

Traditional materials marketing wisdom suggests that new markets for materials be selected based on the substitution of incumbent materials in existing markets. This substitution must be based on value—either lower costs or higher utility. While traditional materials marketing wisdom seems to work for materials substitutions between commodity materials, it fails to recognize the high risk of introducing new materials. It also fails to capture the obstacles that must be overcome for materials to reach full commercialization. For this reason, the applicability of traditional materials marketing wisdom to introduction of new materials is quite limited.

There are many types of risk present when introducing new materials. Examples of these risks include:

1. Market risk
2. Product risk
3. Manufacturing risk
4. Latent liability risk

5. Competitive risk
6. Time to market risk

Time to market risk is well known within the materials community, and is often called the "20-year barrier", reflecting the period that is often required for new materials to move from lab stages to full commercialization (an imprecise point at which materials are considered fully accepted by the market and designers). The 20-year barrier has enormous capital implications, making investments in new materials unattractive, to the say the least, to venture capitalists and other investors.

The 20-year barrier is not itself inherent to materials development, but is composed of a series of obstacles that complicate and extend the period required to introduce materials. Once a promising material has emerged from the research lab, the obstacles it faces can be divided into two categories: materials production/technical obstacles and value chain obstacles. While it is popular among materials scientists to believe that these obstacles are caused by corporate obstinacy, there are logical reasons behind them. The costs required to build production facilities and to change value chains are real, and are extra high when many unknowns are present. Many system levels must change for introduction of new materials (requiring heavy investment), and the cost of failure is usually very high.

The internal complexity, depth in the value chain, and difficulty of change put materials in an interesting category from the perspective of general innovation theory. There are several theories that offer some insight into the behavior of materials, but none is complete. Because materials don't fit perfectly into the existing models, studying them provides an opportunity to build additional insight which can be used to strengthen the applicability of the innovation models.

The chapters that follow will use historical data from the plastics industry to show that there are strategies that can shorten, sidestep, and take advantage of the barriers that slow materials commercialization. By identifying the factors of materials that make these strategies work, it will be possible to use them in other industries in the context of general innovation theory.

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Chapter 3: The Pattern of Materials Commercialization

Introduction

Technically interesting devices or materials do not automatically become commercial successes. They must first be made into products that offer compelling value propositions and then must be placed into markets that can absorb them. The field of product development offers many competing processes to develop ideas, materials, and devices into valuable products[64]. The fields of marketing and strategy offer many competing methods for market selection[65].

The field of technology management operates at the intersection of marketing, strategy, and product development. One of the more popular branches of technology management is innovation. An important branch of innovation literature is focused on the concept of architectural modularity, in which market feedback is used to drive product development. Architecturally modular products contain components which can be reassembled in novel ways to meet unmet market needs[66]. This process has been shown to be a powerful force in reshaping industries, and in destroying the competencies of existing firms[67,68,69]. It has also been shown to be an important path to market entry and growth.

Abernathy and Utterback indirectly described architectural modularity in their seminal paper on industry cycles in 1975[70]. They showed that the basis of competition in the early stages of an industry is product innovation, in which many firms compete to find the product attributes that are most desirable to a market. The players make their wares with highly specialized labor and highly flexible processes so that features can be added or removed very quickly. As the market provides feedback, products are reassembled into new iterations with more appealing feature sets. In this stage (called the Fluid Phase), market share fluctuates wildly as new designs emerge.

This cycle continues until the most desirable set of features is obtained, and the product meets the needs of the market. When the best set of features is identified, the Transitional Phase begins. Product innovation slows, processes become more rigid, and a "dominant design"—a set of features that is most appealing to the market—emerges. Firms with designs that are not easily adapted to the dominant design leave the market, and the remaining firms begin to focus much more on process innovation, which reduces costs and increaes reliability. Then the Specific Phase begins, in which price, quality, and convenience become the basis of competition, and only the most efficient firms survive[71].

The easiest indicator to measure in the dominant design cycle is the number of firms in an industry. In later work, Utterback presented a characteristic pattern and stated explicitly that this pattern is not evident in materials. He further stated that materials and other process industries do not follow the dominant design pattern of industry development at all[72,73].

That materials do not follow this pattern is relatively easy to explain: iterative cycles are very difficult. There are two reasons for this. First, materials are rarely part of the direct consumer feedback loop. They are integrated into applications, and feedback related to materials is often confounded with feedback on applications. The two can be hard to separate. However, even if material information is discerned, the second problem remains: it is very difficult and very expensive to alter the properties of a material.

Materials are not assembled products, and their features are not modular: they are technically complex and highly interdependent. Materials properties are intimately intertwined with the quality of raw materials, control of manufacturing parameters, and forming processes. They can be refined only through careful research and extensive testing, and this research and testing falls in the realm of chemists, physicists, materials scientists, and engineers from many disciplines. Furthermore, the economies of scale present in the manufacture of materials are substantial; large, inflexible plants have proven to be the lowest cost production method. Altering materials often means that plants have to be altered as well, and the changes can be very slow and expensive. This is not to say that changes don't happen or that materials don't improve—they do—but not as quickly as assembled products.

Because they do not have the luxury of quick reconfiguration to meet market needs, market selection and positioning becomes the key skill that materials producers must develop. It is important that materials producers identify markets which are able to accept and utilize the properties of their materials. This is a particularly important issue in the early commercialization of a new material.

As was shown in chapter two, traditional materials marketing wisdom prescribes a "one size fits all" approach to market selection. The traditional approach is based on three factors, all of which seem to be logical predictors: cost of a material (compared to existing materials), properties of a material (also compared to existing materials), and large market size. The predicted outcome of the approach is also logical, and is quite compelling: if a material offers lower cost and higher performance in a large market, it is bound to quickly reach total market dominance and earn handsome returns for producers. Because there are significant pressures to generate early returns, traditional wisdom implicitly asserts the belief that the factors that lead to quick *placement* into a market are the same as the factors that lead to deep *penetration* in that market.

This chapter will use historical data from the plastics industry to demonstrate that this one-size approach is fundamentally flawed. Traditional materials marketing wisdom is applicable only after a material has earned credibility in the market and viability for producers.

It will be shown first that, contrary to popular wisdom, the factors that lead to quick market placement are different from the factors that lead to deep market penetration. It will then be shown that the successful plastics all followed a three-phase progression of market placement. In the first phase, the materials enabled simple, new applications that could not be done well without them. Having established a degree of credibility in the first phase, they then firmly established their commercial viability in a single platform application. With this application, they quickly and permanently displaced an incumbent material in a large market because their properties fit the needs of the users better. Only after having passed this platform phase were they able to enter the markets that fit the traditional model, with competition and replacement based on both lower cost and better properties.

Subsequent chapters will provide further resolution into the materials commercialization pattern. This chapter intends only to establish that the pattern exists.

Plastics Industry Data

The plastics industry has been selected as the primary data pool for this research. There are three reasons for this. First, plastics have had a significant impact on the products, markets, economies, and lifestyles that are present in the world today. Second, the industry is fairly new: all of the commercially important plastics have been developed in the last 90 years. Finally, the development of the plastics industry has been well documented. The chemical and processing aspects of the industry have been tracked by dozens of peer-reviewed technical journals[74] and by thousands of US patents.

There are two important contemporaneous sources of data on the business, markets, and applications of the plastics industry. The first is a monthly periodical called *Modern Plastics* (MP)—"the voice of the total plastics industry". Published continuously since 1925, it was, until very recently, the most prominent publication in the plastics industry[75]. It is an integrated magazine, with technical, engineering, and business sections, and the development of important applications was often tracked from early research in the technical section to full market penetration in the business section. Reviews of new plastics applications were printed monthly, and the *Modern Plastics* editorial staff went to great lengths to track the basic histories of new developments. Particular focus was given to the first applications of new plastics, and to the challenges faced and time required in commercializing them. It the 1950's and 1960's, it was not uncommon for an issue of MP to have more than 350 pages, mostly filled with advertisements and in-depth coverage of market developments. There are very few important plastics applications today whose inceptions, insertions, and growth were not covered in considerable detail.

In 1938, *Modern Plastics* began publishing an annual review of the US plastics industry. The review was remarkably thorough, covering sales data (as reported by manufacturers), application developments, market analyses, and technical developments for each commercially important material. The annual review serves as a record of the challenges and triumphs of the plastics industry through its own eyes. From 1938 to 1980, a technical review of the chemical and processing developments of the previous year, written by Gordon M. Kline, (MP Technical Editor and Chief of the Plastics Section (1935-51) and Polymers Division (1951-63) at National Bureau of Standards) was included[76]. This technical review is the authoritative record of the state of the art of the plastics industry during its development.

The other important record of the plastics industry that will be used as a source of data is *Synthetic Organic Chemicals* (SOC), a report published by the US Tariff Commission from 1917-1995. Publication of SOC was started in 1917 as an annual statistical survey of the American coal-tar chemical industry. It was mandated into a useful annual statistical survey of the plastics industry with the Tariff Act of 1930[77]. Included in SOC are the self-reported production volumes, sales volumes, and dollar values of all US sales in the plastics industry, classified by material categories. SOC provides thousands of data points on the industry, including the names of all producers of each material.

Several books have been written describing the evolution of the plastics industry. In cases where MP and SOC are unclear, these books have been consulted[78]. Primary data has also been obtained by interviewing some of the pioneers of the industry and by reviewing their memoirs.

The key data for this chapter come from a collection of *Modern Plastics* articles and the 1999 *Modern Plastics* annual review.

Dataset: Biggest Plastics Applications of 1998

It was noted earlier that the purpose of this research is to develop strategies and principles for accelerating the commercialization of new materials (not just plastics), under the assumption that those materials offer some technical value proposition—that their properties are somehow compelling to the market. Working under this assumption, the presence of value proposition becomes a control variable, and it is possible to focus on factors that are intrinsic to the market and to the actions of the players. It is therefore reasonable to examine only the patterns of commercialization of historically successful materials—those that offer a clear and compelling value proposition and became commercially important[79]. Since materials have little value unless they are integrated into applications, it is further reasonable to examine only the most successful applications of the most successful materials. For these reasons, the most successful applications of the seven most successful plastics will be examined in this chapter. This is not to indicate that a thorough examination of the unsuccessful plastics would not be equally telling—it would most likely yield very interesting results. However, this examination is beyond the scope of this thesis.

In 1998, the last year for which *Modern Plastics* provided reliable data, eight families of plastics accounted for 90% of total reported plastics sales volume (lb)[80]. These should be considered the most successful plastics. They are polyvinyl chloride (PVC), low density polyethylene (LDPE), linear low density polyethylene (LLDPE)[81], high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyurethane (PUR), and polyethylene terephthalate (PET). Because of its extreme similarity in composition, processing, and application to LDPE (it was not separated from LDPE in trade journals for nearly 10 years after its introduction), LLDPE is considered a special case, and will not be used in the following analysis.

52% of the 1998 sales volume of the seven largest plastics consisted of sales into 34 application categories with volumes larger than 300 million lb. These are the most successful applications of the most successful plastics, and will be the subjects of the analysis that follows. Descriptive histories were prepared of the introduction of each of these applications, with a particular focus on time to market, challenges faced during introduction, and cost factors at the time of introduction. More than 250 contemporaneous articles were utilized, in addition to 63 years of *Modern Plastics* annual reviews and dozens of US patents. In each case, data were substantiated by more than one article, with sources other than *Modern Plastics* consulted when possible.

There are several limitations to this dataset. First, the generalizability of the model is constrained by the examination of only the most successful applications of the most successful plastics. Its direct applicability is limited (at best) to new products with clear technical value propositions. This is deliberate, because this research does not attempt to predict or describe whether technical value propositions exist, but rather how to proceed once a technical value proposition is identified. The model built on this data will not predict the success or commercialization time of technically impractical materials, nor will it predict which properties of a given material will lead to commercial success.

Focusing only on the most successful applications of the most successful materials also makes it difficult to identify potential pitfalls with any model that is created. It is entirely possible that failed materials followed the same strategies with different results. However, there is little data in the literature on failed materials, making analysis of them very difficult. While limits of any proposed models will be discussed, the findings should be applied with caution.

The generalizability of the findings will also be limited by the historical nature of the data. It is possible that the market conditions in which the materials that will be examined are different from current conditions and that the model is no longer applicable. If this is true, the model would be purely descriptive and of limited use for future materials.

It is also important to question the reliability of data extracted from industry publications such as *Modern Plastics*. It is possible that MP offered insufficient coverage to some of the applications that are examined here. However, it will be shown that most of the applications that are examined were known well ahead of their insertions, and were expected to be commercially important. Data for those that were not known earlier were taken from articles which covered their development but were released slightly after their insertion into the market.

Modern Plastics and *Synthetic Organic Chemicals* were the dominant sources of information in the plastics industry for nearly seven decades. In the absence of other sources of substantive market records, it is impossible to completely disregard the notion of erroneous data. However, the status, reputation, and role of *Modern Plastics* and *Synthetic Organic Chemicals* make them the de facto record of the history of plastics application development, and the structure and goals of the publications lend credibility to their coverage.

Understanding Volume in Plastics

In order to identify a pattern of commercialization in plastics, it is necessary to understand more of the basic business facts facing the industry. The first important fact is that plastics are of little use unless they are integrated into an application. They are rarely specified, except in very general terms, by the consumer. The product/application manufacturer is the most common specifier of the exact material. This being the case, plastics can add many forms of value, ranging from cost savings (because of lower materials, processing, shipping, etc. costs) to value-added features for which consumers are willing to pay extra.

Plastics have been used in millions of specific applications, and have become the dominant material in a small portion of them. For convenience, the plastics industry groups the applications of each plastic family into categories according to a variety of classification schemes. The categories can be based on processing method (i.e. injection molding, blow molding, thermoforming), on broad application market (i.e. automotive, construction, consumer goods), on final form (i.e. film, sheet, bottles), or on specific application market (i.e. shower curtains, milk bottles, paint pails). Each category entails many specific designs and applications.

Some categories are more applicable to specific plastics, so *Modern Plastics* developed an aggregate classification system for its annual reporting in which the most applicable group of categories was used for each plastic. This makes it relatively difficult to compare categories across plastics, but gives an excellent annual snapshot of the position of each plastic. Table 3.1 shows the major plastics and the number of categories listed for 1998, the last year for which reliable data was published in *Modern Plastics* annual resin report[82].

Material	Number of Categories (MP 1998)	Example categories
HDPE	30	Sewer pipe, motor oil bottles
LDPE	17	Blowmolding, food packaging film
PET	6	soft drink bottles, ovenable trays
PP	16	Fibers and filaments, rigid packaging
PS	58	Toilet seats, tumblers
PUR	17	Bedding, industrial insulation
PVC	21	Textile coating, siding, pipe and conduit

Table 3.1: Number of categories and example categories for each major plastic, MP 1998.

It is easy to see from this table that each of the large-volume plastics is sold in a wide variety of applications. In 1998, 83 billion lb of plastic resin was sold. The smallest reported categories consumed about 3 million lb of resin and .5% of total sales of a plastic, and the largest reported categories consumed about 6 billion lb and over 50% of the total sales of a plastic.

The fact that all of these highly successful plastics are sold in many disparate applications shows that these plastics are all very versatile—they have a range of properties that makes them appealing to many markets. It follows that an important factor in the commercial success of a plastic may be the ability to be adapted to fit many needs.

However, while placement in many markets seems to be important to the commercial success of the large-volume plastics, placement is only part of the equation. Penetration into those markets must also be considered. Each of the large-volume plastics has established a dominant foothold in a few large application categories. Table 3.2 shows the largest categories for each plastic in 1998.

Material	Total sales volume (million lb)	Portion of total volume from applications over 300 million lb	Top 3 Applications
HDPE	14065	.44	Liquid food bottles Pipe and conduit Household chemical bottles
LDPE	7748	.41	Food packaging film Extrusion coatings Nonfood packaging film
PET	4330	.82	Soft drink bottles Custom bottles Thermoformed sheet
PP	13739	.61	Fibers and filaments Consumer products Rigid packaging
PS	6589	.16	Oriented film and sheet Vending and portion cups Cassettes/reels
PUR	5265	.55	Furniture foam Building insulation Transportation foam
PVC	14698	.66	Pipe and conduit Siding Windows and doors

Table 3.2: Biggest applications and portion of total sales of major plastics, 1998.

While these materials cannot be directly compared to each other because of discrepancies in category type, it is clear that the top categories account for a large portion (ranging from 16-82%) of total volume of each of the large-volume plastics. In fact, the top 34 application categories accounted for 42% of the total sales volume (in pounds) of *all* plastics in 1998.

It is useful at this point to acknowledge that placement of a material into an application is different from penetration of a material in an application. In order to reflect the active role of materials producers in developing applications, this thesis will refer to initial placement of materials in applications as "insertion". Insertion is an event--the first step in commercializing an application. Penetration, on the other hand, is a process, which is defined here as developing widespread use of a material in an application.

Differentiating insertion and penetration is a contribution made by this work to the general body of innovation, because it asserts that the conditions of insertion are different from the conditions of penetration. While this seems to be a general premise of the innovation literature, the author is unaware of any direct citations where it is explicitly stated.

The implications of this idea are clear: since insertion is the first step, it should be the first focus in the commercialization of a new material.

Is Compelling Value Proposition Enough for Quick Insertion?

Given the pressure to generate profits quickly upon commercialization, the ideal situation for a marketer of new materials would be achieve quick insertion and rapid, deep penetration of a large application market. As presented in chapter 2, traditional wisdom indicates that a compelling value proposition—lower cost, higher performance, and attractively sized markets—would lead to both[83]. Since they achieved such deep penetration and have enjoyed long dominance in their markets, it is obvious that the 34 biggest applications of 1998 offer compelling value propositions. If traditional wisdom were correct, one would expect to see at least three patterns. First, one would expect that insertion of the plastics into their largest application markets would come very soon after commercialization, and would be relatively uniform among the applications. Second, one might also expect to find the reciprocal—that the earliest plastics applications would become very large. Finally, one would expect to find a high negative correlation between insertion time and application category size.

Table 3.3 shows the commercialization year of each plastic, and the insertion year of each of the applications larger than 300 million lb. It also shows the elapsed time between commercialization of each material and its insertion into each application. This elapsed time will be referred to as "insertion delay" from here forward.

Plastic	Application	Sales, Million lb (1998)	Material Commercial Year	Application Insertion Year	Elapsed time (years)	First Application?
HDPE	Liquid food bottles[84]	1334	1957	1963	6	no
HDPE	Household industrial chemical bottles[85,86,87]	954	1957	1958	1	no
HDPE	Grocery sacks[88,89]	648	1957	1972	15	no
HDPE	Trash and can liners[90,91]	406	1957	1978	21	no
HDPE	Pipe and conduit[92]	1240	1957	1960	3	no
HDPE	Pails[93]	930	1957	1958	1	no
HDPE	Crate and totes[94,95]	312	1957	1961	4	no
HDPE	Industrial drums[96]	301	1957	1958	1	no
LDPE	Food packaging film[97]	1018	1941	1947	6	no
LDPE	Extrusion coating[98]	958	1941	1949	8	no
LDPE	Non-food packaging film[99]	856	1941	1947	6	no
LDPE	Stretch and shrink[100]	310	1941	1965	24	no
PET	Soft drink bottles[101]	1975	1967	1975	8	No
PET	Custom bottles[102,103]	1570	1967	1979	12	No
PP	Fibers and filaments[104]	3610	1958	1958	0	yes
PP	Consumer products[105]	1660	1958	1959	1	no

Plastic	Application	Sales, Million lb (1998)	Material Commercial Year	Application Insertion Year	Elapsed Time (years)	First Application?
PP	Rigid packaging[106]	1329	1958	1960	2	no
PP	Oriented film[107],	995	1958	1961	3	no
PP	Transportation[108],[109]	460	1958	1959	1	
PP	Appliances[110]	302	1958	1959	1	no
PS	Oriented film and sheet[111]	380	1938	1957	19	no
PS	Vending and portion cups[112]	340	1938	1956	18	no
PS	Cassettes, Etc[113]	330	1938	1965	27	no
PUR	Furniture (padding) [114]	866	1953	1954	1	no
PUR	Building insulation[115]	780	1953	1960	7	no
PUR	Transportation (flexible) [116]	604	1953	1955	2	no
PUR	Household and commercial refrigeration[117],[118],[119]	322	1953	1956	3	no
PUR	Rug underlay[120]	302	1953	1957	4	no
PVC	Pipe and conduit[121]	5904	1938	1953	15	no
PVC	Siding[122]	2148	1938	1961	23	no
PVC	Windows and doors[123]	538	1938	1958	20	no
PVC	Wire and Cable[124]	482	1938	1938	0	yes
PVC	Extruded packaging[125]	352	1938	1948	10	no
PVC	Pipe fittings[126]	308	1938	1954	16	no

Table 3.3: Elapsed time between commercialization of new plastics and insertion of major applications.

Uniform Quick Insertion

A histogram of the elapsed time between commercialization of the major plastics and their insertion into major applications is shown in figure 3.1.

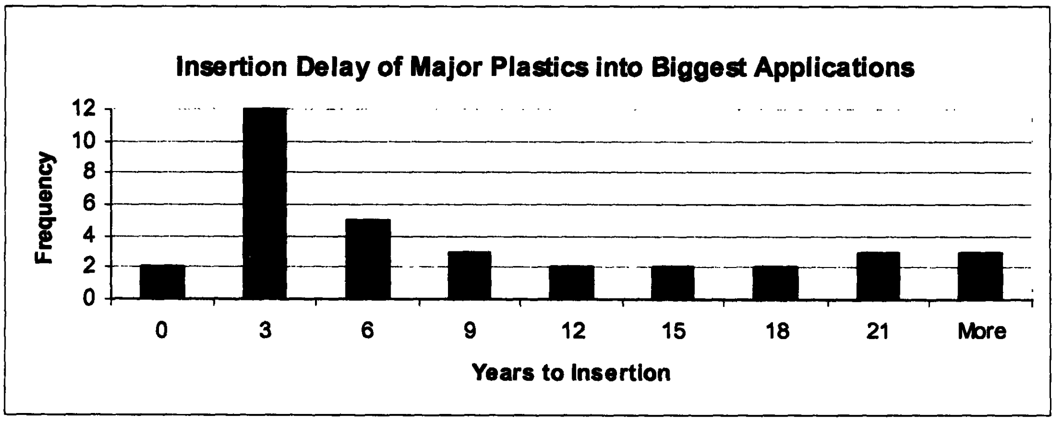

Figure 3.1: Histogram of time elapsed between introduction of new materials and their insertion in biggest applications.

This chart shows that the skew of insertion of materials into major applications is clearly toward the early years after commercialization. The largest group of applications (comprising slightly more than 1/3 of the total) was introduced between 1 and 3 years of the commercialization date of the plastic. In the materials world, an insertion delay of 1-3 years is indeed quite rapid, and this fact would seem to validate the wisdom of the traditional materials marketing approach. However, the statistics of the pool directly contradict it. Over 50% of the biggest applications of the major plastics were inserted more than 5 years after the commercialization of the plastics. The mean insertion delay for the pool is 8.5 years (8.19 years with high and low delays removed). The standard deviation of the pool—8.188 years (7.61 years with high and low delays removed)—is equally telling: a very high degree of variability exists in the insertion delay of the major applications.

Did First Applications Get Big?

It has been shown that more than 1/3 of the biggest applications of 1998 were inserted within 1-3 years of commercialization of their respective plastics. However, only two of the 34 biggest applications of 1998 were the first for their respective plastics, although this can be said of one of them only because of very broad categorization. PVC wire coating was the first commercial use for PVC. It was proposed for use in boiler rooms because of water resistance and flame resistance and grew to be the most commercially important wire coating material available today[127]. PP fibers and filaments are slightly more deceptive—the first uses for PP were in marine ropes and lawn chairs, which are both relatively small volume applications today. The real growth of PP fibers and filaments has been driven by the use of PP in carpet fibers, which didn't exist until several years later, were sold to a different market, and required significantly different production and processing capabilities[128].

If the category deception is acknowledged and PP rope fibers are excluded, the first application of a plastic turned out to be one of the largest applications in only one of the seven major plastics (PVC). The first applications of the other six materials did not make the list.

Correlation Between Sales and Insertion

If value proposition is the main driver of both quick insertion and deep penetration, a strong negative statistical correlation between insertion time and overall sales volume of the biggest applications should exist. These two variable were tested, with insertion time coded "COMTIME1" and overall volume coded "SALES"; the results are displayed in table 3.4. No relationship was found.

-

Correlations

		SALES	COMTIME1
SALES	Pearson Correlation	1.000	-.015
	Sig. (2-tailed)	.	.934
	N	34	34
COMTIME1	Pearson Correlation	-.015	1.000
	Sig. (2-tailed)	.934	.
	N	34	34

Table 3.4: Correlation matrix of insertion periods and overall sales of major applications in 1998

Value Proposition Alone is Insufficient

The experience of the most successful applications of the most successful plastics stands in contrast to the traditional materials marketing wisdom presented in chapter 2. Only half of the major applications were introduced within five years of commercial availability of the major plastics, despite the presence of factors (whatever they might be) that led to very deep penetration of the plastics into all of the major applications. The average insertion time of materials into their most successful applications was over eight years. The first application of only one major plastic grew into a major application category by 1998. There is a very high degree of variation in the insertion periods, and no correlation exits between the depth of penetration (as measured by overall sales) and the insertion period.

These facts indicate that quick insertion is not a simple function of value proposition. As stated earlier, all of the major plastics offer compelling value propositions to their major applications—but these propositions did not lead to uniform quick insertion. Of equal importance is the indication of the data that the factors that lead to quick insertion are different from the factors that lead to deep penetration. In the preceding section it was proposed that insertion and penetration are different stages in the life of a material. It is shown here that the factors that influence each should be explored and treated differently. From this point forward in this thesis, the factors that affect quick insertion will be called "insertion factors", to distinguish them from the "penetration factors" which are presumed to stem from the value proposition of major materials. Insertion factors will be explored more deeply in chapters four through six; penetration factors will be explored in chapter seven.

The Enabler Phase: Establishing Credibility

Having established that the major plastics did not follow the patterns predicted by traditional materials marketing wisdom, it is necessary to identify the pattern that they did follow. The earliest commercial applications of a material were important not only because they were the first opportunities to generate cash for the materials producer, but because they introduced a material to both the market and to processors.

Table 3.5 shows the earliest commercial applications for 14 important plastics, as reported in *Modern Plastics*. The major plastics of 1998 are listed first, followed by other plastics.

Plastic	**Earliest Applications**	**Year**	**Reason for Adoption**
HDPE[129]	Hula Hoops	1957	"not too flexible, not too rigid, and safe for children"
LDPE[130]	Radar wire	1943	"oustanding qualities as a high frequency dielectric"
PET[131]	Bearings	1967	"allows higher loads and speeds than nylon bearings. . .resistance to oils. . .good resistance to high temperatures"
PP[132]	Marine rope/ integral hinge coolers	1958	good strength/weight ratio--"cannot become waterlogged or change its properties because of water absorption"
PS[133]	Capacitor insulation, synthetic gems (costume jewelry)	1938	"excellent dielectric properties. . .low power factor"
PUR[134]	Foam stuffed tubbable toys	1953	"the first stuffed animal in toy history that can safely be laundered in a washing machine. . .thanks to the moiusture resistance of this type of stuffing. . .mildewproof, non-allergic"
PVC[135]	Wire coating	1938	"extruded insulation of comparatively permanent flexibility"
ABS[136]	Tote boxes for textiles	1948	Lightweight (also very tough)
Acetal[137]	Fishing rod parts, toy train bases, egg beater gears	1959	Moldability with "strength, rigidity, dimensional stability, and heat resistance...oustanding corrosion resistance"
Nylon[138]	Dr. West's Miracle Tuft Toothbrush	1938	"dramatic reduction in production costs...ability to control bristle texture..(not) prone to bacterial growth"
PTFE[139]	Gaskets and seals for Manhattan project	1942	Corrosion resistance
Acrylic (PMMA)[140]	Highway reflectors/molded spectacle lenses/aircraft windshields	1938	"nearest approach to glass yet developed", but may be "formed or molded into many useful shapes"
Polycarbonate (PC)[141]	Tiny electrical connectors	1958	"high impact strength, good insulation properties, and good color and gloss properties"
Reinforced Polyester[142]	Radomes	1942	Radar transparency

Table 3.5: First applications for 14 commercial plastics. Seven largest plastics of 1998 shown in bold.

There are several common threads amongst these applications. Possibly the most important common thread is the fact that each application solved a problem for its users. These plastics were not simple improvements over incumbent materials in these applications—their properties enabled fundamentally new product features. Furthermore, the materials features enabled products that were not simple improvements over incumbent competitors— users of these products *could do things that they could not do* *before*: unmet needs were filled. In fact, performance dominated cost in these applications: cost was listed as a factor only in Dr. West's Miracle Tuft toothbrush (see nylon, table 3.5).

The second important common thread is that, with the exception of reinforced polyester radomes and PMMA aircraft canopies, all of the applications were fairly simple—they had few parts and were integrated painlessly into their value chains. Many of them, such as the hula hoop and Dr. West's Miracle Tuft toothbrush, were standalone products for which a simple new value chain was assembled. They did not require tremendous research to develop, were made using existing equipment, and were sold through existing channels. Others, such as polystyrene capacitor insulation, PVC wire coating, and acetal fishing rod gears were not stand alone products but were drop-in replacements for existing parts. They worked with existing machinery, and few other parts in the final application were affected by their adoption. In fact, substitution was only visible to the buyer by the enhanced performance that the materials enabled.

The third common thread is that the markets for most of the applications were relatively small. It was noted in the previous section that PVC wire coating is the only first application that became one of the largest for any of these plastics. That these markets are small is significant, because it strongly contradicts traditional materials marketing wisdom: how excited could a materials producer be about the costume jewelry market after spending several years and millions of dollars to develop polystyrene? In order to recoup high R&D costs, it would seem important to insert new materials into large, attractive markets as soon as possible. Memoirs of some of the early materials pioneers indicate this pressure existed, but the plastics were still used in small market applications first[143].

The fourth common thread between these applications is that the materials solved problems that were relatively new. Researchers and consumers were still searching for the best solution, and were willing to take risks with new materials in order to find it. In the dominant design parlance, the applications were in the fluid state. Utterback and Abernathy have shown this to be very important, since the value chains of such industries and markets are flexible and are more able to accommodate change than established value chains[144]. The expectations of applications in the fluid state are also lower—users tend to be more willing to tolerate product failure. PS capacitor insulators, PVC wire coating, the PMMA aircraft canopy, and the reinforced plastic radome all solved new problems in applications that would become quite inflexible and very intolerant of failure as they matured.

When woven together, these common threads form a pattern of first phase of applications for new materials, which can be called the "enabler phase". Each application in this phase was relatively simple, solved a relatively new problem, had a relatively small market, and enabled people to do things they couldn't do before. The entrance of PUR into foam stuffed tubbable toys and PMMA into acrylic highway reflectors are excellent examples of applications in the enabler phase.

Polyurethane in Foam Stuffed Tubbable Toys

Polyurethane (PUR) was developed by Otto Bayer in Germany during World War II but was not commercially produced in the United States until the Mobay Chemical Company was formed to commercialize it in 1953 (Mobay was a joint venture of Monsanto Chemical Company of the United States and Farbenfarbriken Bayer, A. G. of Germany)[145,146,147]. PUR was first introduced in foam form, and was purported to be "self-extinguishing, (would) not age, oxidize, or rot, (was) not attacked by oils, greases, or solvents" and was "moth proof, verminproof, and non-allergic to skin". In short, it was claimed to be better than rubber foam (which dominated the foam market in 1953) in every way. Its properties made it especially attractive as a natural sponge replacement, and at least two manufacturers undertook programs to develop it into a household sponge. Unfortunately, PUR development was slowed in this application because of some technical difficulties, not the least of which was the hydrophobic nature of the material. Although it was highly porous, the walls did not absorb water, and the proper cell structure had to be designed for it to work.

It was this hydrophobic property, along with the resilience of the material, that made PUR perfectly suited for use in the Bendix "All"—washable teddy bear. This bear was made by the Ideal Toy Co. and was "co-sponsored by Bendix and Mobay". It had a DuPont Orlon acrylic "fur" shell, and was stuffed with PUR foam. Both Orlon and PUR were waterproof, and tests showed that the bear could be repeatedly placed for "30 minute periods in an autoclave under 18-lb steam pressure and at temperatures of 225° F". Having proven itself in this harsh test, the Bendix bear was sold to the public as the first stuffed animal of any kind that could be washed in the washing machine[148]! Figure 3.2 shows a Bendix bear.

Figure 3.2: Mobay/Bendix bear[149].

The Bendix bear followed the enabler pattern very well. It was a simple, stand alone product that could be sold with through existing channels with minimal impact to the value chain. Its market was relatively small and relatively new—children in homes with washing machines in 1954. Most importantly, it let people do something they couldn't do before: wash their toys in the washing machine.

Acrylic (PMMA) in Highway Reflectors

A new problem emerged as the WPA highway projects of the Great Depression neared completion: the lights on cars had not kept up with the speeds that the new highways afforded. At night time, cars were prone to drive off the highway since they could not see the curves. Instead of electrifying and lighting the highways, it was shown that crystal-clear, moldable Lucite and Plexiglas (the tradenames for PMMA) could be made into shapes that would "return a narrow beam of illumination" from the side of the highway[150].

The shapes, of course, were cat eye highway reflectors that are so common today. This type of reflector has a very unique structure, which guides beams of light through three reflective surfaces, and then redirects the light back into the headlights of the oncoming car. To be most effective, a material with very high transparency must be used. Fine glass has similar transparency to PMMA, but the second requirement made PMMA the only material that could make the reflector in 1938: excellent moldability. The compression molding process that was used to press PMMA into the reflector shape would have shattered glass. Furthermore, the toughness of acrylic made it more suitable for the harsh environmental conditions that were encountered beside the roadways. A Smithsonian archive photo of these reflectors is shown in figure 3.3.

Figure 3.3: Acrylic reflectors on Michigan highway[151].

These reflectors were shown in 1938 to be visible for one mile, and made a "definite contribution to the safety and utility of highways at night", according to the chief of the United States Bureau of Public Roads. At $340/mile, these reflectors were not cheap, but were considerably more economical than the alternatives of electrifying and lighting the highway grid or of continuing on with the high accident rate.

Like the Bendix bear, acrylic highway reflectors followed the enabler pattern well. They were simple, stand alone products that could be installed by existing highway crews with minimal training or retooling. Their market was relatively new (though not particularly small)—paved highways with curves. Most importantly, they let people do something they couldn't do before: drive safely on highways at night.

Enabler Phase Applications Establish Credibility

The enabler phase appears to have filled very important roles in commercial development of the commercial plastics. By solving new problems in simple applications, enabler applications were able to sidestep many of value chain and design-in barriers that might have slowed entry into more established applications, so that commercial material production and processing could begin. Enablers allowed materials producers and processors to learn to use and make the new plastics in a "real world" situation which was relatively fault tolerant—potential failure modes were revealed and corrected without the enormous liability that could accompany mainstream markets. Forming and processing challenges were also solved, making the material more broadly applicable.

In addition to process development, enabler applications served as extended evaluation tools. Enablers introduced new materials to the market and to other potential users, who could observe and evaluate their performance. Producers used enabler applications as case studies to convince hesitant customers in major markets of the utility of their material. In short, enablers were the key to solving the dilemma that one materials executive described: "people line up to be the second buyers of new materials, but no one wants to be first"[152].

In most cases, the enabler phase included several commercial applications because the knowledge and credibility necessary for integration of new materials into mainstream markets was not necessarily generated by a single application.

Platform Applications: the Path to Further Growth

While enabler applications were important steps in the commercialization of the major plastics, they were rarely large enough to carry the material to full profitability. The preponderance of insertion delays in the 1-3 year period (see figure 3.1) shows that enablers preceded a concerted push by producers into new applications. Although the majority of the early applications of every plastic were destined for commercial failure, one major success was found by each major plastic in the early years of commercialization. In each case, this major success punctuated the enabler phase, and facilitated mainstream growth. For this reason, it will be called a "platform application".

One plastics executive recently commented that every major plastic has found a "killer application" early in its life[153]. In the software industry, a killer application is a program that is "so successful that it corners the market and/or inspires users to upgrade their systems in order to use it"[154], thereby creating a path for future growth of the system. While this definition is not directly applicable to the plastics industry, it can be altered to become a definition of the platform application: "the first *large-market* application in which a plastic is so compelling that all application manufacturers must use it in order to be competitive, thereby creating a path for future growth of the plastic in other major markets". The term "large market" is intentionally broad in this definition, because the scale required for a market to be considered "large" depends on the size of embedded investment in a material. As a general rule with platforms, the first "large market" application should be considered the one that is large enough to create reasonable return on the development investment of a material.

This definition was used to generate the list in table 3.6.

Plastic	**Platform application**	**Platform year**	**Replaced?**	**Reason for adoption**
HDPE[155]	Household industrial chemical bottles	1958	Glass bottles	6 to 1 consumer preference, "Less commercial look", "more feminine in appeal", reduce shipping costs, resist denting, will not rust, do not leak, more easily handled, color can be molded in
LDPE[156]	Polyethylene food pacakges	1946	Paper, cellophane	transparency, toughness, low temp toughness, chemical inertness, resistance to tastes and odors
PET[157]	2 liter bottles	1975	Glass bottles	Safety, lighter weight
PP[158]	Consumer products (luggage)	1960	PE, PS	good impact resistance, resistance to high and low temperatures, worked on same tools,
PS[159]	Refrigerator parts	1940	Metal	dimensional stability, low temperature performance
PUR[160]	Seat cushions	1957	Rubber foam	flame resistance, lighter than latex, slow springback (to provide firm seat), excellent ventilation,
PVC[161]	Shower curtains/rain wear	1941	Glass/rubber	waterproof, mildew resistant, formable
ABS[162]	Chemical/DWV pipe	1955	Iron, lead	stiff, light, corrosion resistant, chemical resistant,
Acetal[163]	Auto parts	1960	Zinc	lighter weight, moldable
Nylon[164]	Hosiery	1940	Silk	strength, clarity, resilience (runless stockings)
PTFE[165]	Nonstick coatings	1950	n/a	nonstick properties
Acrylic [166](PMMA)	Aircraft canopies	1940	Glass	lightweight, moldability, clarity
Polycarbonate[167]	Tough glazing	1964	Glass	toughness, clarity
Reinforced Plastics[168]	Boats	1944	Metal	lightweight, moldability, corrosion resistance

Table 3.6: Platform applications for commercial plastics. Seven largest plastics shown in bold.

While the credibility necessary to emerge from the enabler phase could be generated by one or many applications of a material, each material had only one platform application. Like the enabler phase applications, the platform applications of the major plastics had several common threads. First, each of the platform applications (except Teflon[169]) replaced an existing material in a major application. Second, each substitution was based on utility from superior relevant properties of the plastic (not low cost). In fact, all but one plastic (ABS) is still, in 2004, the dominant material in its platform application, suggesting that the properties were nearly perfectly matched to the needs of the application. Third, each platform market was very large at its inception and has remained large—all but one was still listed as a category in the 1998 *Modern Plastics* review, and the one that wasn't listed (PVC shower curtains) was simply overshadowed by even larger applications. A fourth characteristic of platform applications will be shown in chapter four: they were all recognized as potential applications during research and development of the plastics. The final (and very important) characteristic of platform applications is that they provided a springboard into other large markets.

HDPE Detergent Bottles

High density polyethylene's (HDPE) conquest of metal containers in detergent bottles in the late 1950s is an excellent platform application example. The development of HDPE was announced in 1955 by Phillips, and the material was formally released in 1957[170]. The material was sold to the industry as a superior replacement to LDPE, offering higher heat resistance and higher modulus (stiffness)[171]. Its enabler application was the Hula Hoop (1957), a thinwalled tubular ring that could be rotated around the hips of children[172]. While the Hula Hoop achieved considerable success (1 million lb/week at its peak), it was hardly enough to justify the enormous investment that had been made by several producers in the catalyst technology required to produce HDPE[173,174]. Because of its stiffness and temperature resistance, it had been proposed in early publications as a potential material for high quality bottles[175].

There were many segments of the bottle market in the late 1950s, ranging from oil bottles, which were metal/cardstock composites, to soft drink bottles, which were glass, to milk bottles, which were also glass. While HDPE would eventually find applications in all of these applications (except carbonated drinks), its chemical resistance, light weight, and toughness made it most attractive to 400 million unit/year dish detergent market[176]. Prior to the HDPE invasion, detergents were packaged in metal containers, and were primarily sold to consumers through neighborhood stores.

Hercules Hi-fax resin was used in the first HDPE detergent container, a shapely pink bottle for Lever Brothers' new Swan detergent. Its cost was slightly higher the same as glass bottles, but it offered several advantages. First, it matched the Swan image. Swan was designed to "overcome consumer objections to previous detergents. . .which were considered 'hard on the hands. The pink colored HDPE offered a "less commercial look and more feminine appeal", would not "rust, dent or leak", and could molded into appealing shapes, making it seem less harsh[177]. It was preferred 6:1 by consumers, and was much lighter, offering savings in shipping[178].

Within one year of this introduction, six major detergents manufacturers-- representing half of the detergent market-- had switched to plastic bottles[179]. Six producers had entered the market with bottle resins, and several glass and metal manufacturers had begun processing plastic bottles[180]. However, even after a year of production, the cost of the plastic bottles was higher than that of metal or glass bottles[181].

The appeal of the bottles to consumers was real: one detergent manufacturer reported 25% increases in market share when it changed its package[182]! The replacement of glass bottles by HDPE was complete by 1961, when over 500 million bottles were sold[183]. Figure 3.4 shows a plastic bottle used by one of the players.

Figure 3.4: Chiffon HDPE bottle[184].

It was a short jump for HDPE to move from the detergent bottle platform into its next big market: bleach bottles. The bleach bottle market, in which HDPE offered safety and huge weight savings (58 lbs/box of bleach) to housewives, absorbed 80 million lb. of HDPE within two years of introduction[185,186]. Figure 3.5 shows two examples of early bleach bottles.

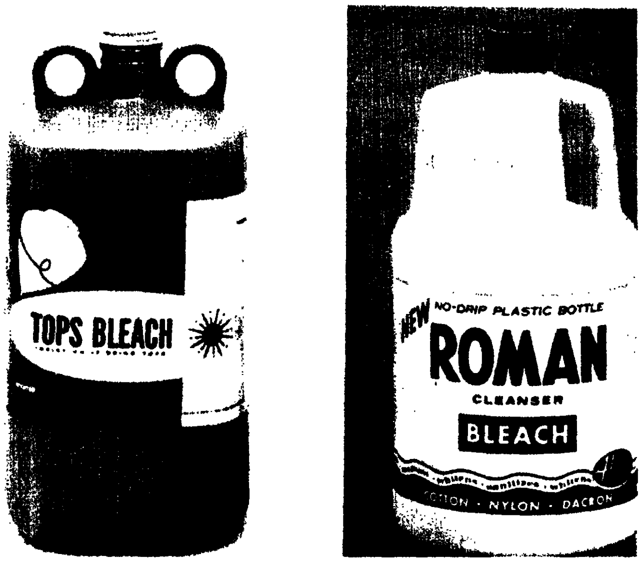

Figure 3.5: Early plastic bleach bottles[187].

The experience gained by producers in making detergent bottles, and the experience of consumers with those bottles, were important factors in 1963 when HDPE was inserted into what would become its largest market: milk bottles.

The move of HDPE into plastic detergent bottles showed all the characteristics of the platform applications. First, it replaced a different material (metal) in a major market (detergent bottles). Second, the replacement was based on property advantages (consumer appeal, rust proof, dent proof, no leaks), not on low cost. Third, HDPE is still the dominant material in detergent bottles, and household industrial chemical bottles remain one of the largest categories for HDPE. Fourth, the application was recognized years before it was introduced. Finally, (and most importantly), detergent bottles provided a platform for other major applications: bleach bottles and milk jugs.

Platforms are Key to Commercial Success

Platform applications filled important roles in the commercial development of the major plastics: they established commercial viability. They were the first applications that were likely to generate profits large enough to justify the investment necessary to develop the major plastics[188]. They forced the development of processing methods and manufacturing parameters that would lead to consistent, reliable end products. They also forced markets to recognize and become familiar with the new plastics, while simultaneously further proving the utility of the materials. An important result of this exposure was the entry of additional producers into the market, creating new competition which resulted in lower costs and superior products[189].

In short, the emergence of a platform application marked the end of the enabler phase, and was a key step in creating a mature material (although applications with similar characteristics to the enabler applications would continue to appear throughout the lives of the plastics). After conquering their platforms, the plastics were proven—markets were familiar with them, processors could make parts with them, and application producers could design with them. They could launch from their platforms into other markets, where they were ready to compete with existing materials on a level playing field.

The Widespread Substitution Phase: Realm of Traditional Materials Marketing

According to traditional materials marketing wisdom, market selection for materials should focus on three factors: cost of the entrant material compared to incumbents, properties of the entrant material compared to incumbents, and overall market size. Thus, if a material is lower cost and offers better properties in a large market, this wisdom suggests that it is bound for success.

This wisdom is certainly useful as a "no-go" test for market assessment: if a new material is more expensive and offers worse properties, it is unlikely to succeed. However, the opposite is not necessarily true. Technical difficulties, consumer unfamiliarity, value chain issues, competitive response, and codes and standards can all prevent a superior material from entering a market. However, once a material has established itself in the enabler phase and has found a platform application, many of these challenges are eliminated. Having been established in these applications, market hesitations and switching costs for the new material are reduced, and the material can compete on level ground with existing materials. The widespread substitution phase begins, and traditional materials marketing wisdom reigns supreme. It is in this phase that long-term profits are generated, and in this phase that materials become commodity products.

In the widespread substitution phase, entrant materials are able to compete with existing materials in large markets based on lower cost as well as on superior performance. While some of the switches create lasting dominant positions (similar to those in the platform applications), many of the switches are more fleeting. Incremental cost differences can trigger massive materials switches (assuming that switching costs, which will be discussed in chapter 5, aren't prohibitive). Materials switches can also be precipitated by other factors, such as fashion and the whims of the market.

The battles between materials in the widespread substitution phase can be fierce, with different materials serving different segments of the same market. Examples are visible in many markets today. For example, there are battles in the auto industry between aluminum and steel for auto bodies, between leather and leatherette (vinyl) for seating surfaces, and even between ABS, PP, and PUR for dashboard surfaces. While these materials are clearly used in different segments (aluminum, leather, and PUR are only available on upscale automobiles), examples from the housing industry show more subtle competition. "Wood" floors can be solid hardwood, engineered laminate, and paper/melamine coated fiberboard (Pergo). Carpets are made from PP fibers, nylon fibers, polyester fibers, and even recycled vinyl.

It appears that the eventual winners are the materials whose properties align perfectly with the needs of an application at the least cost—they are the lowest cost perfect matches. The lowest cost perfect match concept has broad strategic implications for materials, and will be discussed in chapter 7. The competition among established materials for the washing machine agitator market is an example of both competition in the widespread substitution phase and the principle of the lowest cost perfect match.

Washing Machine Agitators: a Race to the Bottom

The first modern, electric washing machine was introduced in 1908 by the Hurley Machine Company of Chicago, Illinois[190]. The Maytag Company introduced the next major breakthrough in clothes washing technology in 1922: the agitator, which forced water through clothes instead of pulling clothes through water[191]. Early agitators were metal, mostly aluminum. Aluminum was well suited to the application: it was light weight, castable, strong, and relatively corrosion resistant. Although it dominated the market for awhile, it faced a tough competitor in 1941: phenolic, which displaced aluminum in several machines based on "greater utility and lower cost"[192]. Phenolic, which had established itself in electrical parts and consumer products, was better suited to agitators than aluminum in many respects. It was more corrosion resistant, lower density, and more attractive to "housewives"...who were "said to like the color"[193]. Figure 3.6 shows a phenolic agitator.

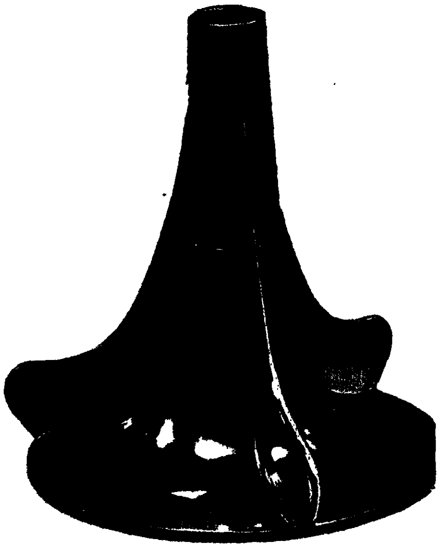

Figure 3.6: Phenolic agitator.

Phenolic's attack on aluminum was accelerated in 1947, when plunger molding and die preheating made it possible to produce phenolic agitators "faster than diecasting"[194]. By 1953, 12 million lb. of phenolic was used in washing machines, representing approximately 3 million agitators—a significant portion of the market. A 1955 survey of producers showed that 23 of 25 used phenolics, which had become especially appealing because of their resistance to corrosion by the detergent-type laundry soaps that had taken the market by storm[195,196]. Its lower cost per cubic inch also helped solidify its position.

As would be expected, sales of phenolic agitators largely reflected the trends of the durable goods industry through the late 1950s[197]. Agitators were sold to manufacturers for $1 in 1961, and were well-proven and highly reliable. Overtures by the nascent polypropylene industry to enter the market were considered ridiculous by phenolics producers, who said they "had nothing to fear"[198].

Kelvinator's introduction of the first polypropylene washing machine agitator in 1963 showed that the phenolic producers had grown overconfident[199]. Polypropylene, which had proven itself in luggage and chairs, did not perform as well as phenolic in washing machine agitators—it was softer and could become "limp" at washing machine temperatures. At the time of its introduction, PP was more expensive than phenolic, but its thermoplastic nature gave it attractive advantages in molding speed. Furthermore, the price of PP had shown a downward trend while phenolic had held steady for several years, indicating to washing machine manufacturers that PP might become far more attractive in the near future[200].

By 1964, the price of polypropylene had indeed dropped further, and PP had claimed nearly 10% of the agitator market. Three types of PP agitators had been introduced, and five more were expected in 1965[201]. The expected switch did not come, and phenolics regained in 1965 at least half of the market share that had been lost, citing that the mechanical properties and price of phenolic remained attractive, and also citing that their previous predictions of continued dominance were right[202].

Unwilling to give up the fight, PP makers countered by teaching appliance makers about designs with a "degree of flex action", which could not be matched by phenolic[203]. Furthermore, PP began to replace metals in many other appliance parts, particularly the wash tub[204]. This gave appliance makers more experience in molding large thermoplastic parts, and the agitator added to economies of scale in manufacturing. At this point, PP was clearly less expensive, and its limp hot water properties had been designed into strengths. It was the lowest cost material that was good enough for customers.

Phenolic sales in washing machines dropped from a high of 24 million lb in 1966 to a mere 7 million lb. by 1971, and were removed from Modern Plastics as a category in 1972, never to return[205],[206]. Washing machines today use PP or HDPE agitators, with battles for individual products fought on very small differences in cost and properties[207].

The agitator battle was a typical one during the widespread substitution phase. Traditional materials marketing wisdom held—materials competed for large markets based on incremental differences in cost and performance. However, this type of competition took place only after the completion of the enabler phase and the establishment of a platform. The potential cost savings of PP in washing machine agitators must have been obvious to both PP producers and appliance makers, but PP was unable to make inroads until it had completed its enabler phase (dominated by ropes, fibers, and portable coolers) and established its platform application—luggage. It was then given a chance to perform, and several years passed before acceptable designs were produced.

Another important point of the widespread substitution phase was also highlighted in this battle: there are no guarantees. Phenolic had passed its enabler phase and established its platform application before the advent of the agitator, but it did not displace aluminum for nearly 20 years, despite obvious advantages. Phenolic producers believed that their product was immutable in the agitator market, and the entire business was destroyed by PP. It is likely that PP producers believed the same thing, until HDPE entered the market.

In this story and others, plastics demonstrated that the only safety in the widespread substitution phase comes from being the lowest cost material that meets the exact needs of the market. This condition can be filled many ways—some materials take dominant positions in applications because their unique properties are perfectly suited to the applications. In other cases, several materials can do the job, and cost becomes the most important driver. It is significant that both PP and HDPE can work in washing machine agitators, because there are many applications that do not need the exact unique properties of a material. They simply need something that is good enough, and the competing materials are simple commodities.

The overwhelming majority of competition for applications occurs between materials that are in the widespread substitution phase, and this fact provides insight into the application of traditional materials marketing wisdom to new materials. If the conditions facing new materials are not explicitly identified, then they appear face the same challenges as existing materials. This is logical but false. New materials display different behavior than existing materials because they face different conditions, and these conditions make them better suited to enabler applications than to widespread substitution or platform applications. Since traditional materials marketing wisdom seems to hold in the widespread substitution phase, it needs to be amended to account for new materials. The next two chapters will discuss the conditions and challenges faced by new materials, and chapter 6 will present strategies to amend traditional wisdom.

Conclusion

An examination of the most important plastics applications has shown that the factors that lead to quick application insertion and deep market penetration are different. In particular, it is clear that the presence of a clear value proposition, although necessary, does not necessarily lead to uniformly quick market insertion. For this reason, the traditional materials marketing approach (in which producers focus on attacking the existing markets of similar materials and winning with incremental cost and performance advantages) should not be applied in all situations.

The traditional approach is streamlined to achieve penetration, and is sound advice for most battles between established materials. However, new materials are different from established materials. Insertion factors dominate until the materials are fully established and ready to play by the same rules as older materials. A clear three phase pattern was observed in the commercialization of successful plastics. Traditional materials marketing wisdom was largely inapplicable until the third phase. The pattern is shown graphically in figure 3.7.

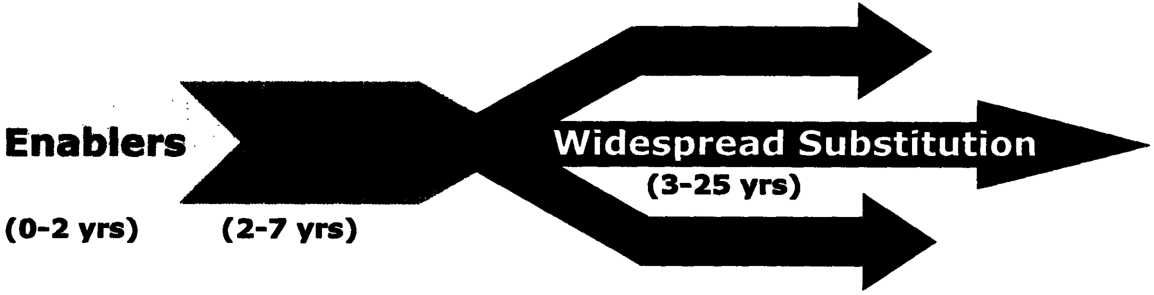

Figure 3.7: Commercialization pattern of plastics.

Important milestones were achieved in each phase of the commercialization pattern, and the applications shared common characteristics. The milestones and characteristics of each phase are shown in table 3.7.

	Enabler Phase	Platform Application Phase	Widespread Substitution Phase
Goals/ Milestones	Establish credibility with application producers Learn to make/ process material Introduce the product to some consumers Identify faults of materials	End enabler phase Establish commercial viability by generating profits Introduce material to mass market Invite new producers to market	Generate profits Mass marketing of material
Application characteristics	Solves new problems Simple applications—simple value chains Applications can only be done with new material Cost not an issue	Single application Replaces existing material by doing job better (properties) Not necessarily lower cost Permanent dominance	Mostly replacement, but some enabler and platform type applications Lower cost than incumbents Slightly better properties than incumbents

Table 3.7: Goals and characteristics of phases in materials commercialization pattern.

The commercialization pattern displayed by plastics appears to hold in other materials, as well.

In addition to identifying the characteristics of situations in which the traditional materials marketing approach doesn't work, this pattern can add resolution to innovation theory. This materials commercialization pattern is fundamentally different from the patterns described by innovation theorists for several reasons. First, it forces discernment between insertion and penetration, whereas previous descriptions and theories have done so only implicitly, and have thus confounded the two. Second, this pattern also deals with products that are not easily changed, whereas most previous work has focused on adapting products to meet market needs. At its core, this pattern describes a pure push situation—producers of new materials must fight their way into the market, and don't have the luxury of quick reconfiguration to meet market needs—forcing a more careful examination of the factors relevant to market selection. Finally, development of this pattern in the next chapters will show that the relevant insertion factors are *limiting factors*. By exposing limiting factors, materials producers and innovation theorists can build strategies to minimize their effects or avoid them altogether.

Chapter 4: Insertion Factors

Introduction

Chapter three showed that the major commercial plastics followed a clear pattern of market progression. It also revealed a convincing difference between the factors that affect placement of a material into a market (insertion factors) and the factors that pertain to large scale success in that market (penetration factors). It further identified insertion factors as limiting factors.

Since market insertion is the first step in commercializing a new material, it should be the focus of producers of new materials. If insertion is to be successful, the producers must successfully deal with any limiting factors. In order to do this more effectively, producers need to have a better understanding of the limiting factors than they do now. The limiting factors of insertion might be avoidable (or at least manageable) if they are explicitly identified and their effects recognized.

This chapter will explore the limiting insertion factors of the most important commercial plastics in their most important applications. It will be shown that some of the traditionally recognized insertion factors, such as cost and market identification serendipity were much less important than technical deficiencies and value chain obstacles. In fact, the presence of technical deficiencies and value chain obstacles accounts for the majority of the insertion delay of the major plastics in their most important applications.

Additional resolution will be added to the pattern of materials commercialization that was shown in chapter three. A progression of insertion factors corresponds to the progression of characteristic applications in each phase of the pattern. Enabler phase applications face very few limiting insertion factors. Platform applications face value chain obstacles. Widespread substitution phase applications often face both technical challenges and value chain obstacles.

Insertion Factors

The major plastics offer a clear and compelling value proposition in their biggest applications. However, in most cases, the plastics and the major applications did not come together until years after the plastics had been commercialized in other applications. There are several possible explanations for this seemingly paradoxical behavior:

1. No one thought to place the new plastics in the applications—identification of the applications was serendipity.
2. The material was more expensive than incumbent materials and therefore was unattractive to use.
3. The material was technically incapable of meeting application demands.
4. Elements of the value chain were unable (or people in the elements were unwilling) to accept the new material for a given application.

Each of these possible explanations will now be discussed.

Materials Serendipity

Perhaps the simplest explanation for the delay in insertion of major plastics into their biggest applications is "materials serendipity": that no one thought of using them for those applications prior to insertion. This hypothesis would indicate that the inventors and marketers were unable to recognize potential applications, and would follow the popular assertion that the only way to find the real applications for materials is to release them to customers and see how they get used (or who finds them)[1].

While this explanation is elegant in its simplicity, it is hardly accurate in describing the insertion of the biggest applications of the major plastics. There are cases in the history of plastics in which commercialization of a plastic predated the existence of an application, but these are relatively rare. Only one of the 34 biggest applications in 1998 falls in this category: polystyrene cassette tapes. In this case, polystyrene was chosen as the material for the new invention because of its relatively low cost and ease of molding[2]. Its use grew as adoption of cassettes and 8-track tapes grew.

The major plastics were proposed as potential suitors for all of the other biggest applications earlier than they were inserted into those applications. The properties of the plastics lent themselves to these applications, and early patent, technical, and industry literature often suggested them. Table 4.1 shows the date and source of early application suggestions.

Material	Application	Insertion Year	Early Suggestion Date	Early Suggestion Source
HDPE	Liquid food bottles	1963	1955	Industry publication--review paper[3]
HDPE	Household industrial chemical bottles	1958	1955	Industry publication--review paper[4]
HDPE	Grocery sacks	1972	1970	Industry Publication--article[5]
HDPE	Trash and can liners	1978	1968	Industry Publication--article[6]
HDPE	pipe and conduit	1960	1955	Industry publication--review paper[7]
HDPE	Pails	1958	1955	Industry publication--review paper[8]
HDPE	Crate and totes	1961	1958	Industry publication--article[9]
HDPE	Industrial drums	1958	1955	Industry publication--review paper[10]
LDPE	Food packaging film	1947	1936	Inventor memoirs[11]
LDPE	Extrusion coating	1949	1936	Inventor memoirs[12]
LDPE	Non-food packaging film	1947	1936	Inventor memoirs[13]
LDPE	Stretch and shrink	1965	1960	US Patent [14]

Material	Application	Insertion Year	Early Suggestion Date	Early Suggestion Source
PET	Soft drink bottles	1975	1969	US Patent[15]
PET	Custom bottles	1979	1969	US Patent[16]
PP	Fibers and filaments	1958	1956	US Patent[17]
PP	Consumer products	1959	1956	US Patent[18]
PP	Rigid packaging	1960	1956	US Patent[19]
PP	oriented film	1961	1956	US Patent[20]
PP	Transportation	1959	1957	Industry publication--review paper[21]
PP	Appliances	1959	1957	Industry publication--review paper[22]
PS	Oriented film/sheet	1957	1943	US Patent[23]
PS	Vending/portion cups	1956	1954	US Patent[24]
PS	Cassettes, Etc	1965	1965	Industry publication--article[25]
PUR	Furniture (padding)	1954	1947	Inventor Review Paper[26]
PUR	Building insulation	1960	1955	Industry publication--review paper[27]
PUR	Trans. (padding)	1955	1947	Inventor Review Paper[28]
PUR	Refrigeration	1956	1955	Industry publication--review paper[29]
PUR	Rug underlay	1957	1955	Industry publication--review paper[30]
PVC	Pipe and conduit	1953	1946	Industry publication--review paper[31]
PVC	Siding	1961	1951	US Patent[32]
PVC	Windows and doors	1958	1953	US Patent[33]
PVC	Wire and Cable	1938	1936	Industry publication review paper[34,35]
PVC	Extruded packaging	1948	pre-1946	Used in military gun covers[36]
PVC	Pipe fittings	1954	1946	Industry publication--review paper[37]

Table 4.1: Introduction dates and early suggestion dates of major plastics applications.

These data show that the mean time elapsed between suggestion of an application and insertion therein was 4.625 years. With the exception of household refrigeration applications for PUR, all of the applications were recognized as potentially large markets at least two years (usually more) before insertion. 82% of the applications (all but six: LDPE shrink film, HDPE grocery sacks, HDPE trash bags, PS cups, PVC siding, PVC windows and doors) were recognized very early in the commercial lives of their respective plastics—either in the foundation patents of the material, the memoirs of the inventors, or in pre-production published reviews. It will be shown in a subsequent section that significant technical barriers had to be overcome for each of the six applications that were not suggested early, indicating that technical problems may have masked the potential of the materials in these applications. However, insertion of these applications still did not occur until well after the early suggestion date, so only part of the overall insertion delay is explained by the delay in suggestion.

It may be concluded that, except for PS cassettes, the need for each major application existed before insertion and was known to the plastics industry. The data show that it would be unreasonable to categorically assert that the delay in insertion of the major plastics into their biggest applications was due to incompetent or serendipitous identification of markets. However, in cases where technical improvement was necessary, some of the delay can be explained by the fact that the properties of the materials did not lend themselves to specific applications, effectively delaying their identification as potential outlets.

It is also important to note that the fact that the applications were suggested much earlier than they were introduced, coupled with the fact that all of the applications grew quickly to become very large, indicates once again that the key factors affecting insertion are *limiting factors*.

Plastics Were Too Expensive to be Attractive

As noted in chapter two, much of the advice and research of materials commercialization experts is focused on reducing cost. In their Investment Methodology for Materials (IMM), Maine and Ashby recommend identifying opportunities based on the applications of materials with similar properties[38]. The cost modeling and multiattribute utility techniques developed at MIT by Field and Clark are designed to identify costs in two existing materials to predict the probability of substitution—with the assumption that rational actors will switch to lower cost materials of equal utility[39] (or, significantly, to higher cost materials of superior utility). This method has been shown to be remarkably accurate in predicting switches between established materials.

The prominence of cost in these and other models suggests that cost is a major limiting factor in the insertion of materials into applications. In fact, a strict interpretation of the prevailing cost theories would dictate that new materials be inserted into new applications only if they were less expensive than competing options, and significantly less expensive than existing materials in those applications. The Field and Clark multiattribute utility models depart from this interpretation, since they allow for insertion based on the overall value of a product (utility/cost).

Table 3.5 shows the biggest applications of the major plastics in 1998, the material that was replaced with insertion of each material, and whether the cost of the finished plastic product was lower than that products made of the displaced material at the time of first insertion, as reported in *Modern Plastics* and other sources. In most cases, *MP* simply reported the substitution costs in one of three states: lower, equal, or higher. If the actual (numerical) price difference was explicitly reported, it is also listed in the table.

The price differences in *Modern Plastics* were judged to more reliable than simple historical materials price data. They generally reflect the change in part cost to the application manufacturer. Because of differences in density, materials prices cannot be compared solely on price per lb, as they are usually reported. Converting the price per lb costs to price per unit density would be more accurate, but would not reflect processing costs. True comparison of historical pricing would require data on both materials costs and state of the art processing costs for each material at a given time in history, which is not available because of the pace of process developments in the periods under consideration. However, *Modern Plastics'* attempts to compare changes in part costs reflected at least some of the processing costs.

The best comparison of historical pricing reflect total system cost, which can be defined as the sum of the costs of all the nodes of the value chain of an application. Ideally, total system cost would be reflected in the end-user price of an item or in the profits of the item's manufacturer. However, the true total system cost of a product is very difficult to assess because value chains are most often disaggregated—nodes are owned by different entities, each of which bases prices on market factors. Because of this disaggregation, it is unlikely that materials selection was based on total system cost in any but the most obvious situations.

Material	Application	Elapsed time	Replaced	Less Expensive?	Price Difference?
HDPE	Liquid food bottles[40]	6	paper	No	$0.06/bottle
HDPE	Household industrial chemical bottles[41]	1	Paper/metal	No	equal, or slightly higher
HDPE	Grocery sacks[42]	15	paper	Equal	
HDPE	Trash and can liners[43]	21	LDPE	No	
HDPE	Pipe and conduit[44]	3	Metal pipe/LDPE pipe	No	
HDPE	Pails[45]	1	Metal (steel)	No	
HDPE	Crate and totes[46]	4	Softwood, hardwood, AL	No	20-100% more, depending on replaced material
HDPE	Industrial drums[47]	1	Metal	Yes	"Approximately 1/3 the cost"
LDPE	Food packaging film[48,49]	6	Paper, cellophane	No (1950)	
LDPE	Extrusion coating[50]	8	Asphalt laminations	No	"only slightly higher than an asphalt lamination of comparable protection"
LDPE	Non-food packaging film[51,52]	6	paper, cellophane	No (1950)	
LDPE	Stretch and shrink[53]	24	Non-shrink plastics	Yes	
PET	Soft drink bottles[54]	8	Glass	No	

Material	Application	Elapsed time	Replaced	Less Expensive?	Price Difference?
PET	Custom bottles[55]	12	Glass/plastic	No	
PP	Fibers and filaments[56]	0	Nylon,PE, dacron	Equal (within 1%)	8.17/ft (PP), 8.26/ft (nylon) (1961--both 20% higher in 1958)
PP	Consumer prod.[57]	1	PE, PS	No	109%
PP	Rigid packaging[58]	2	Urea	Yes	20-30%
PP	Oriented film[59]	3	Cellophane	No	
PP	Transportation[60]	1	Zinc	Yes	
PP	Appliances[61]	1	Metal	Yes	price based on similar applications
PS	Oriented film and sheet[62]	19	Cellophane, acetate	Yes	
PS	Vending and portion cups[63]	18	Paper	No	sundae dishes: "somewhat more costly than paper"
PS	Cassettes, Etc[64]	27	nothing--new application	(least expensive)	
PUR	Furniture (padding)[65]	1	Rubber foam	Equal	"about the same"
PUR	Building insulation[66]	7	Foamed styrene	No	
PUR	Transportation (flexible padding)[67]	2	Rubber foam	No	
PUR	Household and commercial refrigeration[68]	3	Cork, fiber glass	No	
PUR	Rug underlay[69]	4	Rubber foam	No	"premium price"
PVC	pipe and conduit	15	Iron	No	>$.28/ft
PVC	Siding[70]	23	Fiberglass,glass, Al, steel	No	
PVC	Windows and doors[71]	20	Aluminum	Equal	"comparable"
PVC	Wire and Cable[72,73]	0	Rubber	No	
PVC	Extruded packaging[74]	10	Cellophane	No (1953)	
PVC	Pipe fittings	16	n/a	(only material useful with PVC)	

Table 4.2: Prices of new plastics compared to displaced existing materials at time of introduction in major applications

Because they were not replacements for existing materials applications, PVC pipe fittings and PS cassettes will be excluded from the rest of the cost discussion, although it should be noted that one of the reasons cited for adoption of PS in cassettes was its low cost[75]. Excluding these two applications, the table above shows that the entry price point for plastics in the vast majority—81.25%—of their major 1998 applications was *equal to or higher* than the price point of existing applications. This observation indicates that strict interpretation of the low cost theory, in which substitution occurs only when the entrant material costs less than the incumbent, does not describe the entry of the major plastics into their biggest applications. It also debunks the explanation of insertion delay that is being tested: new materials clearly do not have to be lower cost than incumbents to be attractive, and can be inserted at higher cost.

A pure utility-based substitution theory, in which players switch materials based on both utility and cost, fits the data much better. If one assumes that the producers of the major applications were rational actors, it is unreasonable to believe that insertions of new plastics at higher costs were done arbitrarily. A better explanation is that the entrant materials offered additional utility to the application—that the basis of competition at the insertion point was superior performance on some dimension that could not be matched at the same cost by incumbent materials. The entrant materials did the jobs that customers wanted better than incumbent materials did.

It should not be assumed that cost played no part in insertion—it probably did. Cost was explicitly cited as an insertion challenge in six of the applications listed above[76]and was implicit in many others. However, the cost challenges were to get the material down a *feasible* price point for each application—not to get *below* the cost of incumbents. The feasible price point was usually not lower than existing materials, but neither was it extraordinarily high—there were no "golden trash bags". While the data on price differences shown in table 3.5 are admittedly sparse, the greatest price difference shown was in polypropylene housewares, with the costs of PP 109% higher than the plastics it replaced. This seems like a huge difference in cost, but the application in question was a plastic tumbler for household use, which jumped in price from $.21 to $.43. Since tumbler spending was most likely only a small portion of the budget of the average housewife (the stated customer), this was a very affordable price to pay for a plastic cup that could hold ice but would not melt in the dishwasher![77]

The other application in which the price difference of the entrant material was very high was HDPE crates and totes, in which HDPE beverage cases replaced wood cases at approximately 100% higher cost. Since beverage cases were sold in large lots, this price difference required dairies (the main customers) to make significant investment. However, HDPE beverage cases required no maintenance, which could cost up to 40%/year of the original cost of the wood cases. HDPE also offered longer life and lower weight, allowing major reduction in shipping costs. The HDPE cases were priced at a point in which the relationship between utility and cost made them slightly favorable to customers.[78]

Although the majority of the major plastics applications of 1998 were more expensive than competitors when they were inserted, some of them were less expensive or equal in cost. Figure 4.1 shows a histogram of the insertion periods of the major applications of 1998, with bars divided according to the cost position of entrants (lower, equal, higher).

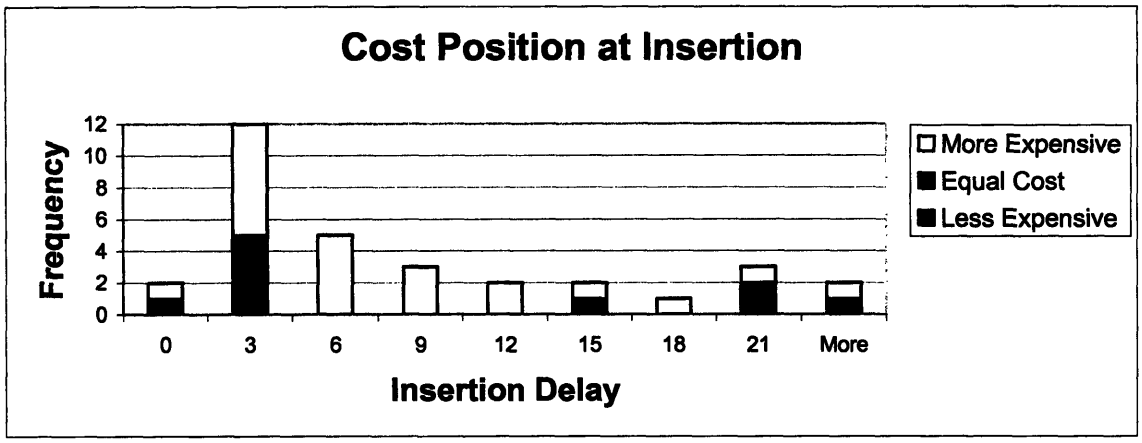

Figure 4.1: Insertion periods of major 1998 applications, showing cost position of entrants.

As expected, the more expensive entrants represent the largest portion of most categories, but the concentration of less expensive entries in the 1-3 year category stands out as an interesting feature of the histogram. There are four less expensive entries in this category, three of which are polypropylene applications, with the other being HDPE industrial drums. In each of these applications, the entrants followed the patterns of the entrants in applications with higher cost positions—they offered additional utility. In fact, the additional utility may have warranted adoption even had they been slightly higher in cost. Polypropylene was relatively strong and much more corrosion resistant than the small metal windshield wiper motor housings it replaced in automobiles and the metal wire dishwasher cutlery racks it replaced in appliances[79,80]. It was also a thermoplastic, making it much faster to mold than the thermoset urea it replaced in bottle closures (rigid packaging)[81]. High density polyethylene drums were far lighter and more corrosion resistant than the stainless steel drums they replaced, making them very attractive for the shipment of corrosive materials[82].

Value Chain Obstacles or Technical Deficiencies Delayed Insertion

Deficiencies in the properties of materials and value chain obstacles are also possible explanations for the insertion delay of the major plastics into their most important applications. However, before exploring these possibilities, it is necessary to draw sharp lines of delineation between the two, because the difference is not always clear.

For the purposes of this analysis, technical deficiencies can be defined as limitations in the intrinsic properties of materials that prevent their use in some applications. Technical deficiencies are solved by technical advancements, which include both advancements in materials science and breakthroughs in processing techniques.

It is obvious that different materials offer different properties, and that different properties are useful in different applications. For example, the low cost and relative toughness of paper makes it useful in bags, but its low strength and flammability makes it useless in jet engines. While each major plastic displayed a unique set of properties at its initial commercialization, significant performance and property improvements were made as the plastics matured.

Both chemistry and processing drive the properties of plastics, and advances in either one can have a dramatic effect on the range of applicable applications. Polymer chemistry is generally recognized as a basic material science, and research is most often executed by materials producers, or by research institutions such as universities or national laboratories. However, changes in chemistry technology are always executed and controlled by materials producers themselves. Thus, any changes in chemistry would be confined to the materials manufacturing node of the value chain, and would be considered technical advancements.

In contrast to polymer chemistry, polymer processing technology is generally considered an applied field. It is developed by a wider range of institutions, ranging from universities to materials producers to processing machinery makers. Advances in commercial processing techniques can be introduced by either materials producers or by processors--and processors are clearly part of the value chain. However, since major advancements in processing techniques can have enormous impact on the properties and applicability of a material, it is necessary to classify them (regardless of their origin) as technical advancements, as well. Major advancements in processing will be defined as process developments which enhance the properties and applicability of a plastic and which were previously unknown or unavailable to *all* processors. Processing breakthroughs such as the invention of extrusion coating of paperboard with polyethylene or biaxial stretching of polystyrene, both of which required significant basic research, changed the physical properties of their respective markets, and opened huge new markets to many processors, will be considered technical advancements.

Not included in the technical deficiencies category are value chain obstacles. A generic value chain is shown in figure 4.2.

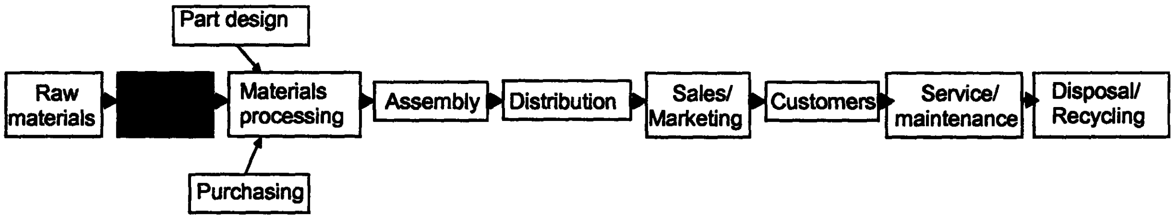

Figure 4.2: Generic product value chain, showing position of material manufacturing.

Value chain obstacles will be defined in this analysis as challenges that stem from nodes that reside in the value chain after materials manufacturing (excluding customers). These include processing, assembly, distribution, sales, purchasing, part design and service, along with other application-specific nodes. Value chain issues are not solved by changing the technical properties of materials—they are solved by learning to deal with the existing set of properties. A key difference between value chain issues and technical issues is that value chain issues are solved with empirical testing while technical issues are solved with basic or applied science. Value chain issues are solved by people or groups outside of the materials manufacturer by adapting and implementing knowledge that is freely available.

Smaller processing challenges, such as label printing for HDPE bottles or heat sealing PE films, for which solutions existed but were not in widespread use, are considered value chain issues. Other value chain issues include code qualification for plastics pipe, refinement of parameters to allow injection molding of PP on existing tools, and designing PET bottles to work directly with the existing bottling equipment in a Pepsi or Coke factory.

Testing the Effects of Value Chain Obstacles and Technical Deficiencies

Since processors and end users were the largest readership of *Modern Plastics*, the magazine was remarkably candid about the challenges that limited entry of materials entering new applications. Appendix A shows the actual challenges listed. These challenges were categorized into value chain obstacles and technical deficiencies according to the criteria listed above (technical: challenges solved by advances in chemistry or by the introduction of new processing techniques; value chain: challenges solved with empirical testing by entities besides the materials manufacturer using commonly available knowledge). The results are tabulated in the matrix shown in table 4.3. A "no challenge" column was also created for applications in which no challenges were cited. Challenges solved before the first commercialization of a material were not considered in this analysis, since the goal is to identify sources of delay of insertion of a plastic into specific applications, not sources of delay during development of the plastics themselves.

Material	Application	Insertion Delay	No Challenge	Value Chain Obstacles	Technical Deficiencies
HDPE	Liquid food bottles	6		●	
HDPE	HIC bottles	1		●	
HDPE	Grocery sacks	15		●	●
HDPE	Trash and can liners	21		●	●
HDPE	pipe and conduit	3		●	
HDPE	Pails	1	●		
HDPE	Crate and totes	4		●	
HDPE	Industrial drums	1	●		
LDPE	Food packaging film	6		●	
LDPE	Extrusion coating	8		●	●
LDPE	Non-food pack film	6		●	
LDPE	Stretch and shrink	24			●
PET	Soft drink bottles	8		●	●
PET	Custom bottles	12		●	●
PP	Fibers/filaments	0	●		
PP	Consumer products	1	●		
PP	Rigid packaging	2	●		
PP	oriented film	3		●	
PP	Transportation	1	●		

Material	Application	Insertion Delay	No Challenge	Value Chain Obstacles	Technical Deficiencies
PP	Appliances	1	●		
PS	Oriented film/sheet	19		●	●
PS	Vending cups	18		●	●
PUR	Furniture (padding)	1		●	
PUR	Building insulation	7		●	
PUR	Trans. padding	2		●	
PUR	Refrigeration	3		●	
PUR	Rug underlay	4			●
PVC	Pipe and conduit	15		●	
PVC	Siding	23		●	●
PVC	Windows and doors	20		●	●
PVC	Wire and Cable	0	●		
PVC	Extruded packaging	10			●
PVC	Pipe fittings	16		●	●

Table 4.3: Table of value chain obstacles and technical deficiencies.

Figure 4.3 is a histogram of application insertion times, with each bar showing proportions of value chain and technical challenges.

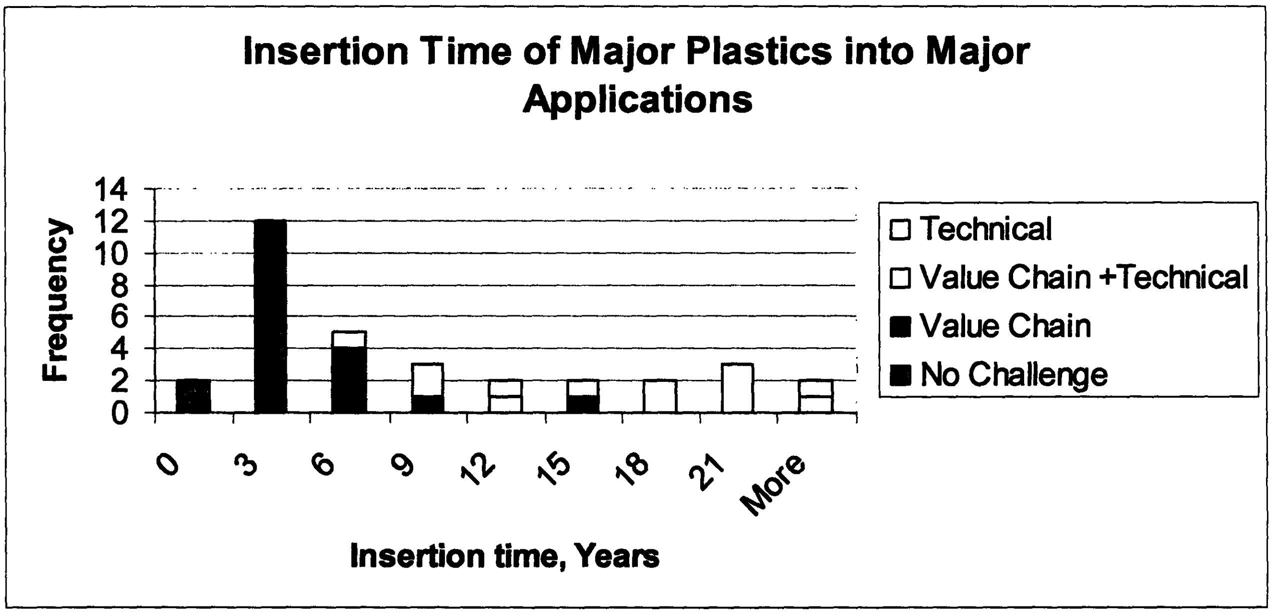

Figure 4.3: Histogram of major plastics divided by value chain and technical challenges.

This histogram shows an important trend: there is a progression of challenges as insertion time increases. The first few years are dominated by applications for which *Modern Plastics* did not report technical or value chain challenges (mean time to insertion for "no challenge" group: .875 years). From years 2-6, value chain issues are the dominant challenges (mean time to insertion for "value chain obstacles" group: 4.75 years). Beyond 6 years, value chain and technical factors combine to dominate the graph (mean time to insertion for "value chain + technical": 16 years). This leads to preliminary set of null hypotheses:

1. H_o: Applications with no stated challenges will take equal or longer time to insert than applications with value chain challenges.
2. H_o: Applications with value chain problems will take equal or longer to insert than applications with both value chain and technical challenges.

One sided t-tests with insertion time as the dependent variable were performed to test these null hypotheses. The results of the tests are shown in table 4.4.

t-Test: Two-Sample Assuming Unequal Variances		
	No Challenge	*Value Chain Obstacles*
Mean	0.875	4.75
Variance	0.410714	14.568182
Observations	8	12
Hypothesized Mean Difference	0	
df	12	
t Stat	-3.444813	
P(T<=t) one-tail	0.002426	
t Critical one-tail	1.782287	

t-Test: Two-Sample Assuming Unequal Variances		
	Value Chain+ Technical	*Value Chain*
Mean	16	4.75
Variance	27.55556	14.56818
Observations	10	12
Hypothesized Mean Difference	0	
df	16	
t Stat	5.646518	
P(T<=t) one-tail	1.82E-05	
t Critical one-tail	1.745884	

Table 4.4: Results of one sided t-tests showing that the categories of "no challenge", "value chain obstacles", and "value chain obstacles + technical deficiencies" are robust.

These tests allow sound rejection of both hypotheses. The t-score of the test of the first hypothesis is 3.44481, and is significant at the .004 level. The t-score of the second test is 5.6446, and is significant at the .0000364 level. Since value chain is the variable tested in each case, the "value chain+ technical" group is also statistically different from "no challenges" group. Thus, we can conclude that value chain obstacles and the combination of value chain obstacles and technical deficiencies each have a statistically significant effect on the period of insertion required for the major plastics into their biggest applications of 1998.

Further understanding of the relationship between value chain obstacles, technical deficiencies, and insertion delay can be gained by performing multivariate linear regression. Although the generalizability of the results is limited by the small size of the sample pool, multivariate regression is useful as a descriptive tool to recognize basic effects of variables. In the following regression, performed on SPSS, insertion time (in years) is the dependent variable coded COMTIME, with dichotomous variables assigned to the presence of value chain obstacles (coded VALCHAIN) and technical deficiencies (coded TECH). The results of this regression are shown in table 4.5.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.816[a]	.665	.643	4.5543

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1237.630	2	618.815	29.834	.000[a]
	Residual	622.249	30	20.742		
	Total	1859.879	32			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.981	1.445		.679	.503
	VALCHAIN	3.699	1.708	.232	2.165	.038
	TECH	11.405	1.648	.742	6.920	.000

a. Dependent Variable: COMTIME

Table 4.5: SPSS output of regression of value chain obstacles and technical deficiencies vs. insertion time.

The regression model adds resolution to the role of value chain obstacles and technical deficiencies in insertion of materials. It allows easy separation of value chain obstacles from technical deficiencies, and shows that both are statistically significant descriptors of the insertion delay of the major plastics into their biggest applications. The high R^2 shows that a large portion (66.5%) of the variation in insertion time can be explained by these factors. Technical deficiencies have a higher level of statistical significance (p=.000) in the model, and their effect is illustrated by their high beta—11.405 years. While value chain obstacles are clearly statistically significant (p=.038), they are less significant than technical factors. The beta attached to value chain obstacles is 3.699 years.

In order to test the interaction effects of the presence of value chain obstacles and technical deficiencies, a dichotomous variable multiplying the two individual dichotomous variables (TECH and VALCHAIN) can be created. This variable can then be added to the model presented in table 4.5. However, this model is suspect from the outset because the ratio of datapoints to variables is very low. Nonetheless, the model was created. The interaction variable was insignificant in the model (t=.340), and the model gave a worse fit (R^2=.592) with lower overall model significance (F=13.542).

It was mentioned earlier that there appeared to be a relationship between the presence of technical deficiencies and the delay in suggestion of new applications for the major plastics. Another regression was performed to test this relationship, in which the elapsed time (in years) between the early suggestion for the use of a plastic in an application and its insertion into that application is used as the dependent variable (coded SUGTIME). The dichotomous variables VALCHAIN and TECH remained the same as in the previous regression. The results are shown in table 4.6.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.589[a]	.347	.303	3.0231

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	145.698	2	72.849	7.971	.002[a]
	Residual	274.181	30	9.139		
	Total	419.879	32			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.406	.959		2.508	.018
	VALCHAIN	3.907	1.134	.516	3.445	.002
	TECH	1.512	1.094	.207	1.382	.177

a. Dependent Variable: SUGTIME

Table 4.6: SPSS output of regression of value chain obstacles and technical deficiencies vs. elapsed time between suggestion and insertion.

In this regression, the independent variable TECH, which represents the presence of technical deficiencies, is not statistically significant. In contrast, VALCHAIN, which represents the presence of value chain obstacles, is statistically significant at a much higher level (p=.002 vs. p=.038) than in the COMTIME model shown in table 3.8. This suggests that much of the variation in insertion time explained by technical deficiencies is removed from the model by using time of suggestion as the baseline instead of time of commercialization. If this is the case, one would expect a high correlation to exist between the presence of technical deficiencies (TECH) and the elapsed time from commercialization of a material until suggestion of use of that material in an application (coded COMSUG). An SPSS bivariate correlation matrix of these variables is shown in table 4.7.

Correlations

		COMSUG	TECH
COMSUG	Pearson Correlation	1.000	.707**
	Sig. (2-tailed)	.	.000
	N	33	33
TECH	Pearson Correlation	.707**	1.000
	Sig. (2-tailed)	.000	.
	N	33	33

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.7: SPSS output of regression of value chain obstacles and technical deficiencies vs. elapsed time between suggestion and insertion.

The correlation between the COMSUG and TECH variables is quite strong (~71%, and is clearly statistically significant. However, the presence of a correlative relationship does not necessarily indicate a causal relationship. It seems equally feasible that suggestion of an application could lead to technical development (which would expose technical deficiencies) as it would be for new applications to be suggested as technical problems are solved. However, if suggestions were presented before technical challenges were solved, one would expect the presence of technical deficiencies to be a predictor in explaining the delay between initial suggestion of a plastic and its actual insertion (the model shown in table 4.6). The presence of technical deficiencies was not a statistically significant factor—it was dwarfed by value chain obstacles. This indicates that technical factors were largely solved *before* the suggestion was made to place the major plastics into their most important applications. Further evidence of this conclusion is seen by examining the sources of the suggestions—in all cases, the suggested applications cited existing materials, and many of the suggestions came from review articles on new properties of those materials. Keeping in mind that materials in general—and plastics in particular—can take many different forms, and that those forms depend on the state of technical development, it is easy to see that at least some technical barriers had to have been overcome for plastics to be suggested for these applications. It would have been unreasonable to suggest them otherwise.

It is clear at this point that both technical deficiencies and value chain obstacles are the most important limiting factors to the quick insertion of the major plastics into the large applications that were examined in this chapter. Technical deficiencies are more important—regression analysis showed that applications with technical deficiencies required nearly three times as long to insert as those with only value chain factors, and technical deficiencies are more statistically significant in the model. Having said this, the presence of value chain obstacles is very important, adding 3.7 years of insertion delay in the regression model.

Adding Resolution to the Commercialization Pattern

The market progression pattern explained in chapter three is shown in figure 4.4.

Figure 4.4: Materials commercialization pattern

The market progression shown in this pattern corresponds to the progression of obstacles that were shown in figure 4.3. Applications in the enabler phase followed a characteristic pattern. They were simple applications that were uniquely suited to solving a new problem. The applications into which they were inserted took advantage of their unique properties, which were obvious even early in the life of the material. Because they took advantage of their unique properties, there were few technical challenges to cause insertion delays.

It is also significant that the enabler applications were relatively simple—they were standalone products or could be easily dropped into existing value chains. This meant that value chain limiting factors would be minimal, since very little investment in adaptation was required. The fact that the problems solved by the applications were relatively new also minimized value chain resistance. When new problems arise, markets are less demanding on their solutions—they don't have to be perfect, they just need to do the job. This meant that liability factors that might have created value chain challenges were minimal for many of the enabler applications.

Most of the platform applications dealt only with value chain challenges—they were replacing existing materials in major markets. The value chains of the applications were designed to supply products made from existing materials, and time was required to make the changes necessary to accommodate the new entrants. Furthermore, the existing applications had established dominant designs—performance criteria were set and customers expected the products to perform in certain ways. They were much less forgiving of failure. Thus, testing and development had to be performed to ensure that the new materials would meet expected performance standards and that they could be produced in a consistent, defect-free manner. This testing and development period contributes to insertion delay.

Many of the major applications that emerged during the widespread substitution phase faced challenges that stemmed from both the technical and value chain arenas. Refinement of both processing and materials had to occur for the entrants to conquer tough existing markets. In some cases, such as PP washing machine agitators, the new material was not understood well enough to be useful in replacement applications and materials and process development were required before competitive designs emerged.

In other cases, the markets themselves were extremely demanding yet incredibly attractive, and warranted development throughout the chain. This was the case with PET soft drink bottles, for which new materials and entirely new processes were developed[83]. The difficulty of overcoming obstacles seems to increase with each phase, but the attractiveness of the application markets also increases. Each phase of the commercialization pattern generates knowledge and credibility so that a material can progress into more demanding, challenging, and attractive markets. Both time and money are required to solve technical difficulties and beat value chain challenges. By following the progression shown in the materials commercialization pattern, producers of new materials can to accelerate knowledge development with real world experience and generate progressively larger amounts of cash needed to fund development of progressively more difficult challenges.

The most severe insertion delays occur when the materials commercialization pattern is not followed. When new materials producers fail to understand the technical and value chain obstacles in an attractive application market, they are prone and focus all of their new material introduction efforts on conquering it, leading to either failure or very slow insertion.

Perhaps this pattern is best understood by examining the experiences of three startups, each of whom took a different path to commercialization. Microcool Technology is an example of a company that failed because of insertion factors, despite its efforts to market a material that offered revolutionary performance. Nanomagnetics also had a material with revolutionary performance, and was on the brink of failure until it changed its strategy to dodge insertion factors. Selectech achieved very quick insertion and record of success by following the pattern of commercialization, despite the limited performance advantages of its core material.

Microcool Technology, LLC[84,85,86]

Microcool Technology was started by a group of students in the Leaders for Manufacturing program at MIT in October, 2001. Microcool's core intellectual property was a process for making "Linear Metal Foam", a highly porous metal with aligned, controllable internal microchannels. Theirs was the first process capable of making this type of material in an economical way.

Developed in the MIT Welding and Joining Lab, linear metal foam (LMF) was originally proposed as a metal/metal composite for thermomechanically compliant anisotropic structures, sound deadening submarine skins, and heat transfer devices for semiconductors[87]. During development, researchers discovered that, because of its tiny pore size and high surface area, LMF had extraordinary heat transfer properties (see figure 4.5). When charged with pressurized air, the material could transfer nearly 50 W/cm^2, far more power than other cooling devices. With full water cooling, 1000W/cm^2 was possible. In fact, microchannel cooling had been shown to have the best heat transfer of any medium[88]. Furthermore, the MIT process was inexpensive. The value proposition was clear: superior heat transfer at a low cost.

Figure 4.5: Microcool Linear Metal Foam

Because of its extraordinary properties in heat transfer, the Microcool team decided to propose a business that would use LMF to attack the market in which it offered the most obvious value: semiconductor cooling. Its small form factor made it ideal for microcomputers, and the Joining group had developed techniques to fuse it directly to the surface of silicon chips. This eliminated the thermal interface material that was a major contributor to overall thermal inefficiencies in semiconductors[89].

Microcool estimated the semiconductor cooling market to have sales of approximately $3 billion per year, with a highly disaggregated structure—the largest semiconductor cooling manufacturers had revenues of less than $100 million in 2001. Furthermore, the market was clamoring for thermal management solutions—Intel had stated that thermal barriers were fast approaching, and that they would limit the overall performance of its products[90].

Venture capitalists also recognized the opportunity. Microcool won the MIT 1K business plan competition, and gained audiences with several prestigious firms, some of whom encouraged the founders to leave graduate school to attack the market. The financiers were interested by the quality of the technology, the size of the market, and the attractiveness of the industry structure. What they did not understand was the complexity of the value chain of cooling products in the computer market.

Microcool did not understand this complexity, either. The strategy it had proposed was to attack first the semiconductor test equipment market, which was facing incredibly challenging thermal barriers as it sought to increase the chip density on its motherboards. LMF was to be formed into large sheets, then attached to existing water cooling systems. Unfortunately, this application was infeasible due to very strict reliability requirements within the industry. Semiconductor test equipment was required to have very high uptime, and producers were unwilling to take the risk of incorporating a new material. The semiconductor test manufacturers were not appetized by the technical difficulties that would be present in developing LMF to fit their products. The largest piece of LMF that had been produced was 1" square. The test machines would require pieces 30" x 50"! Although the basic LMF technique probably could have been adapted, it would have been very difficult.

The second market that Microcool intended to attack was the emerging blade server market. The blade server market was estimated to grow to 2 million units within 3 years, and Microcool incorrectly estimated that $90 of the $2200 selling price would be spent on cooling. At the time the business plan was written, blade servers used low performing chips, and Microcool speculated that it could enable the use of the "latest, greatest chips". Microcool did not understand the value chain barriers that it would face in this market. LMF could not work with existing fans—it required compressed air to be forced through its channels. Since microcompressors with sufficient capacity did not exist, the only way to accommodate this requirement would be to install compressors in the buildings that housed servers. This was impractical for many reasons—it would consume enormous amounts of energy, require revisions in the standard rack mount architecture, and necessitate fluidic logic systems within the blade servers, to name a few. Had the data requirements been impossible to solve in any other way, these value chain obstacles would have been surmountable—within 5-8 years. However, there were several competing methods of both cooling blades servers and delivering data services. Value chain obstacles made Microcool's approach unacceptable.

The final market that Microcool proposed to attack was the chip lid market. Chip lids are the heat transfer covers that are installed in semiconductor packages, and Microcool proposed to use its bonding technology to create a lid with and integral heat sink that would be metallurgically bonded to the chip. This would eliminate two thermal interfaces, which caused the majority of thermal loss in the cooling system, and would replace the existing heat sink with a much more efficient one. Once again, technical deficiencies and value chain obstacles foiled Microcool's plans.

Intel, the largest manufacturer of microprocessors, showed interest in the chip lid idea, but promptly rejected any partnership ideas once it discovered that the material was still in lab stage. Intel needed a proven solution that could go directly into its 18 month thermal proving qualification testing. If it passed qualification, it could be designed into a chip lid (~6 months) and could then be incorporated into a product within 1-2 years. Had the product already been incorporated into a chip lid, the commercialization time would have been around 3 years—on the edge of acceptability for venture capital. However, because the technical challenges to creating a lid were significant, at least two years were necessary for technical development. The total time would probably have been 5-7 years, an unacceptably long period for venture capital.

There were other value chain problems with the Intel deal. For a critical part such as a chip lid, Intel required multiple suppliers. This meant that Microcool would be forced to disclose its processes to potential competitors. The compressor was also an issue—Microcool would have been required to partner with compressor companies to design and build a microcompressor that met the reliability standards of consumer electronics; it is doubtful that a compressor maker would be willing to attempt such an undertaking.

Significant time and effort was expended trying to develop these markets, but, four years after its invention, LMF has not been commercialized. LMF remains the highest performing heat transfer medium, but the founders of Microcool decided to abandon the venture because of the insertion factors it would face. These factors included both technical deficiencies and value chain obstacles, and stemmed from fundamental challenges in the applications that were selected. The founders of Microcool recognized that simpler applications existed for LMF, such as for steaming milk in cappuccino machines, where they could directly compliment existing heat pipe technology. However, they chose not to pursue those applications because their potential paled in comparison to the potential of the semiconductor cooling market.

Nanomagnetics[91,92,93]

Microcool Technology failed because it founders failed to appreciate the effects of insertion factors. Nanomagnetics is an example of company that reached the brink of failure by chasing applications with major insertion barriers, but was able to survive by switching its strategy to attack enabler applications.

Founded in 1997 at the University of Bristol by Dr. Eric Mayes, Nanomagnetics' core intellectual property was a process for embedding nanoscale Co/Pt magnetic particles into apoferritin protein cells (see figure 4.6). These cells were then spincoated or dipcoated onto smooth substrates where they would self assemble into arrays. Once the arrays were formed, the apoferritin was removed, leaving an extremely dense ordered array of magnetic particles[94]. In early research, this magnetic array offered data storage density (areal density) that was as good as or better than any existing technology, and foreseeable technological advancements promised much higher densities.

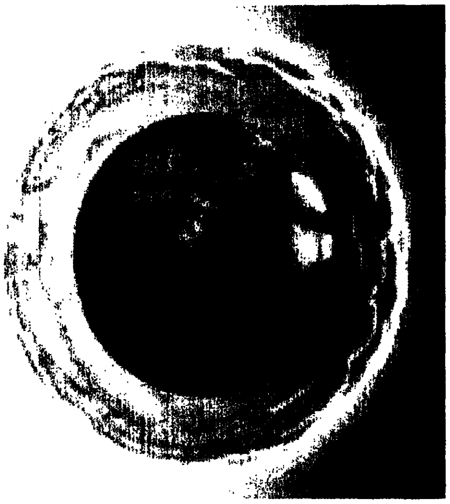

Figure 4.6: Nanomagnetics apoferritin-embedded magnetic particle.

When Nanomagnetics received $10 million of venture capital in 1999, the areal density achievable by its process was groing at 1500%/year, while the areal density of commercial technologies was growing at a mere 100%/year. Nanomagnetics' initial strategy was to attack the most attractive (and most complex and demanding) area of storage technology: hard disk drives. Nanomagnetics assessed the hard disk drive storage media market to be worth approximately $2.2 billion, and believed that it could capture a significant portion of that market by licensing its superior storage technology to manufacturers of completed disk drives.

Unfortunately, Nanomagnetics did not understand the insertion factors of the hard disk drive market. Although the areal density of the media was superior to any existing technology, it was technically deficient in several other areas. Commercial magnetic media were built to extremely tight specifications for smoothness, coercivity (magnetic parametrics), and magnetization (a signal to noise ratio). If these specifications were not met, the existing drive mechanisms—particularly the drive heads—would not work properly. Since the value chains for the drive heads and mechanisms were well established, the drive manufactures required that a new solution drop directly into the system. Maxtor, Quantum, and Komag all wanted the same thing: a finished piece of media that fit into an existing disc drive.

Faced with the challenges of merging its new materials technology with existing value chains, Nanomagnetics sought to establish a joint venture with a disc company. However, the burst of the Internet bubble in 2001 was causing turmoil in the industry, and no company was willing to partner. By 2002, the incremental progress of commercial technologies was bringing them closer to the performance of the Nanomagnetics material, and it appeared that the two would converge.

As they came closer to convergence, another difficulty arose: the forming technology for the apoferritin product (inkjet) was totally different from the existing forming technology that the hard disk market used (sputtering). Nanomagnetics tried to respond to this challenge by partnering with sputter machine makers Intevac and Litrex, but neither company was interested in developing an unproven technology.

Nanomagnetics abandoned its quest for hard disc drive media in 2003. Although its product was clearly superior in a highly relevant dimension, and could be produced at a reasonable cost, it did not achieve insertion. The technical requirements of the established industry (which were derived from the uptime demands of hard disc customers) proved difficult, and the value chain challenges of changing the production processes and disc drive machinery would be extraordinarily expensive. The limiting insertion factors were insurmountable for a company with limited resources, and the timeframes required to get around them would be outside the tolerable limits of the venture capitalists who had funded the company.

Nanomagnetics' second round of funding (2003) was based on a different strategy—attacking the flexible media market. The flexible media market was starting to re-emerge in low performance products; inspired by *The Innovator's Dilemma*, the CEO of

Nanomagnetics believed that the market would grow rapidly as technology improved. The flexible media market offered another advantage: it purchased powders, not finished media. This meant that the magnetoferrtin particles could be sold directly to manufacturers, making integration into the value chain much less painful. Nanomagnetics supplied its first product to Imation in 2004—1 Kg of Data Ink. However, even in the absence of technical deficiencies and with lower performance requirements, a significant testing period was required by the flexible media manufacturers, and several nodes in the value chain would need to change to adapt to the new material. Nanomagnetics expected its first revenues from this market in 2007—four years after starting its attack.

By 2004, Nanomagnetics had spent almost all of its venture funding, and it needed to starting gaining revenues. In realization that revenues from the flexible disc industry would also be delayed, Nanomagnetics began to explore other properties of its material. One of the unique properties of apoferritin is that it can be manipulated to attach itself to other types of molecules. Once attached, the embedded particles can be manipulated by magnetic fields. The most obvious application for such technology was in MRI contrast enhancers, since the ferritin could be "programmed" to attach to certain antibodies, which could be targeted to areas of interest for doctors. The techniques were relatively straightforward, and would give doctors new visibility into the human body. Because of this enabling ability, a major medical company began a development project with Nanomagnetics in 2004—the first ever development partnership for Nanomagnetics.

While Nanomagnetics was working on MRI scanning, a company in the United States had developed a new water purification pouch for the US military. This pouch used forward osmosis to make desert water drinkable. By wrapping a sports drink powder in a polymer membrane pouch, it was possible to filter water by drawing it through the pouch into the powder, where it created a sports drink. The system could start with "any water source. . .(including) a septic tank or a toilet", and could filter any bacteria to create a high quality sports drink[95]. However, the pouch had a significant drawback: because it required a concentration gradient, the filtered water had to be mixed with some type of powder. There was no way to make pure, clean water.

Nanomagnetics' embedded nanoparticles turned out to be the solution to this problem. Apoferritin powder proved capable of drawing water through the membrane. Once the water was in the pouch, it did not mix with the protein wrapped nanoparticles. Since the particles were magnetic, it was possible to remove them easily with a permanent magnet as the water was poured out of the pouch. The remaining product was pure, filtered water. An added benefit was also found: the pouch was reusable. As soon as the water was poured out of the bag, the magnet could be removed and the nanomagnetic particles would return to their original position, ready for another round of osmosis.

The forward osmosis pouch was a new product that was very simple and allowed people to do things they couldn't do before. Although some small technical issues were anticipated, the powder would streamline very easily into the existing value chain of the osmotic pouches—and if it didn't, the value chain of the pouches was simple and new enough that it could be easily changed to accommodate the new material. Upon discovering Nanomagnetics' product, the maker of the pouch quickly partnered with the company, and anticipated sales into the recreational market (much less demanding than the military) within 1.5 years—much faster than the data storage or MRI applications.

Both companies hoped that the utility of nanoparticles and forward osmosis would be shown in this product so that they would have the credibility necessary to move into markets of their other development partner—a major water purification company.

Like many new materials producers, Nanomagnetics attempted to follow a strategy that was exactly opposite the commercialization pattern established by the major plastics. It first pursued an attractive application that fit the characteristics of late entrant in the widespread substitution phase. The hard disk media market was well established—performance expectations were in place, and Nanomagnetics' product offered improvement over incumbent in one of the aspects of competition. However, the application had many limiting insertion factors, stemming from both technical deficiencies of the material and value chain obstacles of the application.

Since Nanomagnetics found that entry into this market would require much longer than its venture capitalists could endure, it was forced to switch its strategy to focus on a market that had the characteristics of a platform application: flexible disc media. The flexible disc media market was large, and Nanomagnetics offered substantial benefit to both producers and consumers—they would be able to do the same things they had been doing, but do them better. There were far fewer limiting insertion factors than in hard disc drives, and they stemmed mostly from value chain obstacles. Although Nanomagnetics found flexible media manufacturers to be more receptive, overcoming value chain obstacles would delay product revenues by at least four years.

At the time of this writing, water purification pouches—enabler applications—were the savior of the company. The simple, new forward osmosis process was in need of the exact properties that apoferritin embedded nanomagnetic particles offered, and was willing to incorporate them quickly into a product. Nanomagnetic's products would let people do things they couldn't do before. This prospect renewed venture interest, and allowed the company to move forward toward the MRI and flexible media markets.

Selectech[96]

Microcool and Nanomagnetics marketed products which offered properties that were vastly superior to those of incumbent materials. In each case, they tried to attack applications in which the insertion factors had strong limiting effects, and failed in those applications. The experience of Selectech, an injection molder of recycled plastics, was very different. Selectech's new material was not vastly superior to incumbent materials—it was recycled from trashed plastics—but Selectech followed the materials commercialization pattern and has enjoyed quick insertion in each market it has attacked.

Selectech was founded by three environmental entrepreneurs in 1995 "with the objective of becoming an integrated, low cost manufacturer of injection molded plastic parts using post-consumer and post-industrial feedstock". Its core intellectual property is a process that can convert "commingled, dirty plastic into commercially viable injection molded products"[97]. Given the highly technical nature of plastics, it is obvious that "commingled, dirty plastic" did not offer properties to match those of virgin grades. The basic Selectech feedstock was PVC and HDPE wire coating that had been removed from wire by copper recovery companies.

Selectech's initial strategy was to produce recycled products for other companies, who could use the products to enhance their environmental image. Because its feedstocks were wither free or very inexpensive, Selectech could offer substantial savings in many applications. However, these savings were not enough to overcome the risks of failure in the application markets that Selectech had chosen to attack. The costs of plastic in these applications constituted only a small part of the overall costs of the application itself, and the application manufacturers were unwilling to shoulder the risk of a new material for these small savings. The fears of these application manufacturers were perfectly rational—why would computer makers, whose plastic cases accounted for less than 1% of the total cost of the computer want to risk warranty repairs if the cases broke? This would have been a bad decision even if Selectech had given the cases to the computer companies at no charge!

Selectech changed course as soon as it realized the flaws of its original strategy. It decided to focus on large parts, where any savings it could offer would be compelling. However, its ability to enter this market was limited by the its appearance—"commingled, dirty plastic" did not make beautiful parts, especially with Selectech's early process. It chose a market that was very simple, relatively new, and in which its product could offer significant cost advantage: plastic parking stops. (see figure 4.7).

Figure 4.7: Selectech plastic parking stops.

The limiting factors of the parking stop market were minimal. Since they were accustomed to dealing with concrete stops which routinely crack, chip, and break, users of plastic stops were very fault-tolerant. The light weight of the plastic stops made them very easy to replace and even gave them portability—something which was hardly available with concrete stops. They also offered color throughout the stop, so painting was not required. In the words of the founder, the Selectech parking stop "look(ed) like crap, that's what it's supposed to look like!".

Plastic parking stops had been available previous to the Selectech product, but had been either too thin to be reliable or too expensive to appeal to a wide market. Selectech was able to become the largest producer of parking stops within one year. However, the plastic parking stop market is quite small (stops last a long time!), and was insufficient to build a sustainable business.

The parking stop market helped Selectech establish its large part injection molding capability, and also built a degree of credibility—the plastic had been used successfully in an application that seemed demanding. Selectech used its experience and credibility to move into its platform market: large plastic planters. The overall planter market was roughly 500 times the size of the plastic parking barrier market, so it offered much more room for growth.

Selectech's EcoPlanters were designed to enter the existing planter market through existing channels to compete with terracotta and HDPE. The EcoPlanter material offered advantages over terracotta in that it was practically unbreakable and would not crack in cold weather. It offered both price and performance advantages over HDPE, which had to be formed into pots by rotomolding, a very slow process that could only yield hollow parts. The solid EcoPlanters were much tougher, and were less expensive (see figure 4.8).

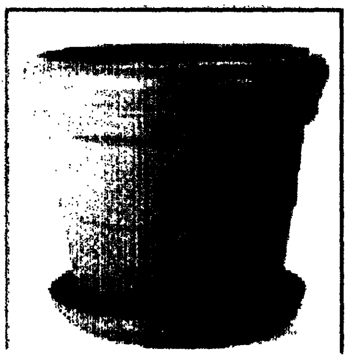

Figure 4.8: Selectech EcoPlanter

Although the planter market was more sensitive to appearance than the parking stop market, Selectech had achieved sufficient finish quality to be competitive. The EcoPlanter was a standalone product, with a short manufacturing value chain, and Selectech used its parking stop experience to quickly work out any potential technical deficiencies. However, despite the simplicity of the planters, value chain obstacles did exist. The first value chain obstacle was distribution. Selectech received orders from Wal Mart and Home Depot very quickly, and found that each company demanded that the planters be shipped to stores throughout the US, presenting a significant logistical challenge for Selectech. Each company also required special types of labeling, packaging, and palletting. Since Selectech was a relatively small company, it couldn't afford to automate these processes, and the packaging costs were quite high.

Selectech made significant inroads into the large planter market, which it still dominates. However, further growth in planters would have required it to develop a much wider variety of planters, and to develop a much higher degree of operational expertise, accompanied by large investments in logistics management. Given the investment that would be required, Selectech decided to devote only enough resources to planters to maintain its position, and to divert the rest of its development budget to more attractive market: commercial free lay flooring.

The commercial flooring market was far larger and more competitive than either of Selectech's previous markets. Standards had been established, and users were not tolerant of failure. Furthermore, competition was fierce. Despite these challenges, the commercial hardsurface flooring market was very large, and producers enjoyed healthy profit margins. The properties of Selectech's recycled plastic were well suited to the market. In short, the pull to flooring was irresistible.

Selectech believed that its experience with the home improvement industry would be applicable to its new enterprise. However, Selectech found that its commercialization experience with parking barriers and planters would be more important than its technical experience or the relationships it had built with big box stores. It chose to enter the flooring market with an enabler application.

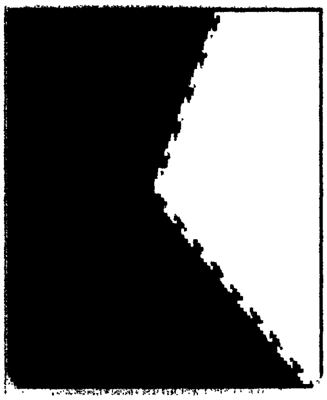

Figure 4.9: Selectech SelecTile

The first Selectech flooring product was SelecTile, an interlocking plastic tile system (see figure 4.9). The system was "free-lay", meaning that it did not need to be glued to a subfloor. This feature greatly decreased installation costs and allowed SelecTile to economically solve problems that had been previously been very expensive to fix, such as replacing flood damaged vinyl tiles in commercial applications. In fact, one of the first applications for SelecTile was in a carpentry supply store in which a faulty floor had been installed. Replacing the floor with conventional tile would have required the store to be closed for nearly a month, during which time the lack of cash flow would have driven it out of business. Instead, SelecTile was overlaid onto the existing floor over a weekend, allowing the store to continue business as usual.

The SelecTile product line was industrial—it was not attractive. However, Selectech used it to establish credibility in the market and to develop the technical capabilities it needed to enter the mainstream free lay market with FreeStyle flooring. At the time of this writing, this entry was just beginning, but the product was received quite well. It had been used in several large retail stores, and was beginning to find acceptance in home garages.

By starting with application markets that were small and simple, Selectech was able to avoid insertion factors that might have limited the limited the progress of its new material. The material found commercial applications quite quickly, despite the fact that its properties were worse than existing applications. The learning and credibility it established in its first market, parking stops, allowed it to move easily into EcoPlanters, which generated Selectech's first profits. Using the planters as a platform, Selectech moved into the more competitive and rewarding flooring market with a disruptive entry. In short, Selectech followed the materials commercialization pattern, and achieved quick insertion into all of its application markets.

Conclusions and Contributions

The analysis presented in this chapter adds significant resolution and understanding to the pattern of materials commercialization in several ways. It reinforces the fact that that the factors that lead to quick insertion are different from the factors that lead to deep market penetration. This is a very important point for the materials industry, because it requires different attitudes toward research, development, and commercialization.

This analysis has also refuted the traditional belief that serendipity is a major driver of insertion delay. Most of the biggest applications were known early in the lives of the major plastics, but still did not enter the market quickly, despite clear value propositions that propelled them to incredible commercial success after insertion. If serendipity did play a role in the biggest applications, it occurred during development of the material. The analysis has also shown that, contrary to popular belief, entrant materials did not need to be lower than competitors to be inserted into the market. Finished costs of most of the plastics were equal or higher than the materials they replaced at insertion; they were inserted on merit, for some property that could not be matched by the incumbents. Even the plastics that were inserted at lower cost offered additional value beyond price.

The fact that the major plastics were more expensive than their competitors yet still displaced them constitutes an anomaly in Christensen's disruptive theory of innovation[98]. Christensen asserts that large-scale replacement happens when several conditions are met, one of them being that the entrant is less expensive and attacks from the bottom up—the entrant actually offers worse performance in conventional measures, but is better on other measures. In most of the replacement cases, plastics offered new properties that couldn't be matched at a similar price by incumbents. However, the plastics captured this value by entering at higher prices, not from below.

The most important limiting insertion factors for the biggest applications of the major plastics were technical deficiencies and value chain obstacles. The finding that technical deficiencies limit insertion of materials into applications would probably seem intuitive, obvious, and mundane to most materials scientists; after all, why would anyone place a material in an application for which it is not well suited? However, a component of this finding has important implications for research and development of materials. Many of the most important applications of the major plastics weren't suggested until later in the lives of the plastics *because the properties of the plastics weren't developed to the point that people could see their value.* If this pattern is generalized, it indicates that specialized development approaches, though attractive in the short term because they keep development costs down, face the distinct danger of concealing important properties of a material and missing major market opportunities. Indeed, finding the right balance between breadth of development and market potential could be a fruitful area of further research. Preliminary evidence suggests that the cost of lost opportunities may make it far less expensive to undertake a broader (and more costly) development approach so that both marketers and users can more easily identify potential applications.

The second important limiting factor, value chain obstacles, is well known but widely overlooked, making it interesting and important to study. The evidence is strong that value chain factors play an important part in insertion delays. In the course of this research, several experts have proclaimed that "materials just take a long time to sell". This seems to suggest that users are unwilling to change, even in the presence of superior value. The field of switching cost analysis has shown that this is rarely the case—unless there is a compelling reason not to change[99]. Value chain obstacles may be the compelling reasons that products don't change materials as often or as quickly as producers of new materials might like. Subsequent chapters of this thesis will show that value chain obstacles are understood by experts, and that judgments on the degree of challenge associated with value chain obstacles correlate quite well with the insertion delay of materials into applications. It will also be shown that strategies exist for dealing with value chain obstacles—they can be managed and manipulated to the benefit of new entrants.

As bigger materials data sets become available, further research can focus on identifying exactly which value chain factors are most important. It is likely that specific value chain factors will vary among applications, but useful patterns may emerge.

Technical deficiencies were shown to be the insertion factors with the largest effect—their presence added over 11 years of insertion delay. Value chain factors were less important, but still added four years of insertion. The presence of these factors showed a strong pattern of insertion delay. Neither technical deficiencies nor value chain obstacles were cited as limiting for any of the earliest big applications of the major plastics. Value chain obstacles were the dominant limiting factors for the applications that achieved insertion in 2-6 years after commercialization of the plastics. Both technical deficiencies and value chain obstacles were cited as factors in the majority of the biggest applications that were inserted more than 6 years after commercialization.

The progression of insertion factors correlates well with the materials commercialization pattern shown in chapter three. If the two are overlaid, it becomes apparent that:

1. Applications in the enabler phase faced few limiting insertion factors
2. Applications in the platform phase faced value chain obstacles
3. Applications in the widespread substitution phase faced both technical deficiencies and value chain obstacles.

Given the characteristics of the applications in each phase, the progression of limiting factors is logical. Characteristic applications in the enabler phase were very simple (they did not have large value chains) and solved new problems based on their properties (the properties that were sought were already present—no new technical development was necessary). Characteristic platform applications were also adopted because of their properties (no new technical development necessary), but had to replace existing materials in major markets. Replacing existing materials is a large undertaking, since value chains must change to adapt to the new material. Furthermore, existing markets had established expectations, so value chains had to be refined to the point that they produced products that could meet those expectations while offering the additional value brought by the new material. Plastics in widespread substitution applications entered into markets where they offered less revolutionary performance, and could be subject to switching based on cost. Competition in this phase requires that a material be competitive based on both technical competence and value chain refinement. This is only possible with significant development of both areas.

The case studies presented in this chapter highlight the importance of insertion factors. Although the often appear attractive, markets with high technical barriers and inflexible value chains are very difficult to enter for new materials. A more reliable path is to identify and enter markets in which the insertion factors are minimal, and then progress into other applications as the material becomes more mature and markets become more familiar with it.

Once a material shows potential value, and can be produced reliably, market selection becomes the most important competency of the producer.

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Chapter 5: The Effects of Value Chain Complexity

Introduction

It was shown in chapter four that technical deficiencies and value chain obstacles were important barriers to quick insertion of the 34 biggest applications of the major plastics. Insertion delay caused by technical deficiencies is attributable to two factors: the time required to solve technical problems and the concealing effect of undeveloped properties on new application identification. It is well known that some technical challenges are more difficult to solve than others, and that a corresponding distribution exists in the time required to solve them: difficult problems often take longer. The field of materials science is constantly producing new tools with which technical problems may be solved, with the goal of finding the best solutions in the shortest amount of time. This development effort has made significant contributions—companies like Accelrys have demonstrated the ability to develop new polymers from scratch in less than three years [1]! New technologies will doubtless lead to even faster development of future materials.

From a strategic standpoint, the correlation of technical deficiencies with delayed suggestion of new applications is more interesting. The sequence of technical solutions and application suggestions indicates a causal relationship: technical deficiencies caused suggestion delays. The properties that made materials attractive for applications had to be exposed by technical advancements for the applications to be proposed. This phenomenon may also partially explain the quick insertion of PP and HDPE. The inventors of PP and HDPE (Phillips and Ziegler) both licensed their technology to several US producers, and those producers entered the market simultaneously. Because the producers were all entering simultaneously, they had incentives to develop different properties of the materials. Having developed different properties, each producer could identify different markets, leading to a barrage of insertions very soon after commercialization of the materials[2].

PP and HDPE were also unique in that they were the only major plastics that were highly compatible with existing processes upon commercialization. Both were billed as polyolefins, similar to existing low density polyethylene except that they would offer "improved stiffness", "better gloss or finish", and be "harder, with higher temperature performance"[3]. They would be superior in every property that mattered, and thus offered a clear value proposition. They were claimed to work on the same molds and extrusion machines, with slightly higher temperatures required. Integration into existing value chains was not as seamless as was promised, but turned out to be quite easy.
This ease was crystallized into history when "scores of extruders" made 20 million HDPE hula hoops in 1958, the first full year of HDPE production[4].

The field of materials science was developed to deal with technical deficiencies of materials, and has done a remarkable job of improving their quality. However, very little attention has been given to the development of techniques for dealing with the effects of value chain obstacles. The previous chapter established that value chain obstacles are limiting factors to insertion of new materials. This chapter will seek to give additional resolution to the concept by measuring the effects of complexity in application value chains on insertion times of new materials. It will be shown that more complex application value chains correlate to longer insertion times, and a theory of switching costs will be presented to explain the results.

Approach

This chapter will compare insertion times of historical plastics applications to three instruments that measure complexity in their value chains. One strictly quantitative instrument will be used, along with two instruments based on expert assessment.

Historical Data

Through the course of this research, a database of basic facts on 145 key plastics applications was built from the annual reviews of *Modern Plastics*. Each of these applications was commercially important, either as a stepping stone for development of a plastic or as a major contributor to overall sales. This database includes insertion dates, stated reasons for adoption, application description, and industry classification (aerospace, construction, appliances, etc.). It is complimentary to the data presented in chapter three; it contains less information about a greater number of applications.

In consideration of the schedules of the experts who would be interviewed (see subsequent section), a representative sample of 58 applications—40% of the original pool—was selected. Screening of applications for this smaller pool was based on several criteria:

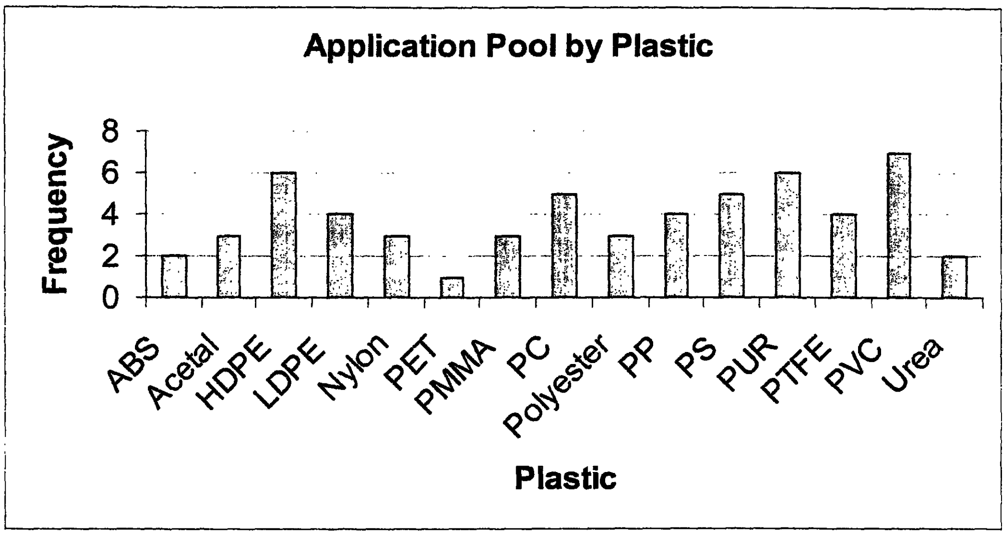
1. *Minimal technical deficiencies*—since this research intends to identify value chain effects, screening was performed to remove applications for which a major portion of insertion time could obviously be explained by technical deficiencies. This removal is a possible source of bias, since technical deficiencies were usually coupled value chain obstacles in the analysis in chapter four. However, this bias is acceptable, since it would tend to attenuate the effect of value chain obstacles; if the effect is present with this bias, it will be stronger without it.

2. *Application familiarity*—an effort was made to select those applications that would be reasonably familiar to experts. Some of the applications in the original database were either highly specialized or short-lived, and would require significant explanation by the researcher to the experts. In order to reduce the risk of the interviewer biasing the experts, these applications were removed from the pool. It should be recognized that reducing this bias came at the risk of introducing a stronger bias toward successful applications, since short lived applications were excluded. However, this tradeoff was judged to be acceptable because the broader pool from which the applications were selected was comprised only of the successful plastics.

3. *Broad representation of plastic type*—while the pool in the previous chapter was selected from only the largest commodity plastics, this pool was designed to include both commodity and engineering plastics. At least one application for each of 15 plastics was included. Included plastics were acrilonitirile butadeine styrene (ABS), acetal, high density polyethylene (HDPE), low

density polyethylene (LDPE), polyamide (nylon), polyethylene terephthalate (PET), polymethyl methacrylate (acrylic/PMMA), polycarbonate (PC), polyester (thermoset), polypropylene (PP), polystyrene (PS), polyurethane (PUR), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), and urea. Figure 5.1 shows the distribution of the pool by plastic.

Figure 5.1: Distribution of application pool by plastic.



4. *Broad representation of industry*—there are seven major application categories for plastics: 1) transportation, 2) electrical (including appliances), 3) building and construction, 4) consumer and institutional, 5) packaging, 6) industrial, and 7) furniture[5]. Each of these industries was represented in the pool by several applications. More applications were taken from the automotive industry and the consumer products industry than the other industries, reflecting the importance of those industries to plastics, as well as the preponderance of *Modern Plastics* to report them. A more balanced inclusion of industries would most likely create less bias, but the representation chosen here is acceptable given the constraints of the other selection criteria. Figure 5.2 shows the distribution of the application pool by industry.

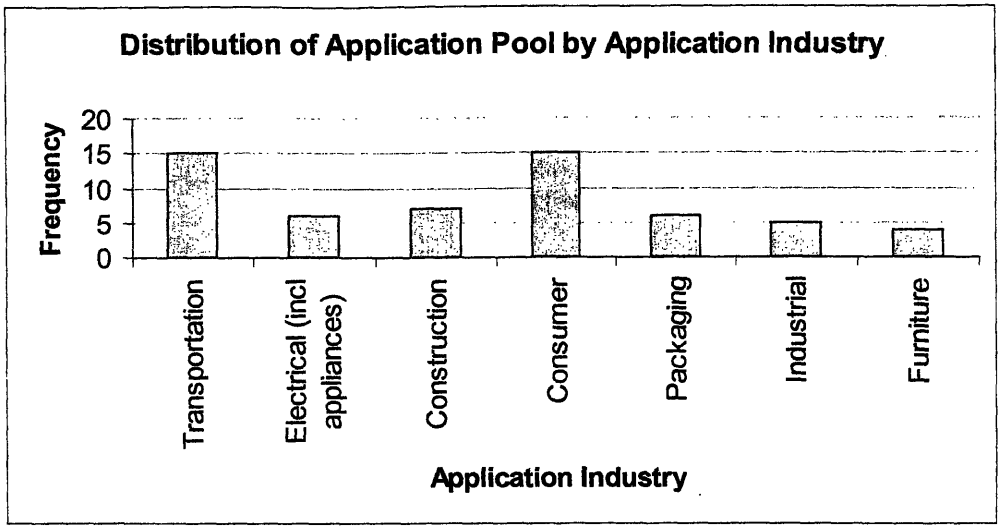


Figure 5.2: Distribution of application pool by application industry

5. *Broad variation of insertion time*—in order to maximize the possibility of finding meaningful results, applications with a broad distribution of insertion times were selected. The mean insertion time for the pool of 145 applications was 14.1 years, with a standard deviation of 13.1 years. The mean time of insertion for the selected pool was 11.12 years, with a standard deviation of 12.33 years. The shorter mean insertion time is attributable to the removal of many of the applications with technical deficiencies, but the degree of variation is similar. Figure 5.3 is a histogram of the insertion time distribution of the selected applications.

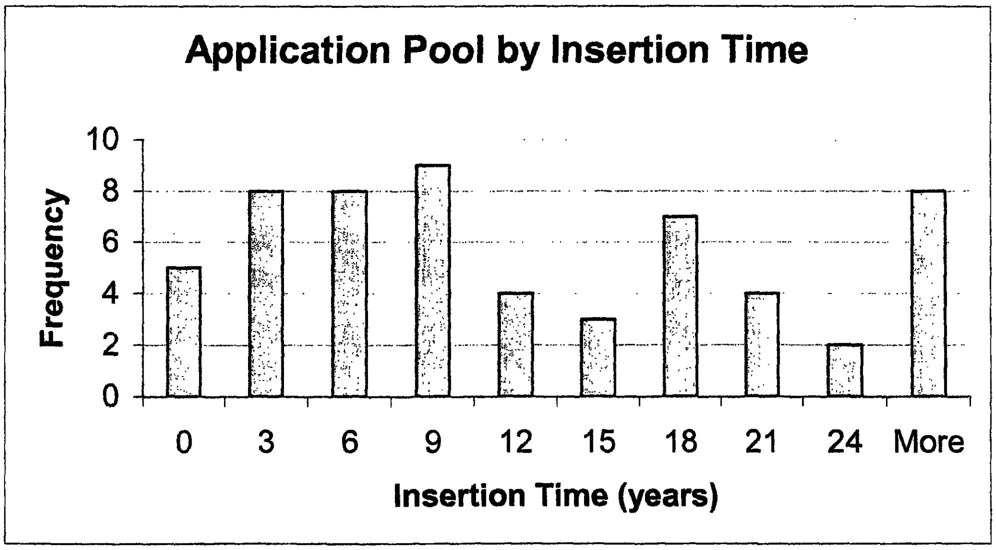


Figure 5.3: Distribution of application pool by insertion time.

Appendix B shows a table of the applications and included data for the pool.

Value Chain Complexity Measures

This analysis will build on the value chain definitions presented in chapters two and four: the value chain is the set of activities that occurs in transforming a material into a finished product that is sold to an end user. It includes product design, material processing, part assembly, product distribution, marketing, sales, and maintenance. Since these activities are affected by codes and standards, codes and standards are also considered value chain factors. Because this analysis attempts to reveal challenges faced by materials manufacturers in introducing new products, raw materials production and materials manufacturing are not considered part of the value chain in this analysis. Customers are not considered as part of the value chain, either, since their acceptance of the product is a different issue.

A generic materials value chain is shown in figure 5.4.

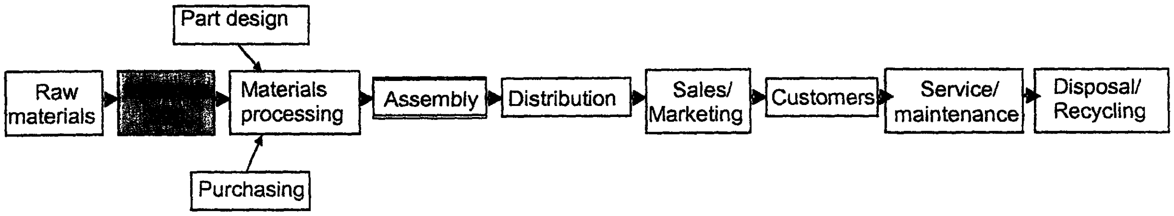


Figure 5.4: Generic materials value chain. Everything to right of materials manufacturing is included in this analysis, with the exception of the customer.

The concept of value chain analysis was established by Porter in 1980 as a tool for developing sustainable competitive advantage based on cost and differentiation[6]. Porter's approach focused on identifying opportunities in industries, with the specific goal of assessing industry attractiveness. He presented five measures to consider in this assessment: industry rivalry, barriers to entry, threat of substitutes, bargaining power of suppliers, and bargaining power of buyers[7]. This method has been widely distributed, and seems to have proven quite effective at accomplishing its stated task. However, this type of traditional value chain analysis is less applicable to the assessment the effects of the value chain in delaying insertion time.

Because this analysis attempts to measure insertion delay instead of industry structure, it was necessary to create a different approach. The approach taken here was designed to test the hypothesis that a progressive effect exists between value chain complexity and insertion times: more complex application value chains correlate with longer insertion times for new materials into those applications. A positive result would implicitly assert that there are inherent factors in value chains that extend insertion.

There are many competing approaches to measurement of complexity, most of which focus on the number of elements and interdependencies of a system[8]. Some are quantitative and others are qualitative, based on the opinions of experts. A simple and valid quantitative approach for measuring complexity in a value chain would be to create nodes in the chain according to function (i.e. manufacturing, distribution, etc.), and then to count the number of nodes and the connections between the nodes in the chain. However, this and several other quantitative types of measurement would be problematic in most historical contexts, because technology changes cause changes in value chain structures. Effective historical quantitative assessment of complexity in value chains would require contemporaneous accounts of industry structure and value chain flow. Although clues about industry structure were provided by the sources used for this research, they are far too incomplete for meaningful quantitative analysis.

Since the limitations of historical data prevent the direct quantitative measurement of value chain complexity, a triangulation of three value chain complexity measurement instruments was used. The first instrument is quantitative; the second and third are based on the assessment of six experts in the field of materials and materials applications.

All of the experts are recognized authorities in the fields of materials engineering and materials applications. An attempt was made to select a broad variety of experts, with viewpoints of research, processing, materials design, and application design all represented. The names and relevant credentials of each expert are shown in appendix C.

Each expert was interviewed by the same researcher (the author), and was asked to rate each application according to the scales provided. In order to provide a consistent basis for response, each expert was given the same explanation of the basic facts of each application, including the year of introduction, the exact application, and a brief explanation of use (when necessary). Great care was taken to avoid influencing the responses of the experts, and additional information for each application was given only if requested. Each interview lasted 2-3 hours[9].

Method 1: Total Number of Parts

If it is recognized that a value chain is nothing more than a series of steps that adds value to a product, a tractable quantitative instrument to measure complexity can be created. Since each step in the value chain should aim at creating or delivering part or parcel of a final product, it is reasonable to use complexity of a final application itself as a proxy for value chain complexity. The most practical (and probably most common) way to assess complexity in an application is to simply count the number of parts therein[10]. This will be the first instrument used in this analysis, and will be called the "total number of parts instrument".

For the total number of parts instrument to work, it is necessary to create a clear definition of the concept of an application. In this analysis, the concept of application will refer to the product that was purchased by the consumer at the point of insertion. For example, if PP tumblers were the first applications of the category "PP housewares", the number of parts counted would be 1, since a tumbler is a stand alone product that is purchased by the end consumer. However, if the first application for the application category "nylon auto parts" were a speedometer gear, the number of parts counted would be ~40,000, the number of parts in an automobile, the product that is purchased by the end consumer. There are two exceptions to this rule—HDPE and PVC wire coating. Because they are used in a wide range of applications, and the end product bought by the consumer is electric power, the appropriate point of parts counting is the wire itself; this would include the wire and its various shielding components.

Because of the wide range of applications contained in the sample pool, it was necessary to use a broad scale with the number of parts method. Otherwise, the large number of parts in aircraft and automobile applications would heavily skew the numbers, making statistical analysis all but meaningless. The scale that was used is listed in table 5.1.

Scale Number	Number of Parts	Examples
1	1	Hula Hoop
2	2-10	Industrial cooking pan
3	11-100	Faucet
4	101-1,000	Scientific calculator
5	1,001-10,000	Washing machine
6	10,001-100,000	Automobile
7	>100,000	Commercial Jet

Table 5.1: Scale of number of parts method

Appendix D shows the application definition for each application, its rating, and the sources for the ratings.

Method 2: Number of Parts Affected

While the total number of parts instrument may be a reasonable proxy for the complexity of the value chain of a product, it is arguably a poor measure of the value chain complexity that is faced by a material when it is being inserted into an application. The measure is a gross oversimplification, and would tend to overstate the impact of materials changes in large assemblies: it is unlikely that the entire value chain of an aircraft or automobile would be impacted by a material switch in a part in a subassembly. For example, the entire value chain of a car would not be changed because of a switch from brass to nylon in speedometer gears. However, with simpler applications, such as PP tumblers, a materials switch could have drastic impact on the entire value chain.

It seems, then, that a more accurate and relevant measure of the degree of value chain complexity faced by a material at insertion would be a count of the number of other parts in the final application that would be affected (meaning changed in some way) by such a switch. Unfortunately, the exact data for these applications is very difficult to obtain, since it would involve review of design documents for products made by dozens of companies several decades ago. Another possible approach would be to compare products before and after a materials switch, but this would also be intractable unless all of the applications were found in a museum. Otherwise, parts would be extraordinarily difficult to identify, find, and obtain, and may have degraded[11].

Because of the difficulty in finding an exact measure for the number of other parts affected by the introduction of historical materials to their applications, a different approach was taken. Each of the experts was asked to provide an estimate of this number, on a scale of 1-7. The scale shown to experts is displayed in table 5.2; because the number of parts affected was generally much smaller than the number of parts in the applications themselves, the scale is different from table 5.1. Construction of this scale was largely arbitrary--it reflects the judgment of the author and of several other materials engineers regarding the appropriate degree of resolution for the research question[12].

Scale Number	Number of Other Parts Affected	Final Application Example
1	0	Hula hoop (no supporting parts)
2	~1-5	Milk jug
3	~5-25	(none given)
4	~25-50	Auto instrument panel
5	~50-100	(none given)
6	~100-1000	Auto body
7	>1000	777 carbon fiber tail section

Table 5.2: Scale of number of parts affected method

This method will be called the "number of parts affected instrument".

Method 3: Change Required in Value Chain

While the first two instruments use the end product as an indicator of value chain complexity, the third instrument uses the value chain itself. For the instrument called "value chain difficulty of change", experts were asked to estimate, on a scale of 1-7, the degree of change required in the value chain of the final application to accommodate the material change. The underlying assumption of this proxy is easy to see: both difficulty of change and complexity increase in a value chain as the number of value chain elements increases. That difficulty would increase is obvious—all else equal, it is more difficult to manage more elements than fewer elements. That complexity would increase is also obvious, but it is important to recognize that additional complexity results from more than just an increase in the number of elements—it results from an increase in the interconnections between the elements. In fact, an increasingly popular method of measuring complexity in engineering systems is to measure the number of interconnections between elements[13].

In the interview, experts were given an overview of the value chain concept, and were asked to focus specifically on manufacturing challenges, code and standard obstacles, and distribution challenges. Members of the expert panel were not expected to be experts in each of the areas of the value chain, but rather were asked to use judgment, in light of expertise in some of the areas, to create a ranking of the overall impact that a material change of part in a final application might have on the value chain of the final application. Since a variety of expertise was represented by the panel, the responses paint a composite picture of the difficulty of change.

The measure of difficulty of change in the value chain is itself a composite. It is a function of both the number of elements that are affected by a materials change and the degree of change required in each. Experts were instructed to consider both, with explicit recognition that cost of changing the value chain, of course, is a function of the same factors[14].

It is acknowledged that separating the number of elements changed from the magnitude of change required in each element would be useful. However, this research attempts simply to establish whether a progressive relationship exists between value chain complexity and insertion time. If this relationship is established, future work can focus on separating the factors. This type research would most likely require many more data points than are used here.

The experts were given the scale shown in table 5.3 as calibration.

Scale	Example
1	Aluminum gym weights
2	Aluminum heat sinks
3	Aluminum wheels
4	Aluminum transmission casings
5	Aluminum engine blocks
6	Aluminum car bodies (Audi A8)
7	CFRP replacement of Aluminum in 777 tail section

Table 5.3: Scale of difficulty of change in the value chain method.

Because the reader may not be familiar with the applications listed in table 5.3, the explanation provided to the experts is also provided here.

1. **Aluminum weights**: (final application: gym weights) aluminum can be used in barbells for gym weights. There is almost no change required in the value chain to do this—no redesigns would need to occur, and the aluminum could be cut or cast in the machines that currently make steel or iron weights. The costs of change would be minimal.

2. **Aluminum heat sinks:** (final application: personal computers) extruded aluminum can be used instead of folded copper in personal computer heat sinks. Some design cautions need to be taken, such as thermal coupling, but the heat sink clips directly on to the chip, and nothing else in the computer needs to change (unless the heat sink is too big). It is relatively inexpensive to switch heat sink materials.

3. **Aluminum wheels:** (final application: automobiles) the huge aftermarket for aluminum wheels shows that they can easily replace steel wheels. However, to introduce them, automakers had to invest in new fabrication and casting equipment and performed extensive testing to ensure that they would not fail or cause adverse effects.

4. **Aluminum transmission casings:** (final application: automobiles) aluminum transmission casings are very common, but required significant investment to introduce. Automakers had to redesign the transmission casing, and probably many of the valves, fittings, and mounts, in order to introduce them. They also had to undertake extensive testing and make large investments in specialized

casting and fabrication infrastructure. However, it is doubtful that entire transmission redesigns had to occur to incorporate them.

5. **Aluminum engine blocks:** (final application: automobile) aluminum engine blocks were considerably more costly to introduce than any of the previous applications. They interact with many engine parts, and are key components in the subassembly process. New casting and machining techniques had to be developed, parts had to be redesigned, subassembly lines had to change, and vehicle designs had to change to accommodate the weight and vibration characteristics of aluminum blocks, leading to very heavy costs. Despite these changes, aluminum blocks did retain a degree of interchangeability with iron blocks. Vehicle maintenance and final assembly did not need to change much to accommodate the new material.

6. **High volume aluminum bodies in automobiles:** (final application: automobiles) switching to aluminum bodies would require a massive redesign not just of a vehicle, but of the supply chain and the processes required to manufacture and assemble the vehicle. Current stamping processes cannot deal with the springback of aluminum, and would have to be redesigned; the welding processes would need to be replaced; paint processes would change. Many interface parts would need to change. Nearly a century of design knowledge in steel bodies would be largely obsolete, and extensive testing would need to occur. Extraordinary costs would be incurred in making this switch.

7. **Replacement of aluminum in the Boeing 777 tail section:** (final application: commercial aircraft) the 777 design was brand new, but Boeing had to create entirely new competencies in design, engineering, manufacturing, and maintenance in order to use carbon fiber instead of aluminum in the tail section of aircraft. It has been estimated that nearly $1.2 billion was spent developing the carbon fiber tail[15]. Extensive design, manufacturing, qualification, and development issues had to be overcome, and thousands of other parts had to be redesigned to make the tail section work.

Results

In order to provide a measure of the effect of value chain complexity on insertion time, the results of the number of parts analysis and the expert ratings were compared to the time delay between the recorded year of commercialization of each material and the year that the material was first used commercially in each rated application. This delay period was named "insertion time" in a previous chapter.

Actual scores are displayed in appendix E. In order to shown progression, the results of each measurement instrument are displayed in several ways. The first display is a bar graph that compares mean insertion times for four separate categories of each instrument. Each category is based on the pool mean and standard deviation of the instrument, as reported in appendix D:

1. Very low: rating greater 1σ below the mean.
2. Low: rating between mean and 1σ below mean

3. High: rating between mean and 1σ above mean
4. Very high: rating greater than 1σ above mean

Because the measurement categories are imperfect, a second bar graph is displayed comparing mean insertion times for broader categories of each measurement method: above the mean rating and below the mean rating.

A chart with summary statistics and one sided t-tests is shown to test the integrity of the categories. The following progression hypotheses were tested (where T=insertion time of the applications in each category). For the four category model:

Null Progression hypothesis (H_o): $T_{\text{Very high}} \leq T_{\text{high}} \leq T_{\text{low}} \leq T_{\text{very low}}$
Alternative hypothesis (H_a): $T_{\text{Very high}} > T_{\text{high}} > T_{\text{low}} > T_{\text{very low}}$

For the two category model:

Null Progression hypothesis (H_o): $T_{\text{above mean}} \leq T_{\text{below mean}}$
Alternative progression hypothesis (H_a): $T_{\text{above mean}} > T_{\text{below mean}}$

In order to provide a measure of inter-rater reliability, the results of the expert rating instruments were pooled in two ways for the bar graphs. First, a mean of the all of the expert ratings was found for each application. Second, a mean of expert ratings was found for each of the applications excluding the high ratings and the low ratings (if the high and low were unique; if the high or low was duplicated by more than one expert, it was included).

A scatter plot is also displayed for each method to compare actual ratings to insertion times. A regression line is shown on each scatter plot, followed by SPSS regression output.

Number of Parts

Bar graphs showing the relationship of the number of parts value chain complexity measurement method and the insertion time of plastics applications are shown in figures 5.5 and 5.6, and are followed by a chart of summary statistics in table 5.4.

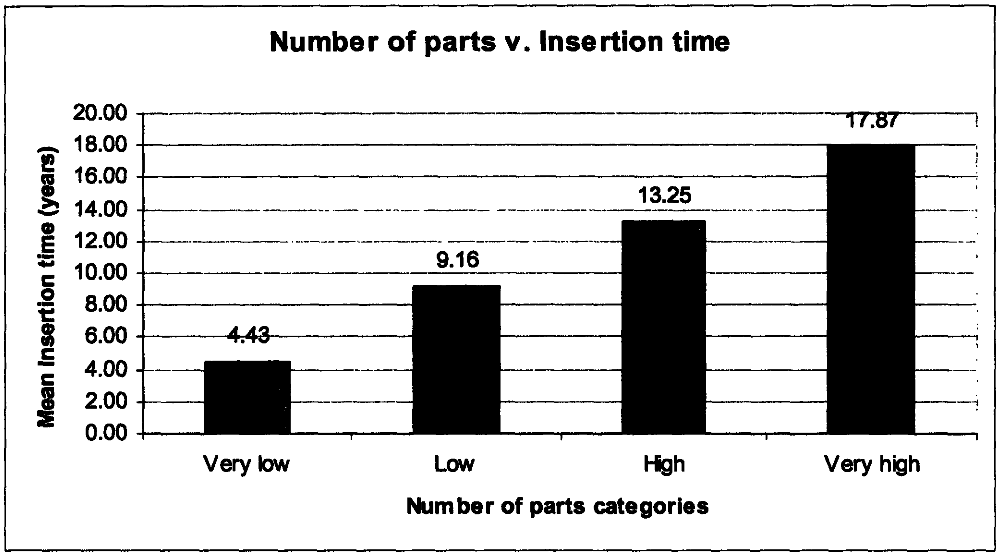


Figure 5.5: Four category display of number of parts v. insertion time.

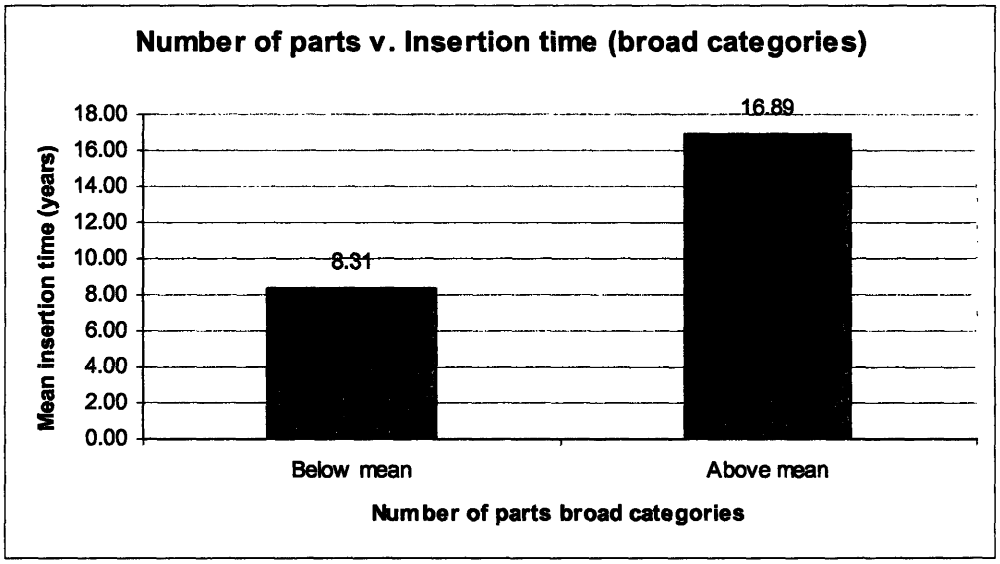


Figure 5.6: Broad category display of number of parts v. insertion time.

Summary Statistics and T-Tests for Number of Parts Instrument					
	Total Number of Parts Instrument Mean Insertion	Standard Deviation	N	T score (compared with next larger category)	p < next larger category
Very low	4.43	6.60	7	1.44	0.0847
Low	9.16	12.08	32	1.06	0.1653
High	13.25	6.47	4	0.96	0.1776
Very high	17.87	13.69	15		
Below mean	8.31	11.37	39	2.52	0.0083
Above mean	16.89	12.51	19		

Table 5.4: Summary of number of parts method categories.

Both of these graphs show a rather dramatic (nearly linear) relationship between the number of parts in an application and insertion time. However, the statistical summary shows that the null progression hypothesis can be rejected at the 5% confidence level (p=.008) only in the two category model ($T_{\text{above mean}}>T_{\text{below mean}}$). It cannot be rejected for any of the categories in the four category model, indicating that the higher resolution categories are not robust.

A scatter plot comparing number of parts and insertion time is shown in figure 5.7. It is followed by a regression analysis in table 5.5 of the linear equation.

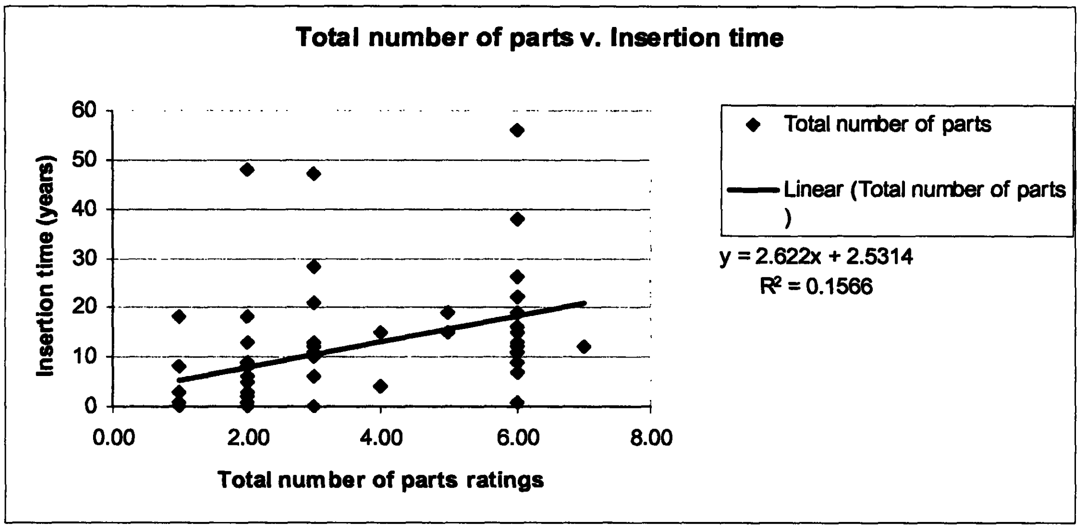


Figure 5.7: Number of parts scatter plot.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.396[a]	.157	.142	11.4297

a. Predictors: (Constant), TOTALNUM

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1358.371	1	1358.371	10.398	.002[a]
	Residual	7315.784	56	130.639		
	Total	8674.155	57			

Coefficients[a]

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	2.531	3.057		.828	.411
	TOTALNUM	2.622	.813	.396	3.225	.002

Table 5.5: Regression analysis of trendline shown in figure 5.7

This analysis shows that the total number of parts instrument renders results that are statistically significant (p=.002) in explaining the insertion time of the examined applications. However, these results explain only 15.7% of the insertion time variation. The regression coefficient shows that one additional rating point corresponds to an additional 2.6 years of insertion time.

Number of Parts Affected

Bar graphs showing the relationship of the number of parts affected value chain complexity measurement method and the insertion time of plastics applications are shown in figures 5.8 and 5.9. The graphs for the complete set of ratings and the ratings excluding high and low measurements are shown together. The graphs are followed by charts of summary statistics in tables 5.6 and 5.7.

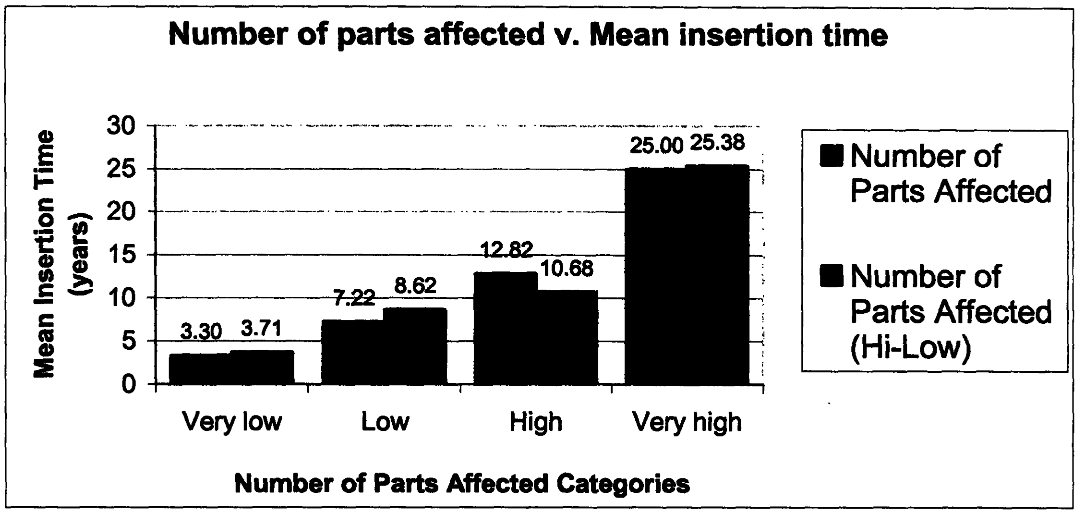


Figure 5.8: Number of parts affected v. mean insertion time (four categories).

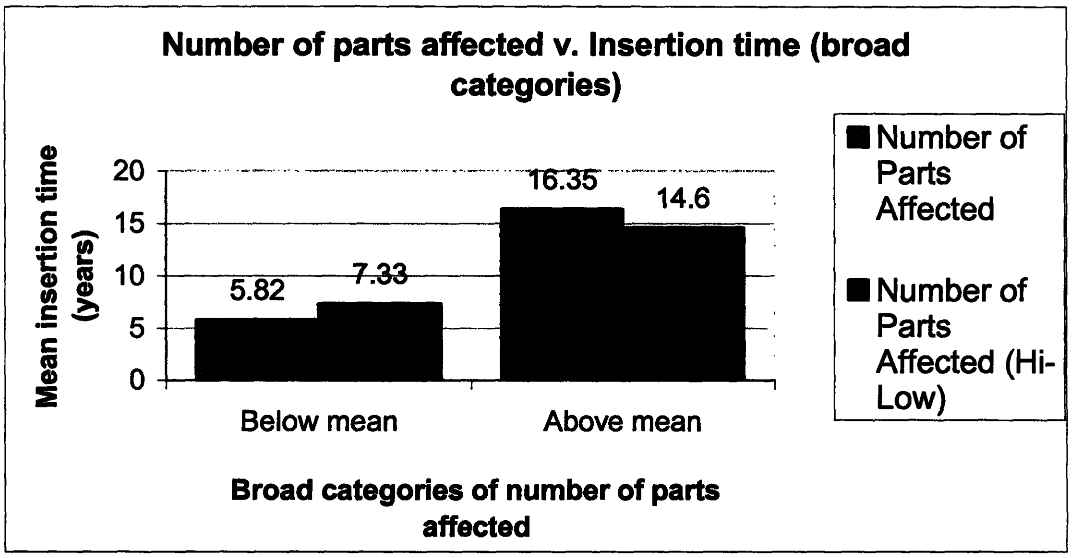


Figure 5.9: Number of parts affected v. mean insertion time (two categories).

Summary Statistics and T-Tests for Number of Parts Affected Instrument

	Number of Parts Affected	Standard Deviation	N	T score (compared with next larger category)	p < next larger category
Very low	3.30	5.35	8	1.84	0.0411
Low	7.22	8.90	22	1.73	0.0477
High	12.82	13.29	18	1.88	0.0435
Very high	25.00	14.23	10		
Below mean	5.82	5.93	28	3.42	0.0007
Above mean	16.35	14.47	30		

Table 5.6: Summary of number of parts affected instrument categories.

Summary Statistics and T-Tests for Number of Parts Affected Instrument (with high and low ratings removed)

	Number of Parts Affected	Standard Deviation	N	T score (compared with next larger category)	p < next larger category
Very low	3.71	6.37	7	1.4818	0.078
Low	8.62	10.41	21	0.063	0.2666
High	10.68	11.06	22	2.547	0.0145
Very high	25.38	14.89	8		
Very Low+Low	7.33	9.62	28	2.298	0.0127
Very High+High	14.6	13.63	30		

Table 5.7: Summary of number of parts affected method categories with high and low scores removed.

The graphs of insertion times categorized by the number of parts affected method of measuring value chain complexity have different shapes than those of the total number of parts method. The progression of insertion times does not appear linear, but rather appears to be larger at the tails. This effect is particularly pronounced in the graph with the high and low ratings removed.

The summary statistics in table 5.6 show that the null progression hypothesis can be rejected for all four categories, indicating that the categories are robust and that an upward progression in the number of parts affected by a materials switch in an application corresponds to an upward progression in the time required to insert a new material therein. However, the robustness of this categorization is called into question by the results shown in table 5.7, in which the high and low expert ratings for each application were removed. These statistics accentuate the patterns in the full ratings. They show that the null progression hypothesis can be rejected at the .05 level only between the very high and high categories, although it can be rejected at the .078 level between the low and very low categories. It is impossible to reject the difference between the low and high categories.

The null progression hypothesis can be soundly rejected in the two category classification scheme in both cases.

A scatter plot comparing the full rating set of the number of parts instrument and insertion time is shown in figure 5.10, followed a table of regression analysis.

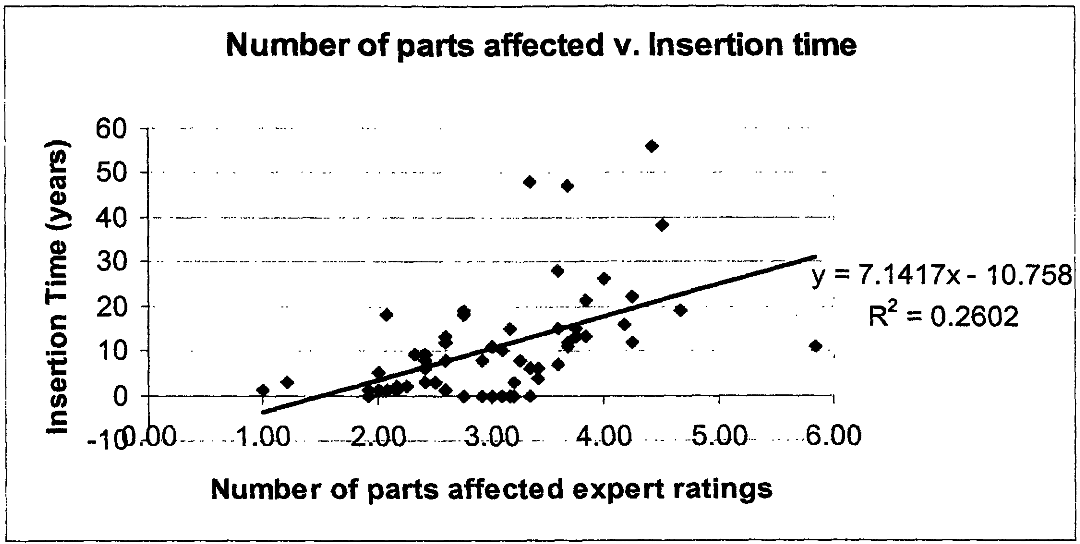


Figure 5.10: Scatterplot of number of parts affected.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.510[a]	.260	.247	10.7052

a. Predictors: (Constant), NUMAFF

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2256.529	1	2256.529	19.690	.000[a]
	Residual	6417.626	56	114.600		
	Total	8674.155	57			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-10.762	5.128		-2.099	.040
	NUMAFF	7.143	1.610	.510	4.437	.000

Table 5.8: Regression analysis of trendline shown in figure 5.10

This analysis shows that the number of parts affected instrument renders results that are statistically significant (p=.000) in explaining the insertion time of the examined applications. The instrument accounts for 26% of the variation in insertion time.

Difficulty of changing the value chain

Bar graphs showing the relationship of the value chain change difficulty instrument and the insertion time of plastics applications are shown in figures 5.12 and 5.13. The graphs for the complete set of ratings and the ratings excluding high and low measurements are shown together. The graphs are followed by charts of summary statistics in tables 5.10 and 5.11.

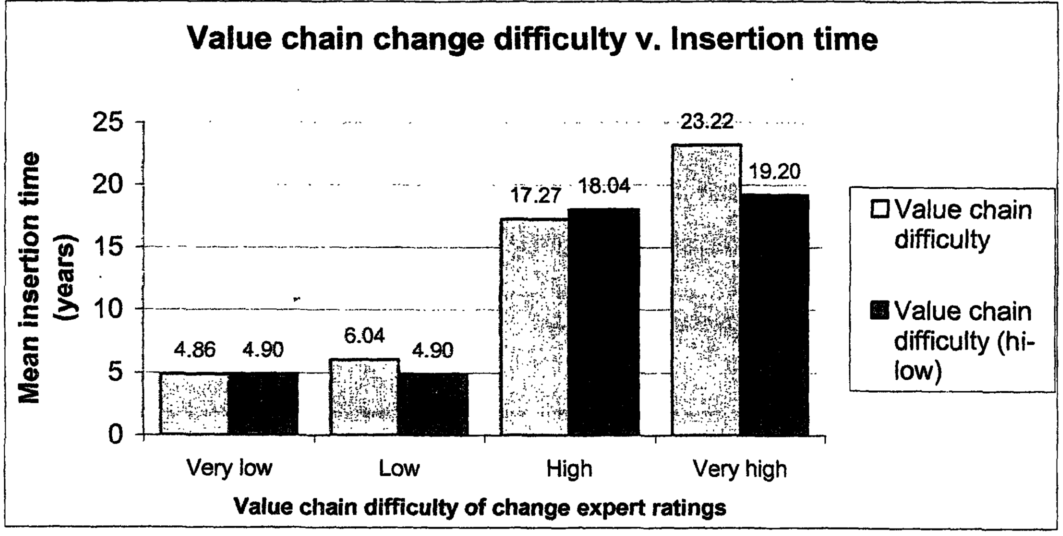


Figure 5.11: Number of parts affected v. mean insertion time (four categories).

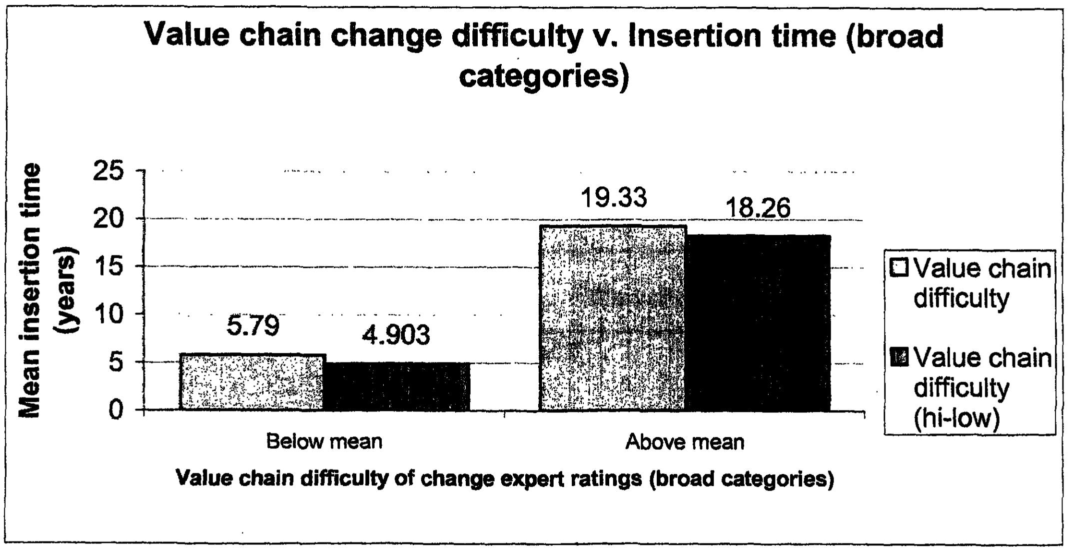


Figure 5.12: Number of parts affected v. mean insertion time (two categories).

Summary Statistics and T-Tests for Value Chain Change Difficulty Instrument

	Value chain difficulty category mean insertion time	Standard deviation	N	T score (compared with next larger category)	p < next larger category
Very low	4.57	4.16	7	0.48	0.31910
Low	5.52	6.17	27	2.94	0.00454
High	16.73	14.02	15	1.13	0.13856
Very high	23.67	14.96	9		
Below mean	5.79	5.77	34	4.49	0.00005
Above mean	19.33	14.47	24		

Table 5.9: Summary of value chain change difficulty measurement method categories.

Summary Statistics and T-Tests for Value Chain Change Difficulty Instrument (with high and low ratings excluded)

	Value chain difficulty category mean insertion time	Standard deviation	N	T score (compared with next larger category)	p < next larger category
Very low	4.9	5.5866	10	0.0002	0.499
Low	4.9	5.233	21	3.848	0.0003
High	18.045	15.0917	22	0.1965	0.4245
Very high	19.2	10.986	5		
Below Mean	4.903	5.255	31	4.908	3.09E-05
Above Mean	18.259	14.239	27		

Table 5.10: Summary of value chain change difficulty method categories with high and low scores removed.

While the number of parts affected method graphs showed significant disparity at the tail categories, the value chain change difficulty method shows clear resolution at the middle categories. The summary statistics and t-tests in table 5.9 show that the null progression hypothesis can be very safely rejected (p=.004) between the low and high categories, but cannot be rejected between the very low and low categories or between the high and very high categories. The effect is accentuated when high and low scores are removed. Table 5.10 shows that null progression hypothesis can be rejected at the p=.0003 confidence level between the low and high categories. As would be expected in this situation, the null progression hypothesis can be rejected at a very high confidence level between the two broad categories.

A scatter plot comparing full rating set of the value chain change difficulty instrument and insertion time is shown in figure 5.13, followed a table of regression analysis.

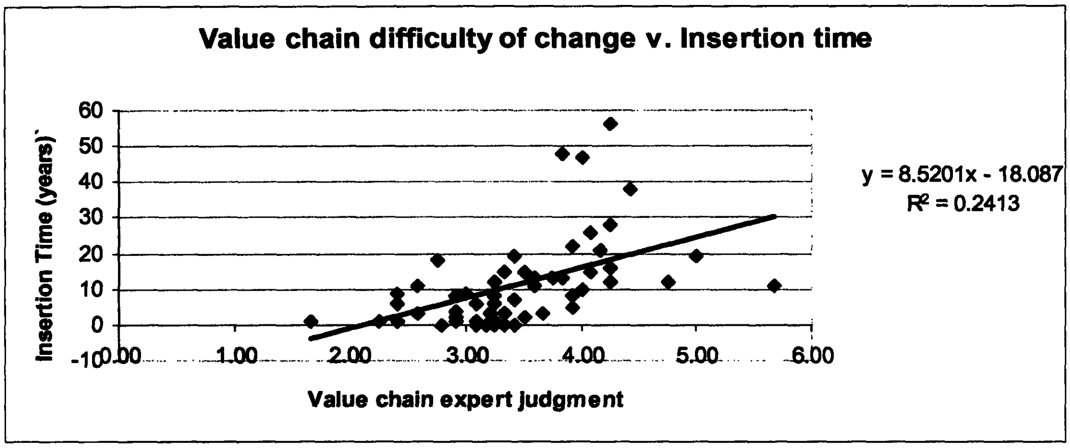
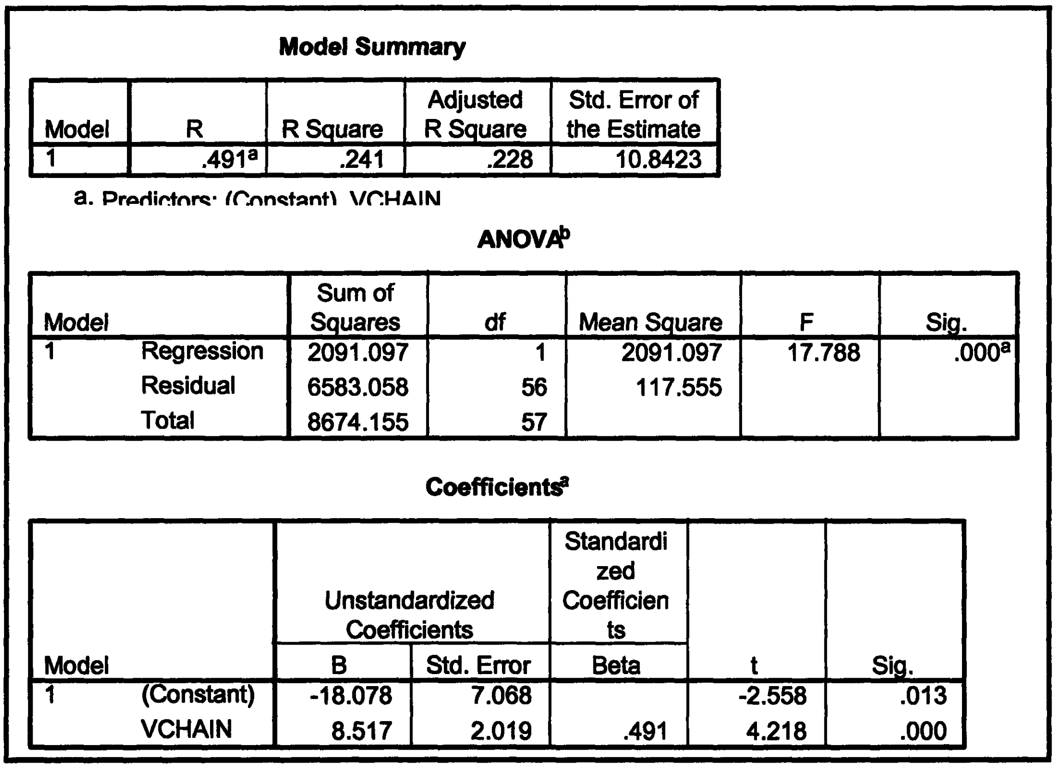


Figure 5.13: Scatterplot of value chain change difficulty.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.491[a]	.241	.228	10.8423

a. Predictors: (Constant), VCHAIN

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2091.097	1	2091.097	17.788	.000[a]
	Residual	6583.058	56	117.555		
	Total	8674.155	57			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-18.078	7.068		-2.558	.013
	VCHAIN	8.517	2.019	.491	4.218	.000

Table 5.11: Regression analysis of trendline shown in figure 5.13

The scatter plot and regression show that the value chain change difficulty instrument renders results that are statistically significant (p=.000) in explaining the insertion time of the examined applications. The instrument accounts for 24.1% of the variation in insertion time.

Triangulating Value Chain Complexity

All three instruments of value chain complexity give results that are statistically significant in describing the insertion times of plastics. Furthermore, the category analysis appears to show that each instrument describes different parts of the insertion variation—number of parts appears to be fairly linear, number of parts affected appears to differentiate at the tails, and value chain change difficulty appears to differentiate in the middle. If these things are true, one would expect a multivariate model to offer significant insight. Unfortunately, this is not the case. Figure 5.14 is a scatterplot of these three variables against insertion time. It shows that all three are very similar.

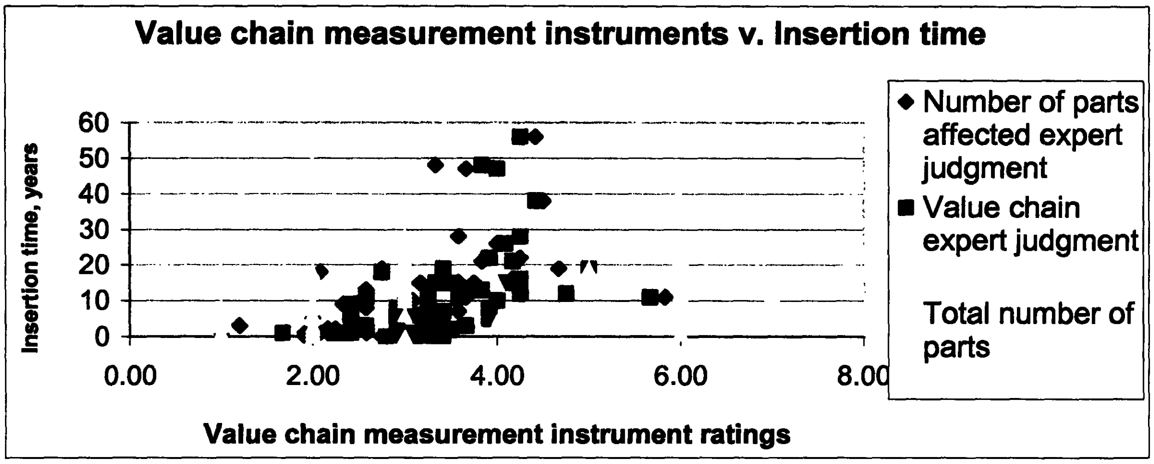


Figure 5.14: Scatterplot of value chain instruments.

Table 5.12 shows bivariate correlation matrices for the three value chain instruments.

Correlations

		NUMAFF	VCHAIN
NUMAF	Pearson Correla	1.000	.724*
	Sig. (2-tailed)	.	.000
	N	58	58
VCHAIN	Pearson Correla	.724*	1.000
	Sig. (2-tailed)	.000	.
	N	58	58

**.Correlation is significant at the 0.01 leve

Correlations

		NUMAFF	TOTALNUM
NUMAFF	Pearson Correla	1.000	.646*
	Sig. (2-tailed)	.	.000
	N	58	58
TOTALNU	Pearson Correla	.646*	1.000
	Sig. (2-tailed)	.000	.
	N	58	58

**.Correlation is significant at the 0.01 level (2-

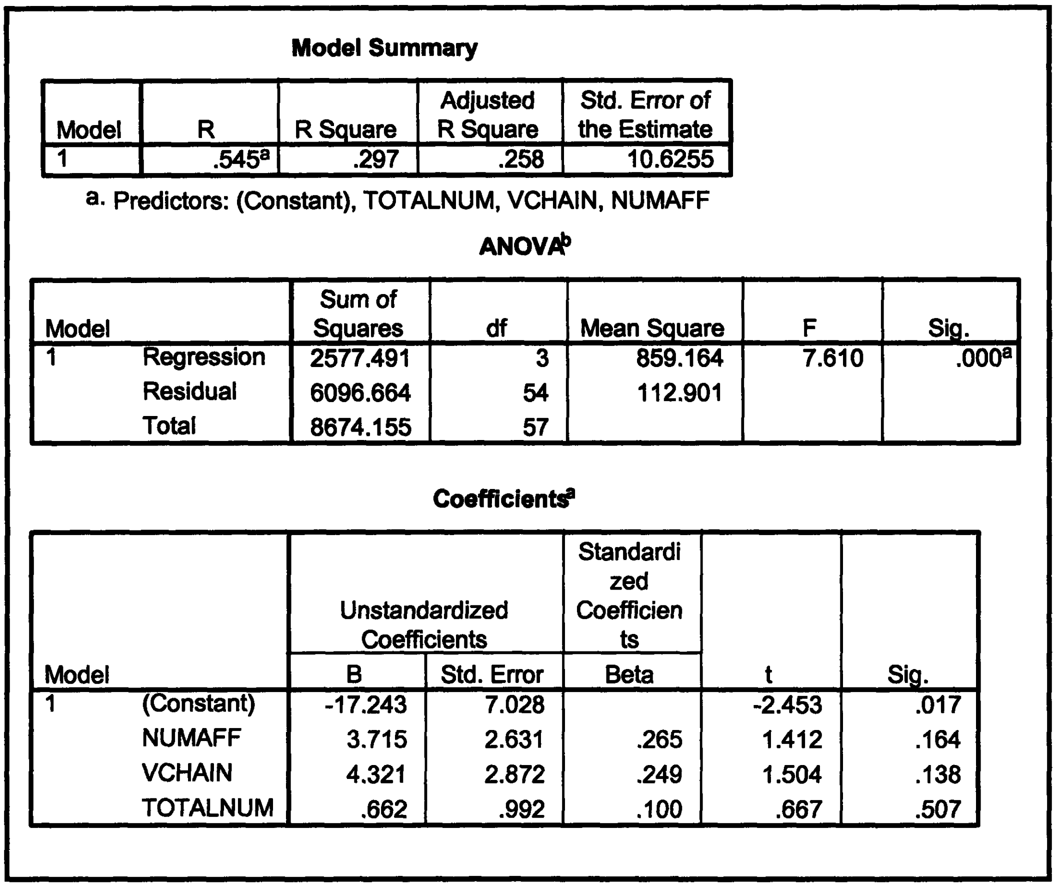
Correlations

		VCHAIN	TOTALNUM
VCHAIN	Pearson Correla	1.000	.500*
	Sig. (2-tailed)	.	.000
	N	58	58
TOTALNU	Pearson Correla	.500*	1.000
	Sig. (2-tailed)	.000	.
	N	58	58

**.Correlation is significant at the 0.01 level (2-

Table 5.12: Bivariate correlation matrices of value chain instruments.

The correlation between the variables is very high, with number of parts affected having the highest correlation with the other variables. This is logical, since the instruments were all designed to measure the same thing: value chain complexity. However, variable correlations at this high level often lead to problems with multicollinearity in regression models, and the present research is no exception. The results of a trivariate linear regression using the value chain instruments are shown in table 5.13.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.545[a]	.297	.258	10.6255

a. Predictors: (Constant), TOTALNUM, VCHAIN, NUMAFF

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2577.491	3	859.164	7.610	.000[a]
	Residual	6096.664	54	112.901		
	Total	8674.155	57			

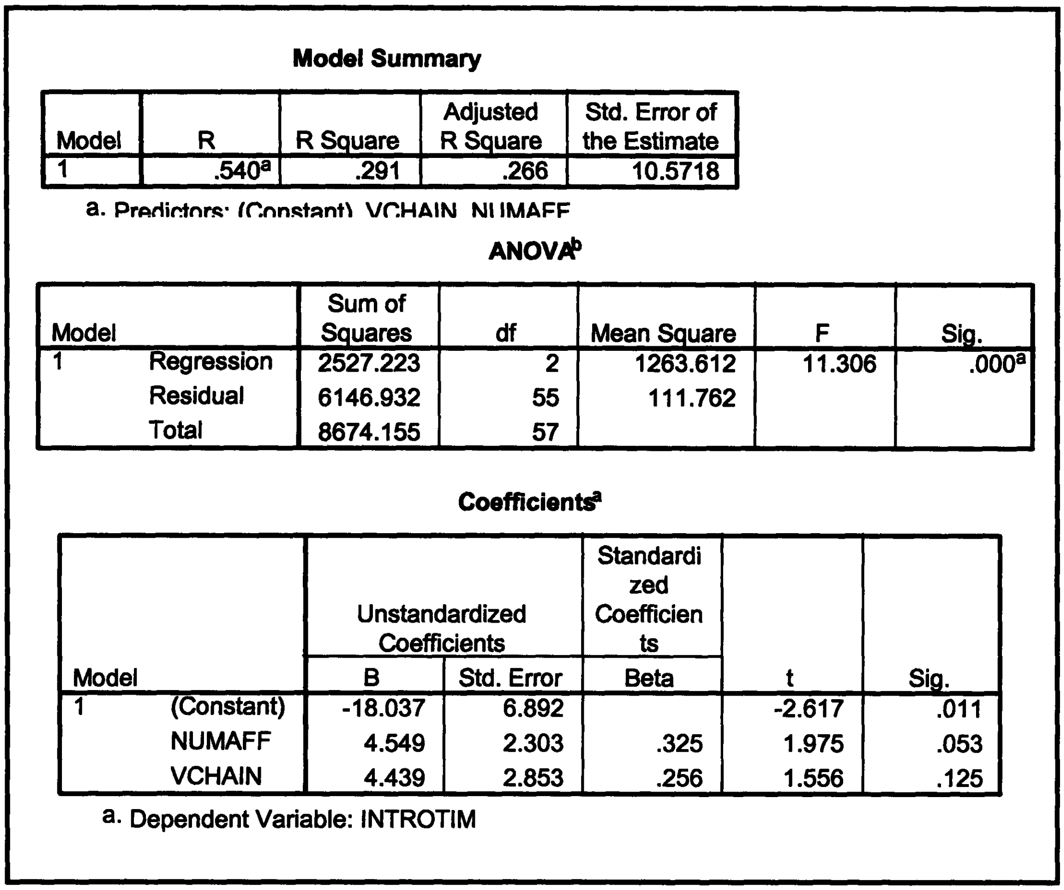
Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-17.243	7.028		-2.453	.017
	NUMAFF	3.715	2.631	.265	1.412	.164
	VCHAIN	4.321	2.872	.249	1.504	.138
	TOTALNUM	.662	.992	.100	.667	.507

Table 5.13: Trivariate regression analysis of insertion times showing multicollinearity.

The F statistic shown in the report above indicates that the model is highly significant, but the t statistics show that none of the variables are. Given the statistical significance of the variables when measured alone against insertion time and the correlations of the variables, multicollinearity is obvious. Multicollinearity cannot be removed from this model, but future work may separate the variables with a higher number of data points and more precise instruments for the measurement of value chain complexity.

A model with higher overall significance and individual variable significance can be built by removing the total number of parts instrument. The results of this model are shown in table 5.14.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.540[a]	.291	.266	10.5718

a. Predictors: (Constant), VCHAIN, NUMAFF

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2527.223	2	1263.612	11.306	.000[a]
	Residual	6146.932	55	111.762		
	Total	8674.155	57			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-18.037	6.892		-2.617	.011
	NUMAFF	4.549	2.303	.325	1.975	.053
	VCHAIN	4.439	2.853	.256	1.556	.125

a. Dependent Variable: INTROTIM

Table 5.14: Bivariate regression analysis using number of parts affected instrument and value chain difficulty instrument.

In this bivariate model, the number of parts affected instrument is significant at the p=.053 level, and the value chain difficulty instrument is significant at the p=.125 level. Both scores are better than in the trivariate regression while the R^2 is only slightly lower and the F statistic is much higher; this is a more robust overall model.

Instrumental Variable Regression Analysis

Because most measurements have noise, measurement error is a classic problem in regression. Measurement noise tends to attenuate the variable coefficients, biasing them toward zero and understating the effects of the variables. Since the measurement instruments used here were designed to triangulate the true effects of value chain complexity, they are clearly imperfect. However, since multiple measures of the same effect were taken, it was possible to use two-stage least square regression analysis to filter measurement noise and attain a closer estimation of the coefficients[16].

Two stage least squares analysis was performed using one measurement instrument as a regressor and the other as an instrumental variable (IV). Because the value chain difficulty and number of parts affected instruments were shown to create the most robust model, two-stage least square regression was performed twice, with each instrument acting as the regressor (and the other as IV) in each case. Insertion delay (coded

INTROTIM) was the dependent variable in both models. The results of the models are shown in tables 5.15 and 5.16.

```
Dependent variable.. INTROTIM
Multiple R          .48872
R Square            .23884
Adjusted R Square   .22525
Standard Error    10.90867

F =     17.57237       Signif F = .0001

----------------- Variables in the Equation -----------------
Variable            B           SE B        Beta        T    Sig T
NUMAFF          9.502510    2.266852    .678559     4.192  .0001
(Constant)    -17.991398    7.090953               -2.537   .0140
```

Table 5.15: Two stage least squares regression with number of parts affected as regressor and value chain difficulty as IV.

```
Dependent variable.. INTROTIM
Multiple R          .49427
R Square            .24431
Adjusted R Square   .23081
Standard Error    11.16430

F =     18.10415       Signif F = .0001

---------------- Variables in the Equation ----------------
Variable            B           SE B        Beta        T    Sig T
VCHAIN         12.226884    2.873603    .704890     4.255  .0001
(Constant)    -30.798549    9.960464               -3.092  .0031
```

Table 5.16: Two stage least squares regression with value chain difficulty as regressor and number of parts affected as IV.

Both of the models show stronger significance than the least squares model, and the variable coefficients are higher in both cases, giving further evidence of the strength of the progressive relationship between value chain complexity and insertion delay. However, this type of analysis is not perfect. Two stage least squares works best if measurement errors between regressors and IVs are uncorrelated, and this is probably not true in the present case since the same experts rated both variables. However, under the reasonable assumptions that the measurement errors are uncorrelated with the true complexity of the applications and are uncorrelated with any measurement error in insertion time, the results of this analysis are superior to conventional linear regression.

Discussion

Value Chain Complexity Extends Insertion Times

This model was not designed to predict insertion time for materials of the future. It was designed to test whether a positive relationship exists between the insertion times of historical plastics applications and the complexity of the value chains of those applications. The statistical significance of each instrument in the individual regressions clearly shows that each of the instruments is significant in explaining insertion time variation. The multicollinearity of the multivariate regression model and the high correlations between the instruments indicate that they are different measures of the same phenomenon: value chain complexity.

Noting the statistical significance shown in the regression of the individual value chain complexity instruments in explaining the variation in insertion time, it can be asserted that the tested relationship does exist. The bar graphs for each instrument show that, at worst, there is a statistically significant difference between the insertion times of applications rated below and above the instrument rating mean. In all cases, this relationship is positive: higher value chain complexity corresponds to longer insertion times.

Because each of the instruments measured an adjacent effect to value chain complexity, and because the possibility of a bidirectional causal relationship (in which new material insertion causes increases in value chain complexity) would be captured by the difficulty of value chain change and number of parts affected instruments, it is rational to assert that the variation of observed delay in insertion time was caused, in some part, by the variation of value chain complexity. Furthermore, since end user demand was explicitly excluded as a factor in value chain complexity, it should be considered a limiting factor to insertion. This assertion is supported by the experience of other chain-type models (such as supply chains) in which lags and delays increase significantly as complexity increases[17].

The three instruments together give only a slightly higher R^2 square than either the number of parts affected instrument or the value chain change difficulty instrument, indicating that the either of these instruments alone is a reasonable proxy for value chain complexity. The fact these instruments were rated by experts also shows simply that they *can* be rated by experts.

The R^2 of the total number of parts instrument is considerably lower (although significant). The shortcomings of this instrument were acknowledged earlier—it can be a gross oversimplification of the problem at hand. However, it could probably be used as very preliminary screening tool for assessing the level of value chain complexity to be encountered in an industry. For example, one would expect lower value chain complexity in the toy industry than in the commercial airplane industry based simply on the number of parts in the final application.

Switching Costs Help Explain the Effects of Value Chain Complexity

While each of the individual instrument regressions are clearly biased by the other instruments, the β statistics shown for each variable are worth considering. One rating point in the value chain change difficulty instrument corresponds to an additional 8.5 years in the insertion time of the historical applications analyzed here; an additional rating point on the number of parts affected instrument added 7.1 years; an additional rating point on the total number of parts instrument added 2.6 years. Even if they are not exact, these are large delays, which cannot be explained by simple logistical issues that might arise with additional value chain complexity. Much more complex networks than these value chains are managed everyday by logistics groups and networking systems.

The more plausible explanation is that increases in value chain complexity correspond to increases in value chain inertia. It was noted in chapter 1 that materials are the first point of product differentiation in the value chain, and that other nodes in the value chain often must be adapted to accommodate material choices. Because efficient value chains are optimized for the jobs they do, they can be difficult to change—inertia is built into them. There are rational reasons for this inertia to remain in the system, and these reasons are largely explained by the concept of *switching costs.*

Switching costs are defined by Porter as "one time costs facing the buyer of switching from one supplier's product to another's"[18], and are usually associated with consumer (end user) behavior. Switching costs are recognized as a cause of brand loyalty, in which customers become "locked-in" to a product they have purchased because it is more expensive to switch to a new one than to continue purchasing the same brand[19]. Switching costs can be very beneficial to sellers because they allow quasi-monopoly (or at least non-cooperative collusive) behavior: consumers will pay higher prices than they would in an efficient market because they don't want to pay switching costs[20].

Klemperer has characterized switching costs into three categories: transaction costs, learning costs, and artificial/contract costs[21]. Transaction costs are those costs which are incurred directly by the transaction of switching, such as purchase costs of the new product and direct modifications necessary to accommodate the new product. If one were to switch cell-phone providers, the costs (including labor) incurred in purchasing the cell phone, notifying friends of a new number, and programming saved numbers into the phone would be transaction costs. Learning costs are the costs, including lost productivity, of training and of learning to use a new product. In the cell phone example, these would be the time costs of learning the features of the phone, and the lost productivity due to failed calls caused by operator error. Artificial costs are costs imposed by sellers to prevent customers from switching brands or products—the contract charges that a cell phone switcher would have to pay.

It is also useful to separate capital equipment costs (from transaction costs) into a fourth category. Capital equipment costs include complimentary assets (tooling, machinery, etc.), which are often specific to a certain product. Any changes required to adapt one's car to a new cell phone would be capital equipment charges, as would the costs of the phone itself.

In many cases (including the cell phone example), all of these costs can be quantified before a purchase. The total switching cost for a product is:

$$(C_T + C_L + C_A + C_C) \tag{4.1}$$

where C_T is the transaction cost, C_L is the learning cost, C_A is the artificial (contract) cost, and C_c is the capital equipment cost.

These costs can be compared by a rational consumer to the value provided by the switch. The value provided by the switch can be defined as the difference in value to the consumer between the original product and the new product, with value measured as utility (U [measured in dollars]) divided by price (P)[22]:

$$\Delta V = \frac{U_2}{P_2} - \frac{U_1}{P_1} \tag{4.2}$$

Therefore, assuming all costs and value changes are quantifiable, a rational consumer will choose to switch if:

$$\Delta V > (C_T + C_L + C_A + C_C) \tag{4.3}$$

When switching costs are high, the seller is free to increase prices to capture near-monopoly rents. However, when switching costs are very low or non-existent, purchasing decisions are solely value driven since there is no reason for consumers to stay with the original product. This leads to a more efficient market, with competition based on solely on price and utility. If products are differentiable—different features offer different utility—a stable market may exist with many products, since each product would offer a unique utility/price ratio that would appeal to a group of consumers.

Multiple equilibria should not exist in markets with undifferentiable products (such as those faced by many materials). In these markets, purchasing decisions rest solely on purchase price. If multiple undifferentiated products are freely available, competition is on a commodity basis, and is often transacted by electronic markets in a hedonistic price reduction situation, dragging all sellers to the lowest possible margins.

Unknown Switching Costs as Risk

Switching costs are not always required, but neither are they always known a priori. There are many cases in which buyers are surprised by switching costs that were unknown to them before a purchase. Thus, making a switch involves some risk, because there is a probability that costs of unknown magnitude will be discovered

Learning costs seem to be the most common category of unknown switching costs, because utilizing new products often involves a steep and unpredictable learning curve. The surprise is often especially strong with unproven technology, because the potential costs are practically unquantifiable. These costs can extend well beyond lost productivity and training costs to include search costs (for complimentary assets), contract renegotiation costs, and high maintenance costs, to name a few. If products are highly interdependent with other products, significant interaction effects may be discovered, which can require significant learning costs to solve.

If learning costs are unknown beforehand, a rational buyer must recognize the risk that those costs will be substantial, and sometimes extreme. Dell Computer learned this when it implemented an SAP enterprise resource planning (ERP) system—at a supposed switching cost of $60 million—and found itself so crippled that it jettisoned the system 6 months later. The learning costs of making the system interact properly with the other Dell systems proved to be extraordinarily high, and operational performance and customer satisfaction were also hurt, since workers in the company didn't know how to make the system work. Overall switching costs were much higher than anyone had anticipated, due mostly to unknown learning costs[23].

When products are unproven or interactions are unknown, learning costs can act as a major (and very rational) disincentive for switching. The other categories of switching costs can also be unknown, but probably are considerably smaller than unknown learning costs. A buyer can acknowledge the possible presence of unknown costs by including them as another term ($C_?$) in the rational purchase inequality, and assigning them a probability ($p_?$):

$$\Delta V > (C_T + C_L + C_A + C_C + p_? C_?) \tag{4.4}$$

Both the probability and magnitude of unknown costs will increase if the switch involves unproven/undeveloped technology or if the technology has many interactions.

In general, the magnitude of switching costs (known or unknown) will vary with the magnitude of change that is forced onto a consumer. Small changes may require very little spending in only one category of switching cost, while major changes may require heavy spending in all categories. However, it is important that the consumer consider all potential classes of switching costs so that a rational decision can be made.

Switching Costs in the Value Chain

Up to this point, the discussion of switching costs has been limited to the costs faced by a single rational consumer. However, materials are rarely sold to single rational consumers; they are sold to product manufacturers, who must pass them through value chains in order to sell them to consumers. Because materials come early in the value chain and interact with most of the nodes, the switching costs faced by materials are not simple. There are at least three important factors to examine when considering the effects of switching costs on products with long value chains:

1. Multiple switching costs
2. Handoffs between nodes
3. The distance between the end consumer and early elements of the chain

Multiple switching costs

Although the nodes of most value chains are interrelated, the specificity of their functions forces them to be largely independent—particularly when the nodes are owned by different people or companies. This independence is important to recognize because each node in the value chain has its own interests, and separate switching costs are incurred at each node that is affected by a product switch. Thus, switching a product that is purchased early in the value chain and affects multiple nodes requires multiple switching costs. These costs are much higher than they would be in a simple consumer switch, and would be borne in most situations by the product manufacturer (who would have to pass them to the consumer). A rational product manufacturer would be faced with the following inequality:

$$\Delta V^* > \sum_{a}^{n} (C_{Tn} + C_{Ln} + C_{An} + C_{Cn} + p_? C_{?n}) \tag{4.5}$$

where n is a node a in the value chain, and C_{Tn}, C_{Ln}, C_{An}, C_{Cn}, $C_{?n}$ represent the transaction costs, learning costs, artificial (contract) costs, capital costs, and unknown costs of switching at each node. ΔV^* indicates a special profit maximizing value case for rational product manufacturers (or any reseller of a product), and is defined as

$$\Delta V^* = (R_2 - C_2) - (R_1 - C_1) \tag{4.6}$$

where R is revenue that can be expected from ongoing sales of a product and C is cost that can be similarly expected.

It is obvious that the number of nodes and the categories of switching costs that are affected will vary with the magnitude of product change that is required. Most materials changes are relatively simple changes of grade, and require very little change in the value chain. However, major materials changes, such as the change from iron pipe to PVC plumbing pipe, can induce heavy shock to the existing value chain, requiring billions of dollars and significant time to complete.

Handoff costs

Unfortunately for materials (and for other parts that are deep in the value chain), the compounding effects of long value chains aren't limited to switching costs within the nodes. The close working relationship and inter-relatedness of the nodes leads to high handoff costs between them. Handoff costs can be defined as the costs which are incurred when a product moves from one node on the value chain to the next; handoffs themselves are the interactions between nodes and are represented by arrows in the value chain diagrams shown earlier.

The field of Transaction Cost Analysis (TCA) has been developing since the mid 1970s as a method of determining optimal firm structure in light of handoff costs. Multiple sources of handoff costs have been identified, and most can be traced to two sources: environmental uncertainty and opportunism[24].

TCA asserts that the rationality of decision makers is limited, and that the costs of handoffs in an uncertain environment—one in which challenges and difficulties cannot be predicted before writing a contract—can be extraordinarily high. This is because communication between nodes of the value chain can be very difficult, and adaptation requires communication. Furthermore, it is very difficult to assign credit (or rents) for successes or failures when nodes must work together, and constant renegotiations must be undertaken. Negotiations, adaptation, and communication can be very expensive, and can significantly extend the time required to make a switch[25].

To a large degree, handoff costs due to uncertain environments are captured in the costs of learning within the nodes. Like learning costs, the effects of uncertain environments are most likely to be present when switching to products or technologies for which full knowledge has not yet been developed, or which are changing rapidly. However, handoff costs focus specifically on the knowledge required for integration across nodes, and integration is a major task[26]. Handoff costs due to uncertain environments can be expected to be very high if a technology is not well defined[27].

TCA also asserts that handoff costs can be very high in situations in which the quality and performance of the activities of a node on the value chain are difficult to monitor. This is not because of limited ability to communicate, but because of the temptation for actors within the nodes to exploit the situation by cheating on contracts or otherwise taking advantage of the chain. Oliver Williamson has called this behavior "opportunism", which he defined as "self-interest with guile"[28]. It is particularly acute when nodes of the value chain are not owned by the same company, and when assets are highly proprietary to one side. Very tight controls must be installed to prevent the other side from using the proprietary technology against the first firm, and these controls can be expensive.

Although the effects of opportunism are most potent when applied across firms, a similar effect occurs within firms which can be called "suboptimization". In suboptimization, one node of the value chain optimizes its process or design without regard for the other nodes. This can add large rework and redesign costs to a product switch. It can also extend the time required to make such a switch by a large margin.

Although handoff costs have proven very difficult to quantify, it is clear that they exist and can be very substantial. The costs of handoffs in which adaptation is required can be expected to be very high if the adaptation is difficult to specify, and the costs of opportunism and suboptimization can be very high if quality of node activities is difficult to measure and spoils must be divided. When handoff costs are included, the switching inequality faced by a rational product manufacturer grows:

$$\Delta V^* > \sum_{a}^{n}(C_{Tn} + C_{Ln} + C_{An} + C_{Cn} + p_{?}C_{?n}) + \sum_{a}^{n} H_n \tag{4.7}$$

where H_n the handoff cost required by the interface of each node, n, with the node that immediately precedes it.

Additional Value Chain Risk

Learning costs have a higher probability of occurring in value chain switches than they do in single buyer situations since interactions between nodes are guaranteed to occur. They are also higher, since learning has to occur as several nodes. Handoff costs are also probable, and are likely to be expensive. Strategies must be taken to minimize the risk of underestimating these costs.

The unknown cost category is also much larger in value chain switches than single buyer switches. All of the same potential costs exist (search costs, high maintenance costs, etc.) but several others must be added. Two important sources of unknown costs which would be very expensive and whose probability would increase with unfamiliar suppliers or products are supply disruptions and product failure.

Supply disruptions early in the chain can be very expensive. A "bullwhip" effect has been demonstrated in value chains, in which small supply variations early in a chain can lead to major disruptions at the end[29]. This can leave production and distribution nodes idle, and can starve the customer of supply, causing missed sales, weakened credibility, and a loss of customer loyalty.

Product failure can also be very expensive, particularly if it is caused by a product used early in the value chain, such as a material. Since each step in a value chain makes a product more specialized, products bought early in the chain are usually bought in very large batches. This means that defective batches have the potential to ruin large lots of products. Furthermore, if defects in an early value chain activity are discovered after other steps have been executed, all of the steps must be repeated. This can lead to very expensive rework, or worse, recalls.

Unexpected learning and handoff costs, as well as other unknown costs, become both more probable and more costly if the switched technology is new or unproven. They are also more probable when the switched product interacts with many of the nodes, like materials do. Learning delays can cause lags and inefficiencies in the chain and can lead to unexpected product failure rates and major recalls.

Both switching costs and handoff costs increase as value chain complexity increases. The first order effects are obvious, and are probably fairly linear: a larger number of nodes corresponds to a larger number of potential switching costs. The second order costs are also substantial: a larger number of interactions between the nodes leads to a higher number of handoff costs. It is likely that handoff costs are nonlinear, since many value chains require a high degree of intercommunication, which can stretch well beyond the nodes immediately before and after each node. Furthermore, overall coordination required to manage such a change is probably nonlinear with respect to the number of nodes. This would be an interesting area of future research, and could build on network and supply chain theory.

Conclusion

A significant portion of the variation in insertion time of plastics when entering historically important applications can be explained by variation in complexity of the value chain of those applications. The relationship between value chain complexity and insertion time is progressive: additional value chain complexity leads to additional insertion time. Although the concept of value chain complexity seems nebulous, it can be estimated by proxy: expert ratings of the number of parts affected in a final application by a materials switch and expert ratings of the difficulty of change in a value chain are excellent predictors.

Additional Resolution to the Materials Commercialization Pattern

It was shown in chapter three that new materials follow a clear pattern of commercialization, displayed graphically in figure 5.15. The recognition of a positive progressive relationship between value chain complexity and insertion time gives insight into the pattern.

Figure 5.15: Historical pattern of materials commercialization.

Enabler applications were found to have three common elements: the materials let people do things they couldn't do before, the applications were relatively simple, and the applications were relatively new. The value proposition of the materials was clear (since they let people do new things), and their speed of insertion indicates that few limiting factors existed.

Examining the common factors of enablers in light of the value chain instruments shows that value chain complexity—and therefore delay--would be expected to be low. In simple applications, the ratings of total number of parts instrument and the number of parts affected instrument converge—they are both low. Furthermore, Utterback has shown that new products are generally built with flexible value chains so that features can be changed quickly[30]. This corresponds to a low degree of value chain change difficulty. Value chain complexity was low by all three instruments in enablers, so limiting value chain effects were minimal.

Chapter four showed that value proposition alone could not explain the variation in insertion time of the biggest applications of the major plastics into the platform and widespread substitution applications. Technical factors and value chain effects were shown to be the major limits. It was noted earlier in this chapter that insertion delay due to technical factors is known in to vary with difficulty of the technical challenge. This chapter has shown that the delay due to value chain factors varies with value chain complexity. Thus, additional resolution is given to the materials commercialization pattern: enablers can enter quickly because they have no technical challenges and very low value chain complexity. Variation in insertion delay into platform and widespread substitution applications corresponds to variations in technical challenges and value chain complexity.

The relationship between value chain complexity and insertion delay is largely explained by the presence of switching costs in the value chain. The additional profit or competitive advantage gained by a rational application producer because of a material switch must exceed the sum of the switching costs and handoff costs in the value chain. When all of the costs are known *a priori*, this sets a very high hurdle. However, when the costs are unknown beforehand, it presents a very high degree of risk. This is especially acute if the processes and techniques necessary to form a material are poorly understood, since learning costs can be extraordinarily high. Because of the risk and switching costs inherent in complex value chains, it is far more rational in most cases for application producers to continue use of incumbent materials or switch only between grades that are compatible with existing value chains than to switch to new materials.

Understanding the nature of the relationship between value chain complexity and insertion delay provides a basis for further work. Chapter six will explore options that producers of new materials can take to minimize the effects of value chain complexity on insertion.

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Chapter 6: Toward Faster Commercialization of New Materials

"Forcing a new product into the market is like pushing a string"
-Popular adage in innovation

Introduction

The materials commercialization pattern has now been described, and some of its underlying factors have been identified. It has been shown that traditional materials marketing wisdom does not hold for new materials, even if they offer a superior value proposition to existing materials. Cost and serendipity have been debunked as the major drivers of insertion delay in new materials—technical challenges and value chain obstacles are much more important barriers. Furthermore, the earliest application insertions of new materials are not based on incremental property improvements over existing materials—they are based on fundamentally different properties. The earliest applications of new materials let people do new things: they are enablers.

This is not meant to imply that traditional materials marketing wisdom is useless. Competition based on incremental price and property advantages between incumbents and entrants is clearly an important part of the later stages of commercialization of a new material. The platform application, in which a new material replaces an incumbent in a major application because of superior properties is also important—it is a hybrid of the enabler applications and traditional materials marketing wisdom.

The fact that the typical applications for each phase of the commercialization pattern have unique characteristics reveals that the traditional "one size fits all" approach is insufficient. The traditional approach has its place, but the proper introduction and market selection strategy for new materials is *conditional:* limiting insertion factors depend on the relationship between the market and the material. When this relationship is understood, insertion factors can be managed.

New materials are different from established materials in two important ways. First, they have no track record of success. Their properties and failure modes are not as well understood as those of the established materials. These are technical challenges that must be overcome for the entrant to be viable. Second, new materials do not have an installed base from which to work. Players in the application value chain rarely have the equipment or knowledge necessary to fully utilize their potential. Value chain issues must be solved for the material to become a reasonable alternative to existing materials.

This chapter will show that the concept of compound switching costs, introduced in chapter five, is a useful tool for understanding the conditions of insertion. It will show that the most important conditions driving switching costs are the degree of understanding of a material (both by producers and application manufacturers) and the value chain complexity faced by that material. Once the effects of these conditions are established, strategic tools will be presented which can help mitigate the effect of insertion factors so that new materials can enter markets more quickly.

Assumption of Rationality

The discipline of economics has been described as the study of choice and tradeoffs[1]. One of the important tenets of much of the field is the assumption of rational actors[2]. This assumption states that people (and groups of people such as companies) will take the best option that is available to them in a given situation. Clearly this assumption is not always true—there are a variety of reasons for which poor decisions are made. Many sources of bad decisions are particularly acute in large organizations, where systems and controls can be in place that are optimized for overarching goals, leading to suboptimization of individual decisions.

The presence of irrationality must be recognized, but the following analysis will be based on a general assumption of rational and benevolent action on the part of individual adopters of new materials. This assumption has important implications for this analysis. First, it asserts that people will change if a better option is presented to them. Second, it implies that decision makers will act on the best information that they have, and will decide based on many criteria in order to reach an overarching goal. In most businesses, the overarching goal can be assumed to be profitability.

Switching Costs Create Rational Barriers

Many new materials have offered a clear value proposition to many applications, without being immediately inserted into them. It has been shown that the applicability of the materials was well known, yet the decision makers within the application manufacturers delayed their move to adopt them. If the decision makers are assumed to be rational, there must be reasons for this delay. The research reported in earlier chapters suggests that insertion factors—particularly technical deficiencies and value chain obstacles—were the reasons.

Both technical deficiencies and value chain obstacles can be very expensive to overcome, and can significantly extend the period required to earn an acceptable return on investment. It is easy to see that value chain obstacles and technical deficiencies translate into switching costs, and that these costs prevent rational application manufacturers from adopting new products. New materials will only be adopted by rational application manufacturers if the potential value of the switch is greater than the costs of the switch.

There is an amusing adage in the dry cleaning, construction and engineering fields that says "you can have two of the three: cheap, fast, or good". This is a practical recognition of a fact that the field of managerial psychology has long recognized: a tradeoff exists between time delay and coordination. Uncoordinated efforts increase the time necessary to accomplish a task[3]. On complex projects such as product engineering or construction of buildings, coordination can be very expensive since many layers of management and control systems are required. Less coordinated efforts are generally less expensive than highly coordinated efforts, but require much more time[4].

Since the willingness of application manufacturers to invest in switching costs is capped by the potential value of the material in an application, the tradeoff between capital investment in adopting the new material and coordination required to adopt the new material is often made. It is more rational for application manufacturers to delay introduction until switching costs are reduced or to allow the material to pass through acceptance and design-in procedures slowly (with less coordination) than to invest the money necessary for quick qualification and insertion.

Because materials are the first point of differentiation in the value chain, they are followed by many nodes. If a new material is chosen, many of these nodes must change to adapt to the properties of the new material. The adopters of the new material generally bear the costs of making this switch. The materials switching cost equation shown in chapter five can help explain the potential costs that adopters of a new material might face. The equation is shown below.

$$\Delta V^* > \sum_a^n (C_{Tn} + C_{Ln} + C_{An} + C_{Cn} + p_? C_{?n}) + \sum_a^n H_n$$

Where, for nodes *a* through *n*:

C_T=transaction costs
C_L=learning costs
C_A=artificial (contract) costs
C_C=capital equipment costs
$C_?$=unknown costs
H=handoff (coordination) costs between nodes

and V*=difference in value perceived by application manufacturer between incumbent material and entrant material.

At first glance, the materials switching cost equation shows that switching costs in a value chain are much higher than those faced by a simple consumer, and they act as powerful deterrents to change. This is an important insight, since it directly refutes claims by academics and materials producers that application manufacturers are "dinosaurs"—irrational actors in their slow pace of adoption of new materials.

However, inspection of the materials switching cost equation also gives much deeper insight into conditions required for change. The variables in the equation can be rolled into two important conditions. The first condition can be called "value chain complexity" which a material faces when it is introduced. As explained in chapter five, value chain complexity includes the number of nodes that might be affected *(n)*, the degree of change required in those nodes (C_T, C_A, C_C), and the interaction between the nodes (the coordination portion of H). The second condition can be called "understanding of material" possessed by both a material producer and an application manufacturer at the time of insertion. This condition includes the learning costs (C_L) of each node, the probability and degree of potential unknown costs ($C_?$), and the opportunism portion of handoff costs (H).

Because it contains several of the switching cost elements, higher value chain complexity equates to higher switching costs. The relationship is positive. In contrast, the relationship between understanding of a material and switching costs is negative. Higher understanding equates to lower switching costs. A baseline of understanding must be in place for a material to be useful in an application, that understanding must be developed in the form of learning costs. Opportunism is more likely in situations of asymmetric understanding between parties, and unknown costs are also more likely if a material is not well understood.

The highest and lowest potential switching costs situations are easily seen by mapping the conditions against each other, as shown in figure 6.1. The severity of the intermediate situations varies between applications, with value complexity being a more powerful driver of switching costs in most situations.

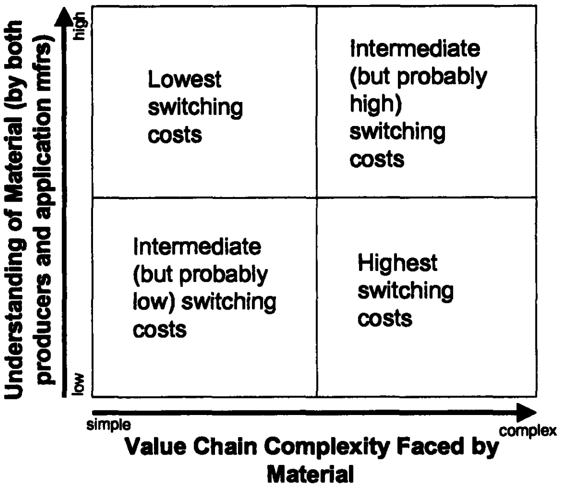

Figure 6.1: Switching cost severity matrix

While the effects of switching costs are formidable, there are ways to minimize them. If the effects of each of the conditions are understood and minimized, so too will be switching costs, and materials can be expected to be adopted more readily. The next section will discuss ways to reduce the value chain complexity faced by a material, and the following section will discuss ways to increase understanding of a material.

Reducing Value Chain Complexity

The first way to reduce the switching costs required to insert a material is to reduce the complexity of the application value chain faced by that material. It may seem that a materials producer has little control over the complexity of the application value chain that a material faces. However, consideration of the topic reveals that there are many levers that a materials producer can pull to change to simplify the value chains into which its materials must integrate. The first lever is market selection: materials producers can launch their wares into applications with simple value chains. The second lever is integration: materials producers can integrate forward to control any potential problems in the value chain. The third lever is technical development: materials producers can develop materials and processes that maximize the compatibility of new materials with existing products and processes.

Each of these levers will now be discussed.

Market Selection: Reducing Nodes

The easiest way to eliminate challenges from value chain complexity is to dodge complex applications. The unique versatility of materials makes them candidates for use in many different applications, and materials producers must decide into which of those applications a new material will be pushed. Value chains are designed to produce products, and vary in complexity just as their products do. A spectrum of value chain complexity exists, and the requirements and specifications imposed on a material vary accordingly. Materials producers can reduce the value chain complexity faced by their materials by choosing to launch their products in application markets that have simple value chains and low materials requirements.

Consider the case of carbon fiber reinforced plastic (CFRP). Developed in the late 1960s for military and space applications, CFRP offers the highest specific strength and specific stiffness of any material. It is also very expensive, cannot be formed using conventional processes, and is virtually impossible to recycle[5]. The strength and stiffness of CFRP make it very attractive for applications that must retain structural integrity at high speeds, but its cost, recyclability, and incompatibility with existing processes limit its applicability to high value, low volume applications.

The most obvious applications for CFRP are as replacements for lightweight structural metals such as aluminum and titanium alloys. Most of these are in aerospace, which values a pound of weight saved at around $200 and requires very strong, stiff materials[6]. Sporting goods, such as tennis rackets, bicycle frames, skis, or golf shafts, are other possible applications, since consumers are often willing to pay premium prices for performance increases[7]. Since producers of CFRP can choose where to launch their products, comparing the value chain of golf shafts to the value chain of aircraft skins gives an excellent illustration of the effectiveness of market selection in reducing value chain complexity. A snapshot of the steps that the new material would face in the (post qualification, post design-in) value chain for each application is shown in figures 6.2 and 6.3[8].

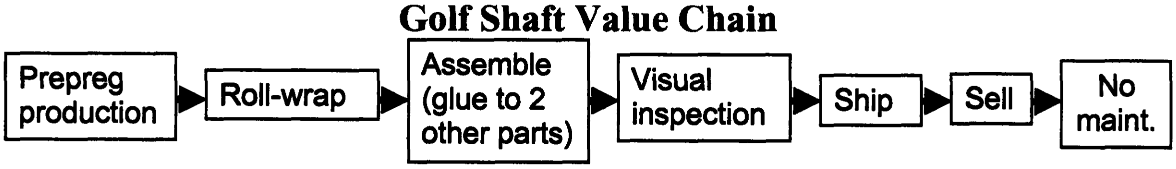

Figure 6.2: Simplified CFRP aircraft skin value chain.

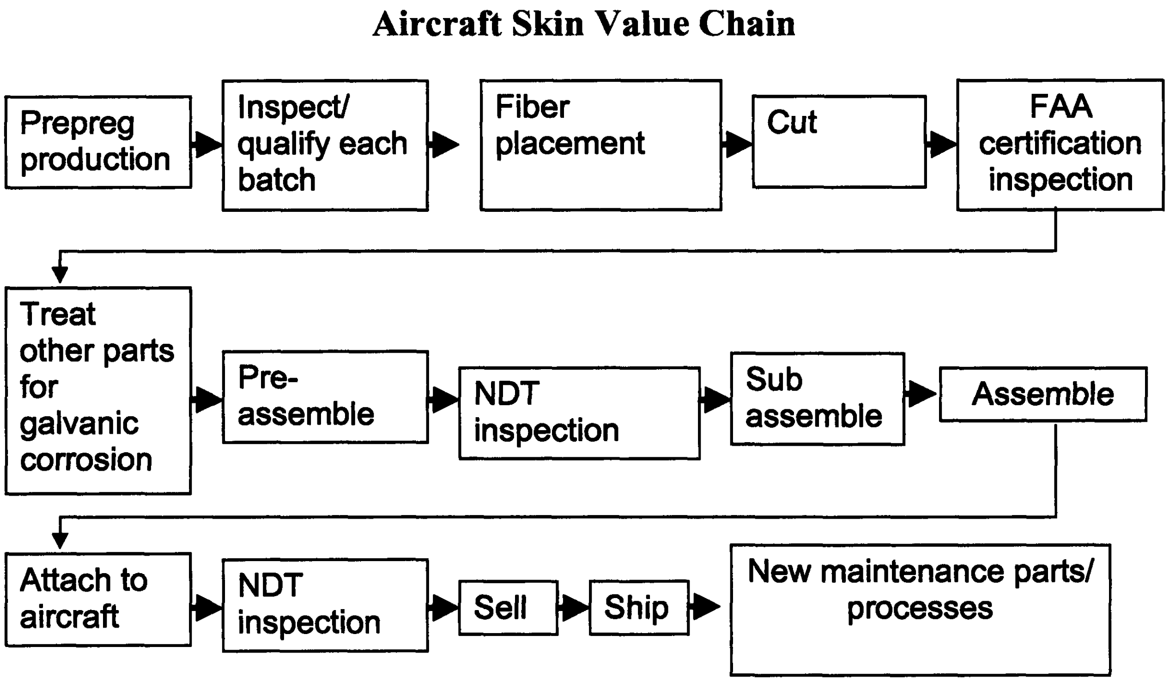

Figure 6.3: Simplified CFRP aircraft skin value chain.

This figure shows that the aircraft value chain is much more complex than the golf shaft chain. To insert CFRP in golf shafts, the golf club manufacturer would have to change (at most) three nodes. In contrast, the aircraft manufacturer would have to change dozens of processes at more than 10 nodes. The extensive change required by the aircraft manufacturer would equate to heavy switching costs, while the golf shaft switching costs would be relatively small. Furthermore, the safety and reliability requirements of the aircraft market would induce long and expensive qualification cycles—the golf shaft would require minimal certification. A materials producer could expect to face less resistance from the value chain of the golf shaft than from the value chain of the aircraft skin.

The net effect of choosing simple applications on the materials switching cost equation is clear: it reduces the number of nodes (n in the equation), along with their corresponding switching costs. Since there are fewer nodes in simpler value chains, handoff costs are also reduced. Choosing applications with simple value chains is the surest way to eliminate complexity and potential switching costs.

While choosing applications with simple value chains is powerful, it is only practical if the properties of a material lend themselves to those applications. There are many attractive established application markets that do not have simple value chains, such as aerospace, automobiles, and medical devices. The levers discussed in the next sections are applicable to applications with both simple and complex value chains.

Value Chain Integration: Reducing Unmanaged Nodes

The field of transaction cost analysis has shown that additional coordination can reduce inefficiencies and significantly improve the profitability and effectiveness of a value chain[9]. While coordination does not necessarily reduce the number of nodes in a value chain, it can significantly reduce complexity by eliminating handoff challenges, increasing communication between nodes, and focusing the nodes on a single target. Strong coordination can also squelch challenges from resistant nodes.

There are many organizational structures for managing complex value chains, but direct management of the nodes offers the highest potential for coordination. In the case of a new material, assuming direct management of the value chain requires that a material producer integrate forward, acquiring the nodes of the value chain that must be coordinated for a material to be inserted. Christensen et. al. have suggested that producers should integrate forward to the activity before the "decoupling point" of the value chain[10]. The decoupling point is the node in the chain in which no further change is required to use the product. In the golf shaft example shown above, the decoupling point would be "assembly", when completed shafts would join with clubheads and grips. A materials producer following this strategy would need to acquire or develop capabilities in the roll wrap stage in order to deliver products to the decoupling point (see figure 6.4). In the aircraft example, the decoupling point would most likely be the "attach to aircraft" node, in which a completed component could be interchanged with another similar component. A materials producer would need to own all of the nodes in the value chain through the assembly stage in order to maximize the necessary coordination.

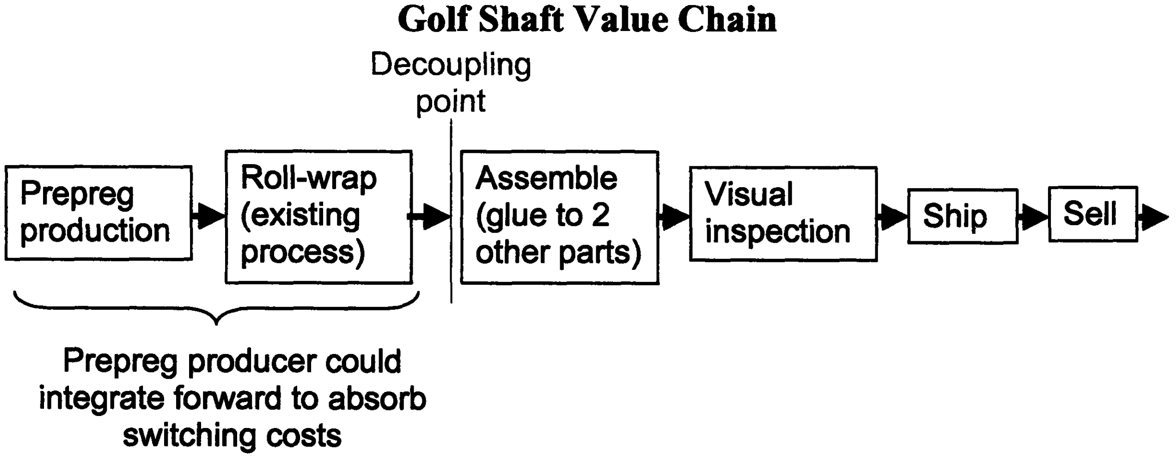

Figure 6.4: Golf shaft value chain, showing decoupling point, forward integration necessary to minimize switching costs

The goal of value chain integration is to reduce unmanaged nodes and produce a product that can be easily substituted into a decoupled value chain activity. However, value chain integration has some rather obvious capital implications: it can be very expensive to develop or acquire the capacities and capabilities necessary to manage all of the nodes up to the decoupling point. Although it reduces insertion time, forward value chain integration fundamentally shifts the switching costs from the application manufacturer to the materials producer. For this reason, it is only feasible in markets that offer potential sales large enough to offset the necessary investment.

Technical Decoupling: The Mimic

Insertion at the decoupling point does not always require a complete organizational transformation, as value chain integration dictates. It is also possible to launch a material in a form such that it mimics the relevant properties of existing materials, and effectively decouples the value chain because of technical compatibility with existing nodes. Of course, this option is not always available—it depends on the properties of the entrant material and on the level of understanding that is possessed about it. Revolutionary new materials often require completely new forming processes and offer completely different properties compared to existing materials. These materials could require an extreme amount of technical development to mimic existing materials and streamline with existing processes. Furthermore, undertaking to mimic the properties of existing materials could compromise the unique and novel properties of new materials, making them less appealing. Since materials are difficult to change, this process could be also be quite slow.

The technical compatibility of an entrant material with existing products and processes is dependent on the target application. Materials producers can choose to launch into applications that are naturally more compatible, or can try to alter the properties of a material to make it mimic existing materials in some attractive market. In either case, a high degree of cooperation and coordination between the application manufacturer and the materials producer is required—both groups need a clear understanding of both the material and the application. If this understanding does not exist, the ability of this approach to reduce switching costs is severely impaired.

Understanding of a material by both the materials producer and an application manufacturer is gained by experience with the material. Thus, the approach of technically decoupling a value chain by mimicking the properties of existing materials is most feasible with incremental improvements to existing materials.

The Injection Principle

Innovation theorists have taught that pushing a product into the market is like pushing on a string: the value chain bends in whichever ways suit it best. This analogy seems particularly applicable to materials, since they are the earliest point of competitive differentiation, and switches can require significant change throughout the value chain. However, the analogy is also applicable to the reduction of value chain complexity. If a thin fiber is short enough, it becomes infinitely stiff (the strongest materials known to man are metal and carbon fiber whiskers), and is able to be injected into any surface. So goes the value chain—a shorter, stiffer value chain allows easy injection of materials into their markets. Materials producers can reduce potential switching costs by choosing applications with simple, short value chains. They can integrate forward to minimize flexibility in unmanaged, resistant nodes, thus allowing easy insertion into decoupled nodes. They can also reduce the resistance of nodes by integrating perfectly into them. In each case, the ability of the chain to bend is reduced.

In any technology push situation, and particularly with new materials, innovators should strive to reduce value chain complexity. Reducing complexity creates a more rigid chain that can inject a product into the market, where it can compete with other materials on the basis of its value proposition.

If a material encounters too much resistance from the value chain of its application, it will either not be adopted or the high value chain switching costs will conceal its true value proposition.

Increasing Understanding of a Material

The second way to reduce the switching costs required to insert a new material into an application is to increase the understanding of the material. It has been acknowledged that learning costs, unknown costs, and the opportunism portion of handoff costs can be significant contributors to switching costs. Knowledge is the antidote to these costs—if the behavior, properties, and processing methods of a material are known and teachable by both the materials producer and the application manufacturer, then these costs are easily controlled. Learning and liability are minimized with a well-understood material.

Just as a spectrum of value chain complexity exists, a spectrum of knowledge of a material exists. Mature materials are well understood. Their properties are published, they can be accurately modeled, and their limitations are known[11]. New materials are understood only to the extent that they have been tested and proven in use. There are many mechanisms for dissemination of understanding of materials, and all are most effective when extensive knowledge of a material has been developed. They include:

- Material qualification
- Codes and standards
- Industry publications
- Listing in engineering manuals/engineering databases
- Product/material warranties
- UL/insurance listings

Inclusion of a material in any of these mechanisms is an explicit recognition of fitness for use, and is an implicit recognition of understanding of its behavior and properties within a range of contingent situations. However, it should be noted that several of these mechanisms are very specialized, and may not translate across industries. Different industries value different properties, have different risk profiles, and may have much different potential learning costs. Furthermore, products in different industries may face vastly different operating conditions.

The Knowledge Gap

At its core, technical development is a knowledge creation activity. During the early stages of technical development, knowledge is created in laboratories about the properties, behaviors, and interactions of a new material. As technical development progresses, knowledge about processing methods, maintenance, and recyclability is also developed. At some point in this process, a material is judged to be understood well enough to be released into the market.

Unfortunately, materials are rarely completely understood when they are released as products, and much of the knowledge created during laboratory development is inapplicable when translated into practical application knowledge. There are at least two reasons for this. First, it is practically impossible for a lab to generate the knowledge necessary to cover every application manufacturing process, every environmental interaction, and every contingent liability. Second, technical development happens within the scientific community of the materials producer, while production development occurs within the technical community of the application manufacturer. It is difficult to transfer knowledge between firms, and even more difficult to transfer knowledge between the scientific and application communities.

Knowledge Generation

Lab development alone cannot generate the knowledge necessary for actual production and application of a material. In a landmark 1995 paper, von Hippel and Tyre asserted that field learning "was sometimes the only practical way to succeed" [12]. They showed that many problems cannot be identified in the lab. Lab development does not necessarily deal with all of the complexities and challenges of volume production, nor can it possibly encompass all the contingencies that are faced in the variety of applications for which a material is destined. Ancillary activities, impurities, and environmental conditions in a production process are difficult to consider at lab scale, and they can have adverse interactions with a material. Field trials are crucial in order to identify unanticipated problems.

The use of bismuth solder was stopped because of an interaction that was undiscovered at lab scale. Working under government mandates to reduce the use of lead in automobiles, auto manufacturers turned to the use of low-melting bismuth solders, which made excellent joints. However, it was later found that even very low concentrations of bismuth severely weakened recycled steel (bismuth attacked the grain boundaries in steel, causing embrittlement). Since bismuth could not be removed from recyclate, it was completely removed from use by the automakers[13].

Lab development is also unlikely to uncover all of the possible failure mechanisms for new materials. While there is a standard battery of tests that are performed on new materials, it would be almost impossible for these tests to predict every condition or interaction that a material might face. These conditions can cause failure, and can lead to very high unknown liability costs. DuPont learned this lesson with a very expensive settlement for the application of its Delrin acetal engineering resin in toilet valves.

One of the first listed applications for Delrin was in toilet valves, where it offered superior economics to brass: a Delrin valve could be made with four machines, compared to the 40 required for a brass valve[14]. Toilet valves (see figure 6.5) seemed to be a perfect application for Delrin—the material had excellent mechanical properties, had been shown to be far superior to other engineering thermoplastics in water absorption, and offered excellent corrosion resistance[15]. Furthermore, DuPont had released laboratory studies showing that the material was resistant to almost all solvents[16].

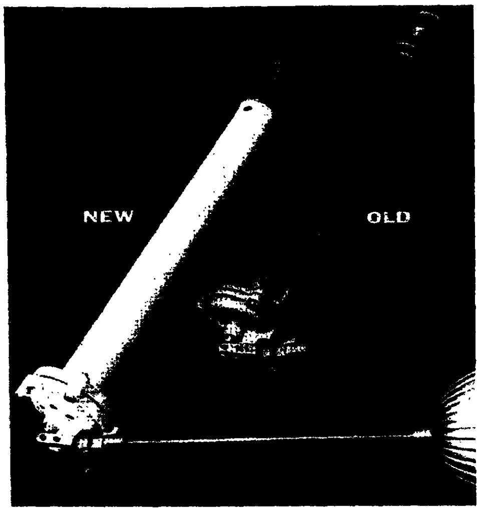

Figure 6.5: 1959 Delrin and brass toilet valves.

Delrin toilet valves enjoyed immense popularity throughout the 1960s and 1970s, despite some signs that they degraded over time. As the installed base of the valves grew, the failure process became more clear. The valves, which were under constant pressure from the water supply, would degrade and flake in water containing chlorine. The degradation led to cracking and separation of the valve. At the point of separation, the unattached portion of the valve was launched through the top of the toilet tank, leaving a fountain of water to flood the bathroom in which the toilet was installed.

Although the basic failure mechanism of acetal was described in 1960[17], a series of scientific investigations in the 1990s showed that acetal is severely attacked by hypochlorous acid, which is the acid formed by chlorine and water[18,19,20]. This attack occurred at extremely low chlorine concentrations: <.5 ppm. Since chlorine is a popular chemical in water purification, the concentrations in municipal water supplies (to which toilets were connected) were well above the threshold of attack[21]. While this appears to have been an honest mistake by DuPont, the company was required to participate in a $900 million settlement in 1995 to repair the damages caused by misapplication of plastics in plumbing[22].

There are many other stories like this one in the materials world, but the message is the same: laboratory testing is very important, but is insufficient to cover all of the potential challenges that a material will face. Although it had extensively tested the chemical resistance of Delrin in the laboratory, the knowledge from these tests was insufficient to cover the actual service conditions of the toilet valves[23].

In addition to their work on identification of unanticipated field problems, Von Hippel and Tyre noted a second advantage of field testing in knowledge generation: the identification of uses for a product that couldn't be anticipated in the lab. The researchers noted that the controlled environment of the laboratory couldn't identify all of the ways that people might use a product, and that field testing would reveal potential new markets or features for product manufacturers[24]. This knowledge may also be important to materials manufacturers.

Knowledge Transfer

Even if materials producers could generate the knowledge necessary to process a material into a final application and to cover liabilities, it is unlikely that they could easily transfer this knowledge directly to application manufacturers. While materials producers have developed tools such as materials-specific engineering manuals and technical support centers, they are incomplete: the versatility of materials makes their application base very broad, and it is extremely difficult to cover all potential scenarios. There is a gap between technical development and application manufacturing.

The gap between application manufacturing and technical development is similar to the well-documented gap between the science and engineering communities. The two groups rarely communicate unless an engineering problem is so difficult that its solution must be developed by basic science[25]. It was noted in chapter four that this situation does occur with new materials—materials producers often have to solve difficult problems themselves and then disseminate them back to the markets. However, it is more common for application manufacturers to solve application-specific problems without the help of materials producers.

There also exists suspicion among application manufacturers that materials producers misrepresent their products in order to gain sales. As one manager stated, "a salesman's job is to sell products" (regardless of the actual applicability)[26]. There are numerous examples of misapplication, and even some applications of deliberate misinformation. Given the enormous pressure that materials producers face to generate sales early in the life of a new material, it is easy to slip to unethical behavior. Known failure mechanisms have been concealed, leading to very expensive and embarrassing recalls and warranty costs for application manufacturers. One example of deliberate concealment of failure mechanisms is the relatively unknown static fatigue property of glass fibers. While most materials fatigue only in cyclic loading, fiberglass composites also fatigue in static loading. Misunderstanding of this property has caused many misapplications of the material, such as in leaf springs and pultruded signposts, both of which face both cyclic and static loading[27].

Network Effects and Real World Applications

The problems of the knowledge gap can be overcome by testing and demonstrating the properties of a material in actual—"real world"—product applications. One executive noted that when a new material is introduced "people will line up to be second but no one wants to be first" to adopt it[28]. Product applications create a track record for new materials, but also allow knowledge to be generated about them in more realistic (and demanding) conditions.

The concept of network effects, so prevalent in information technology, is useful in explaining the importance of actual product applications for new materials. Network effects can be defined as "a change in benefit, or surplus, that an agent derives from a good when the number of other agents consuming the same kind of good changes"[29]. With materials, the network effects are positive: there are advantages to an application manufacturer if other application manufacturers use the same material.

Systems-scale economies of materials are relatively straightforward and well-known[30]. As more users adopt a material, producers can profitably install larger-scale (and more efficient) production processes, leading to lower cost materials for users[31]. These effects contribute to commoditization of popular materials. However, although the systems-scale production advantages are well-known, the knowledge advantages stemming from network effects are at least as important. Knowledge advantages produce reductions in learning costs, unknown (liability) costs, and handoff costs.

Network Knowledge Reduces Learning Costs

The first type of learning that is accelerated by product applications is material production learning. As a new material is sold for use in product applications, and as the performance requirements imposed on the material increase, producers are forced to develop learning about production processes to improve yield and reduce defects. This is a natural outcome of scaling up. As a material finds more applications, a multiplicative network effect is generated, since all application manufacturers can take advantage of improved quality and lower costs.

Processing of materials also benefits from the network effects of product applications. It has been noted that laboratory development cannot cover all of the potential processes and application uses of most new materials. In fact, most application-specific process development is executed by someone in the value chain outside of the materials producer, such as the application manufacturer or a contract manufacturer. As this process development occurs, it can be transferred by the application manufacturer to other application manufacturers through patents, suppliers, labor flow, or even reverse-engineering of products, to name a few of the paths.

The learning network effects of product applications are not limited to production and processing. As the installed base of users grows, markets are created to fulfill the needs of those users. New areas of research and development often emerge, and systems are designed to accommodate the unique properties of the materials. These systems can range from specialized handling systems (such as vacuum conveyors) to enhanced engineering tools (such as finite element systems) to automated purchasing systems to financial instruments designed to hedge inherent risks. These types of derivative products embody much of the specialized knowledge necessary to adopt a material, and significantly reduce the overall learning costs. The presence of these markets can also reduce the capital and transaction costs inherent in a materials switch.

Network effects of learning are accelerated by the common practice by materials producers of employing technical representatives as problem solvers for application manufacturers. Since these technical representatives are exposed to the knowledge generated by the application manufacturers, they can transfer this knowledge to the materials producer and to other application manufacturers. Two-way communication between materials producers and application manufacturers presents a clear opportunity for materials producers to become clearinghouses of knowledge, new knowledge acquired from product manufacturers can be added to knowledge developed in-house. This can significantly reduce future learning costs.

In addition to being broader and deeper than knowledge generated in a laboratory, product application knowledge is more credible. Claims can be supported or refuted with product data: product applications can be seen by other application manufacturers, and achievements and shortcomings of a material are quite visible. This credibility can increase the rate of acceptance of new knowledge.

It must be acknowledged application manufacturers may consider much of their learning proprietary (as it can generate competitive advantage) and may restrict accessibility to it. This practice can significantly reduce the effectiveness of network learning.

Network Knowledge Reduces Liability Costs

Network effects also reduce potential liability costs for future adopters of a new material. As product applications of a new material are subjected to conditions of actual use, failure modes often appear that were invisible in lab testing. As more application manufacturers adopt a new material, the material is exposed to more conditions, and more failure modes are identified. As failure modes are identified, the true applicability of the material is exposed. This allows designers and engineers to design it into applications that are not susceptible to its shortcomings, thus minimizing the probability of failure to a higher degree than either laboratory testing or qualification could.

Network Knowledge Reduces Handoff Costs

The opportunism portion of handoff costs is a direct consequence of asymmetric knowledge between different nodes of the value chain. If one node has more knowledge than another, a temptation exists to take advantage of the situation by charging higher prices. The product application knowledge can minimize this by forcing nodes of the value chain to develop knowledge together. The challenges of knowledge transfer between materials producers and application manufacturers have been discussed, and it is unlikely that materials producers would have much better luck with other nodes of the chain. Furthermore, depending on the level of coordination, a similar problem may exist between nodes of the chain.

As materials are adopted in more applications, they become more familiar to processors and other nodes of the chain, and chances for opportunism are reduced. Players are more able to find alternate suppliers, reducing the chances that they will be gouged. Furthermore, players will be more able to ascertain the true economic price of goods or services, and can discern the presence of opportunism.

The Challenge of Building a Network (or how to reduce learning, liability, and handoff costs)

It is clear that practical product applications are necessary for growth of a new material, because these applications create network effects that reduce switching costs for future adopters. However, materials networks are rarely sui-generous—they must begin with a kernel of application manufacturers. This kernel becomes a validation tool for the materials producers, but the application manufacturers must be convinced to use the new material before validation can begin. The ensuing problem is easy to see: How can producers get validation customers to absorb large learning, liability, and handoff costs for unproven materials so that networks can begin?

The answer is simple: materials producers should carefully choose application markets that are minimally sensitive to these costs, and should integrate forward when those markets are not available.

Enablers as Validation Applications

Because materials are versatile, materials producers can select markets into which materials are launched. Early market choices are crucial, since they determine the speed at which learning can be generated. While launch of a material into an application market is by no means an assurance of adoption into that market (since application manufacturers and consumers have the final say), selecting the proper validation markets will help. There are two important criteria for selecting validation applications as network kernels. First, applications must be capable of adopting the new material quickly. Second, the application should be visible and relevant to other potential markets.

Application manufacturers are most likely to quickly adopt a new material in applications that offer them solid profitability with minimal risk. The best case for solid profitability is made by a very compelling value proposition coupled to low switching costs and low liability costs. The validation markets for the major plastics all met these criteria, and created enough awareness of their materials to spark network creation. They were described in chapter three as "enablers". Four important characteristics of enabler applications were described:

1. The material allows users of the applications to do new things
2. The application solves a relatively new problem
3. The application is relatively simple
4. The market may be small

Each of these characteristics is important to validation.

The value proposition of a material must be compelling in a validation application, and consumers are often compelled to buy products that allow them to do new things. If they are scrambling to solve a new problem, the material can be doubly compelling. However, value proposition is only part of the equation—insertion factors and potential liability must also be minimized.

Avoiding technical difficulties is relatively straightforward: applications should be selected that do not have obvious technical incompatibilities with the new material. While technical difficulties may arise, they are often predictable and avoidable. Further assurance can be gained by selecting very simple applications that have few interactions with other parts.

Value chain challenges can be minimized by selecting applications with very simple value chains. Eliminating nodes and handoffs maximizes potential compatibility. They can also be minimized by selecting relatively new applications. Abernathy and Utterback showed that new products (in the fluid stage) are likely to have very flexible value chains, which can accommodate change easily[32]. The ability to accommodate change is an implicit recognition of low learning costs, and value chains in the fluid stage are often optimized to minimize learning costs so that the correct set of product features can be identified and introduced.

All of the characteristics of enablers reduce potential liability. Consumers are more likely to be tolerant of faults in products that are solving new problems, since they have no other choice. Collateral damage from product failure is likely to be minimal in simple applications—at worst limited to warranty replacement of the failed product. Small application market size can also limit liability—if fewer products are sold, there are fewer opportunities for failure. Furthermore, failure in a small market can allow easy recalls and damage control (in a public relations sense) in the event of failure.

In order to be useful as validation applications, enablers must be visible to adjacent application markets. Since enablers are generally introduced into relatively small markets, it is difficult for them to generate the profits necessary to justify investment. These profits come from the network of applications in which a material is inserted. For this reason, it is extremely important that visibility to other markets be considered when determining potential enabler applications into which a material will be launched.

It is also important to recognize that network effects are only as strong as the links between groups in the network. While materials producers can act as clearinghouses of knowledge, their credibility is limited if they cannot convince manufacturers of the applicability of previous applications to new ones. This challenge can be especially strong if a material is appealing in incompatible industries. For example, it could be difficult to convince an aerospace manufacturer of the applicability of shape memory alloys to a jet engine based on experience in biomedical heart stents. Thus, enabler-type validation applications may be necessary in each disparate industry into which a material is targeted.

From an operational standpoint, enabler application opportunities can be quite difficult to identify. The work of Eric Von Hippel may be quite useful in this regard. Von Hippel has shown that groups of "lead users"--users who face needs that will be general in the marketplace months or years ahead of the rest of the market and who "expect to benefit significantly by obtaining a solution to those needs"—can be useful in identifying and developing ideas[33]. These lead users can provide feedback before any firm has entered a market and can provide new ideas in addition to early feedback. The emerging idea of user innovation toolkits, in which producers transfer the task of idea creation to users, also seems promising[34,35,36].

Integrating Forward: A Second Option

There are industries in which enabler-type applications are not feasible, and there are old, complex applications markets that are so attractive that they are irresistible. In these cases, another option is available to initiate an application network: forward integration to the node before the decoupling point. By integrating forward in the value chain, producers can insert new materials into large, highly visible, complex, and profitable markets that would not otherwise accept them because of switching and liability costs. The benefits of this strategy in value chain management have already been discussed, but reductions in future learning costs, liability costs, and handoff costs have not, and they are very important.

Integrating forward allows materials producers to internally capture knowledge about every step in the value chain. This knowledge can then be disseminated back to application manufacturers with the confidence and credibility of proven experience. However, the dissemination can be selective, since this type of integration can expose potential competitive advantage for the materials producer. It also fundamentally shifts learning costs from adopters (application manufacturers) to materials producers, making future adoption easier.

Potential liability costs are not necessarily lower in a forward integration situation, but they are completely shifted to the materials producer. While the prospect of absorbing liability is never tantalizing, it can eliminate costs for other nodes in the value chain so that an application network can begin.

Forward integration offers clear benefits in reducing handoff costs. If every relevant node in the value chain is owned by the same company, all the profits in the chain are absorbed by that company. The only opportunity for opportunistic behavior is internal transfer pricing, and the incentives for such behavior are low.

Forward integration also minimizes the knowledge gap between laboratory work and field production. By managing the value chain, a single materials producer can provide the coordination necessary to force communication between production and lab groups.

The Importance of Understanding

The degree of understanding held by materials producers and application manufacturers is a major difference between new materials and old ones. Understanding is an important factor in determining insertion strategies because of its effects on learning, liability, and handoff costs.

If both producers and application manufacturers understand a material well, the probability is high that it will adopted or rejected based on incremental cost and performance differences with other materials—traditional wisdom applies. When understanding is high, simple substitution can occur between materials in applications with simple value chains. High understanding also facilitates technological development to the point of mimicking other materials, so that entrant materials can be substituted into complex value chains with minimal impact.

Mapping Insertion Strategies

Having established the conditions of insertion, and having examined their effects and ways of mitigating the effects, it is possible to create an insertion strategy matrix. The goal of this matrix is to identify the strategies that are likely to be most successful at minimizing switching costs, and therefore insertion resistance, under different conditions. The matrix is constructed by comparing the condition of value chain complexity faced by a material to the condition of understanding of the material (by both producers and application manufacturers). It is shown in figure 6.6.

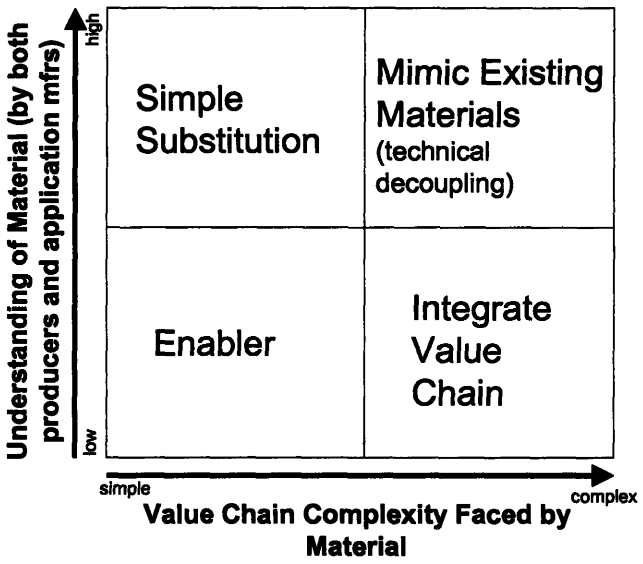

Figure 6.6: Insertion Strategy Matrix for materials

These strategies are designed to minimize switching costs for entrant materials, thus maximizing their insertion potential. For any of these strategies to work, the entrant material must meet two conditions. First, it must be technically compatible with the application; if major technical barriers exist, they will prevent quick insertion no matter how low the switching costs. Second, the material must offer a clear value proposition. If a value proposition is not present, adoption would be an irrational act on the part of application manufacturers, thus violating an underlying tenet of this analysis.

Each of these strategies will be briefly discussed, and will be illustrated with examples from the commercialization of high density polyethylene and other materials.

Enablers

In situations where understanding of a material is very low, either by the materials producer or by applications manufacturers in a market segment, enabler applications are the quickest, least expensive points of insertion. If networks need to be built, markets should be selected for enabler applications. Enablers have been discussed several times in this document, but their defining characteristics are worth repeating: enablers are simple applications that let people do things they couldn't do before. They usually have small markets, and are not simple improvements on existing ideas—they often create new value networks.

Enablers have a different role than other types of applications. They generate knowledge, credibility, and visibility--not large profits. Enablers are the best tools for validation applications, and are crucial for creating a market kernel for future application development.

Despite their importance in application development, enablers are counterintuitive undertakings for materials producers because they generate small (if any) profits. These profits are woefully insufficient to justify materials development investments. However, a small shift in the mindset of materials producers can help overcome this problem. If enablers are recognized for what they are—knowledge and market development activities—then they will not be expected to generate huge returns. Identification and placement of enabler applications should be the capstone activity of the research and development phase for new materials. By doing this, the research group can identify potential pitfalls in value chain activities and failure modes of the material, and build credibility with markets. A more complete material can then be passed to marketing organizations for launch into platform applications.

In order to quickly fulfill their goals of generating knowledge, market credibility, and visibility, enabler applications must be carefully selected. If the following five criteria are fulfilled, enabler applications are remarkably sound investments for materials producers, even if they don't earn profits. First, enablers must be applications in which the properties of a material offer unique value—users must be able to do something new. Second, both the applications themselves and their corresponding value chains must be simple, so that insertion factors are minimized. Third, enabler applications should develop value chain capability. Fourth, enabler applications should be relatively fault-tolerant. Otherwise, failure can be exorbitantly expensive or highly visible, and the ability of the material to move into adjacent markets will be severely retarded. Finally, they should be visible to adjacent, attractive markets. If enabler applications are not visible to attractive markets, they cannot fulfill the role of application network creators, and are a poor allocation of resources for materials producers. The only exception to this rule is if an enabler application might generate important insights or value chain capability that can't be gained otherwise.

One more important criteria of enabler applications should be mentioned: enablers *must* be profitable for application manufacturers. Otherwise, they will not be attempted. This criteria gives some insight into the type of application manufacturer that materials producers might target as enabler customers. The application manufacturer must be willing to undertake a low volume, high risk project and capable of making a profit at it. This probably indicates a small manufacturer with a flexible cost structure. It may also indicate a relatively new manufacturer, which is less protective of its reputation, has less to lose in case of failure, and is hungry enough to take the risk.

Several examples of enablers were given in chapter three, but the most famous example is presented here: the hula hoop, enabler application for high density polyethylene (HDPE). HDPE was the product of one of the most significant research efforts in the history of plastics. Developed simultaneously by Phillips Petroleum and the German chemist Dr. Karl Ziegler, HDPE was "spread eagled to the public with a fanfare that would have done credit to a Mike Todd extravaganza"[37]. It was hailed as a superior version of conventional low density polyethylene—it offered greater stiffness, a higher heat distortion point, and potentially lower cost[38]. Based on these properties, Phillips committed $50 million to build the first large-scale production plant, and other competitors followed suit[39].

Phillips expected the material to sell itself, claiming that it was "a higher quality item and molders (would) require less material because they (could) design for thinner walls"[40]. However, the sales did not come as quickly as Phillips and other producers might have hoped for two reasons. First, scaling the product from lab scale to mass production was very difficult: "you had to have everything exactly right"[41]. Second, Phillips' prediction that molders would have to redesign their products to fit HDPE was correct—both molders and application manufacturers quickly learned "all over again that a new plastic doesn't blossom overnight"[42]. *Modern Plastics* reported in early 1958 that the material could not be "dumped into an old mold and produced forthwith"[43]. Furthermore, there were problems with "creep, stress cracking, odor, catalyst removal, and many others"[44]. Learning costs were high, potential liability costs were high, and existing value chains could not handle the material. In fact, every early order that Phillips had received for HDPE was cancelled[45]!

In late 1957, inventors Richard Knerr and Arthur "Spud" Merlin of the Wham-O company began work on project that would become the white knight application for HDPE: the hula hoop (see figure 6.7) [46,47,48].

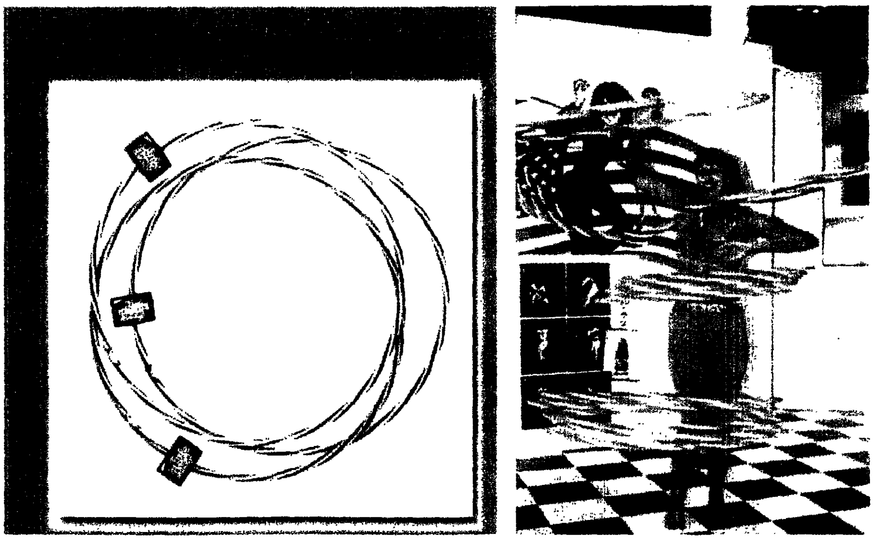

Figure 6.7: Wham-O Hula Hoops and world champion hula hooper.

The hula hoop fit all of the characteristics of an enabler application. It offered a very unique value proposition and allowed people to do new things—it spurred a completely new fad. There was also no other material that was suitable for the application. HDPE was "just right for hoops. It ma(de) hoops that are not too flexible, not too rigid, and are safe for children. Because it floats, it (wa)s just right when hoops are used for water games"[49]. HDPE hoops were also "handsome, two color products"[50]. Wood was probably explored as an alternative, but would have been easily broken, could not be machined quickly into hoops, and could not be colored[51]. Nylon also may have been suitable, but was much more expensive than HDPE and was difficult to color.

The hula hoop was an extremely simple application: a standalone product made from a tube of plastic, a wooden dowel, and two staples, with a simple value chain. It was made by contract manufacturers, then sold by Wham-O to retailers, who sold it directly to children for $1.98. No adjacent products had to be redesigned, very little assembly was required, and no maintenance was needed. The hula hoop was also very fault tolerant: if a $2 hoop broke, children could simply buy another one. In fact, the hoop was so fault tolerant that application manufacturers would purchase warehouse loads of off-grade material[52]

It has been argued that the hula hoop was the most important fad of the 1950s[53]. Whether this was true or not, it is clear that hula hoops gained wide visibility for HDPE--more than 100 million hoops were sold in 1958! The fact that so many hoops were sold seems to undermine the enabler characteristic of a small market, but *Modern Plastics* reported that total 1958 requirements were 12-15 million lb. at a price of $.43/lb.—definitely not enough to justify even Phillip's $50 million investment, let alone the investments of the other producers[54].

In addition to gaining visibility for HDPE, the most important benefits to HDPE producers of the hula hoop were knowledge and capability development, both in materials production and application value chains. Phillips reports that the hoop fad allowed it develop its process so that it could minimize defects and create much more consistent resin—"the kinks (were) ironed out"[55]. Modern Plastics reported that "scores of extruders had been educated in the use of high density polyethylene and were running it on a routine basis"[56]. This was important, given the disenchantment that molders had previously shown toward the material[57].

When the hula hoop craze had died down, Wham-O had earned $45 million, a substantial sum for a small company[58]. While the HDPE producers had earned far less, the knowledge and credibility gained by the hula hoop played a large part in allowing producers to launch HDPE into its platform application: blow molded bottles.

Value Chain Integration

There are cases in which the technical properties of material make the possibility of enabler applications impractical, or in which existing markets with complex value chains are so compatible with the properties of a new material that they are irresistible to producers. If a material is poorly understood by a producer or application manufacturers in a particular market, and that market is attractive enough to justify enormous capital investment, then value chain integration is the more effective strategy for insertion of the material.

Like enabler applications, value chain integration generates credibility and visbility. Whether integration creates superior knowledge is questionable—choosing to integrate a value chain locks a company into a product, and a high degree of specialized knowledge is generated about that product. In contrast, a company can launch many enablers, and can develop a much broader view of the properties of a material. However, it must be noted that the two strategies do not have to be mutually exclusive; large materials producers may have sufficient resources that they can undertake both strategies simultaneously, thus generating both broad and deep knowledge about application value chains and materials production.

In choosing to integrate a value chain, a materials producer is placing a bet on the viability of its material in an application market. This bet is substantial, since integration requires development or acquisition of new competencies and equipment. Because of this, it is worthwhile to invest the resources necessary to understand the application market before integrating, so that unanticipated obstacles can be minimized.

Perhaps the most popular example of forward integration in the plastics industry was DuPont's introduction of nylon stockings in the late 1930s. The first nylon fiber was developed by Carothers in 1935[59]. The enabler application for nylon was Dr. West's Miracle Tuft Toothbrush, but DuPont wanted to force widespread awareness of the material with an application that was "something innovative, something distinctive, something superior"[60]. The chosen application was as a tough, handsome replacement for high end silk stockings. The silk stocking market was very attractive—worth $70 million, with each American woman buying eight pair/year[61]. Nylon offered a clear value proposition: it would be less expensive and much more resistant to runs than silk.

In order to introduce its fiber in stockings, DuPont had "to go beyond the state of the art in several areas", and invested over $4 million developing processes in many "discrete operations"[62,63]. The company systematically sent teams of engineers to solve problems in melt spinning, pretwisting, uptwisting, sizing, and spooling, so that it could produce a yarn that would be compatible with existing technology at the decoupling point: weaving[64,65]. Since DuPont's fiber was sold as a yarn, weavers could drop it directly into their machines, and were able to sell it through existing channels (see package infigure 6.8). The unmanaged nodes of the value chain were easily influenced and did not resist change.

Figure 6.8: Early nylon stocking package.

Nylon yarn earned handsome returns for DuPont. The entire research investment was recouped in the first year of production, and nylon stockings owned 30% of the entire stocking market within two years[66]. More interesting for this analysis is the fact that integrating forward allowed DuPont to establish a dominant platform application within five years of the discovery of nylon.

It should be noted that there are also examples of backward integration, in which end users provide the coordination necessary to force development of a new material. One of the best examples of backward integration is the role of the US military in the development of titanium alloys. Although the military could not acquire the necessary nodes in the value chain, it kept very tight control and management of the titanium development program.

The first commercially pure titanium was made in the United States by William Kroll in 1946[67]. Titanium was a strong as steel, but 45% lighter, and was very corrosion resistant, so it was promising in aircraft applications[68]. The cold war pressures of the early 1950s were driving extensive military development of aircraft, and titanium offered solutions to many of the challenges that designers were facing. However, neither the material nor its processing methods were well understood, so the United States formed the Metal Advisory Board on Titanium, and gave full control of the project, including budget authority, to Watertown Arsenal[69].

Watertown systematically took control of the necessary nodes in the value chain by carefully allocating its resources to suppliers that could build the capabilities needed by the military. It not only granted contracts, but also monitored progress very tightly, and controlled the flow of government funds in order to reach its goal of finding a viable titanium alloy for aircraft use[70]. The contracts granted ranged from alloy development to casting process development to coating and extrusion development. The coordination provided by Watertown facilitated communication, and allowed the contractors to overcome extraordinarily challenging technical obstacles (such as hydrogen embrittlement that would cause titanium to flake in the hands of workers) while developing sufficient production capacity to supply the needs of the military[71].

The end result of the Watertown project was the development of the most important titanium aircraft alloy: Ti-6Al-4V. Furthermore, the Watertown project left a legacy of profitable production capacity that has supplied the United States military and industrial complex with titanium for nearly 50 years. Perhaps most interesting is the fact that the first titanium applications were used in aircraft within seven years of Kroll's development of pure, stable titanium[72]. The coordination provided by Watertown Arsenal was as close to backward integration as was possible by a government agency, and it significantly improved the insertion time of titanium.

Simple Substitution

Simple substitution, in which materials are switched based on incremental price or performance differences, is probably the most common strategy for insertion. It is the strategy recommended by traditional materials marketing wisdom, and many tools, such as cost models and utility analysis, have been built to facilitate it. It is most effective for established materials, where properties are well known by both materials producers and application manufacturers, and value chain elements are in place that can handle the entrant materials.

The principles discussed here are applicable to simple substitution, and can be useful to materials marketers when choosing target markets for established materials. Simple substitution is most likely to result in quick insertion when value chain barriers are small, a condition most likely in products with short value chains. This does not mean that quick substitution cannot happen in products with complex value chains. It can happen, and is most likely if the value chain is in a state of flux, such as at the time of a model change.

Although simple substitution is easiest in applications with simple value chains, it is also less defensible. A value chain that is amenable to quick substitution by one material is most likely susceptible to quick substitution by another. While artificial switching costs (contracts, etc.) can be constructed to prevent substitution, the safest position for a material is to be the least expensive product that fits the *exact* demands of the application—the lowest cost perfect match. This concept will be considered in more detail in chapter seven.

Simple substitution can be much less simple than it appears. There are several examples in the plastics world of in which seemingly simple substitutions went awry because of incomplete understanding (or outright neglect of) the full set of requirements of the application. The most famous is probably the substitution of polystyrene (PS) for other materials in toys.

Because of its shininess, low cost, and ease of molding, PS seemed to be the perfect material for inexpensive toys for baby boom children[73]. However, the producers of these toys seemed to have taken little care for quality—untoughened polystyrene was extremely brittle, and many of these toys quickly failed. These failures had tremendous reverberations for the polystyrene business (and for plastics in general). Toys contributed to a general public perception of "cheap plastics", which would haunt the industry for decades. Materials producers began trying to combat this perception as early as 1948 with certification programs to assure the public that some plastic applications were soundly designed[74]. Had the application manufacturers been more careful when planning their substitution, it is likely that the reputation of plastics would have been much better.

Mimic Existing Materials

There are many applications with complex value chains that are in steady state production and rarely have model changes. Insertion of a different material into one of these applications can be a formidable challenge, since the switching costs could be very high. If the material is well-understood by both the producer and the application manufacturer, then the best strategy to minimize switching costs is to find a way to mimic the properties of the incumbent.

The mimic strategy is not easy to do, because it requires both a thorough understanding of the application and a material that can be altered enough to fit in that chain. It must be applied with extreme caution, because failed attempts at mimicking other materials can be very damaging to the reputation of a material, and can delay its insertion into other applications. In fact, some observers of materials commercialization believe that misapplied mimics ("overpromises") are the most important factors in commercialization delay[75]. The most common problem with mimicking is premature (or even catastrophic) failure of the mimicked application. This occurs because of an incomplete understanding of both the entrant material and the design of the application into which it is placed. It is much easier to match only the outward appearance of a material than to match the complete set of design criteria that is being replaced.

The United States military learned the shortcomings of the mimicking strategy in World War II. Shortly after the attacks at Pearl Harbor, "it was found necessary to restrict the use of many metals required in defense industries", and plastics were required to assume a new role as war materiel[76]. Applications were classified into two categories: those that replaced metal, which was in short supply, and those that were based on the unique properties of plastics[77]. The applications that were based on the unique properties of plastics, and were originally designed as plastics parts met spectacular success. These included both common applications, such as vinyl gas masks, phenolic mortar fuzes, and acrylic airplane canopies and exotic applications, such as high temperature silicones in motor windings and polyethylene wire coating in radar[78,79,80,81].

In contrast to the success of the applications that were designed to be plastic, the mimic applications often met complete failure. *Modern Plastics* lamented that "some of the master planners in Washington thought that plastics would be a panacea for all materials shortages", and "threw" jobs that used too much metal "into the lap of the plastics industry" [82]. "The result of this muddle-headed policy was almost fatal to the industry.

Plastics got a bad name", and decision makers who had seen these failures were unwilling to use plastics even in applications that would benefit from them[83]. The damage incurred "by one job poorly done counteract(ed) twenty jobs well done", driving *Modern Plastics* and others to declare that "Rule No. 1 for the plastics industry in getting more of its products used in materiel (was) to know the function of the parts to be manufactured before it proceeds"[84].

Most of the successful examples of the mimic strategy occurred between relatively similar materials, but still required extensive development of the material. These include the replacement of LDPE by LLDPE/HDPE in trash bags, the replacement of HDPE by PP in battery cases, and the replacement of PP by HDPE in appliance parts. Because the mimic strategy is most applicable between established, understood materials, the value proposition can be less compelling than in enablers or forward integration situations—it can be a lowest cost perfect match situation. However, if a material is adopted based on the mimic strategy, it remains open to attacks from displaced materials if those materials drop in price or increase performance. Once a mimic entry has occurred, a more defensible position can be created by incrementally altering application designs to take advantage of any unique properties a material might have.

The invasion of ABS into the refrigerator liner market of the 1960s was a good application of the mimic strategy, followed by design changes to employ the unique properties of a material.

Refrigerator parts were arguably the platform application for polystyrene (PS), with the first use of PS in refrigerators reported in 1940[85]. The shiny appearance, relatively good resistance to food oils, and dimensional stability at low temperatures of PS made it a natural fit for refrigerators, and it was used in many parts. The complex value chain of appliance manufacturing helped lock in its use, and the advent of high impact PS (HIPS) and thermoforming helped PS conquer the pinnacle of refrigerator parts, the inner door liner, in 1956[86]. HIPS dominated this market for several years, but while it was good for this application, it was not perfect. In the late 1950s, consumers began to recognize that HIPS was not resistant to butterfat, and was fairly brittle, even in refrigerator liner gauges,[87]. It was also difficult to thermoform, making it less attractive to application manufacturers[88] (see figure 6.9 for the shape of liners).

The industry also recognized that ABS would make a superior appliance part, since it was more resistant to chemicals and significantly tougher, but did not adopt it because it cost more than twice as much as HIPS[89]. However, from the perspective of the refrigerator door liner value chain, ABS effectively mimicked HIPS (both were modified styrene resins). The thermoforming process was very forgiving, so price was really the only barrier that prevented replacement. By 1963, the price of ABS had come down significantly (because of volume achieved in auto instrument panels and by replacing cellulose acetate in telephone handsets), and was within $.05/lb of HIPS[90]. At this point, the price gap was low enough to allow substitution of ABS into higher-end refrigerators. Since ABS mimicked HIPS, refrigerator manufacturers were able to profitably change materials based on a small price difference. This indicates that the mimic position of ABS had been successful—switching costs were low.

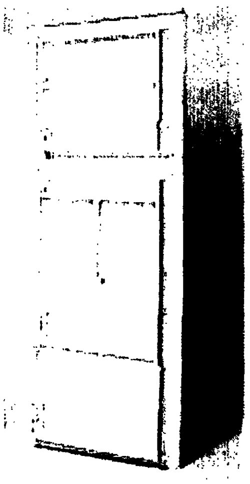

Figure 6.9: ABS refrigerator door liner.

Having finally entered the market, ABS struggled to achieve deep penetration because refrigerator manufacturers could easily switch between it and HIPS. It position did not become dominant until refrigerator manufacturers adopted a design that took advantage of a unique property of ABS: its resistance to polyurethane, a new insulation that attacked HIPS[91]. By 1969, ABS had "finally become the more accepted material for . . .refrigerator inner door liners". Because it was the lowest cost material that fit all the needs of refrigerator materials, it held this position until the 1990s, when it again came under attack by HIPS, which had been developed to mimic its chemical resistance and toughness. The battle continues today.

While the mimic strategy is a viable option for attacking applications with complex value chains, it should be attempted very judiciously. Materials and applications must be well understood, and a strategy to create unique value is necessary for a mimic insertion to be defensible in the long term.

Conclusion

It is the assertion of this thesis that materials producers can insert new materials into the market much more quickly than they have in the past by wisely planning their entry strategy. Switching costs are rational reasons for application manufacturers to resist adoption of new materials, and materials producers must strive to minimize them. Switching costs are conditional on the complexity of the value chain faced by a material and on the degree of knowledge possessed by both materials producers and application manufacturers about that material. The effects of each of the conditions can be minimized if they are understood.

The versatility of materials is both a virtue and a curse for producers. It is a virtue because producers can selectively choose the application markets into which a material will be launched. It is a curse because the range of application markets can be very confusing. If the wrong applications or partners are chosen, the commercialization time of a new material will be significantly extended.

Because materials can be used in many applications, applications can be strategically selected to minimize switching costs. This selection seems most important early in the lives of new materials, when enabler applications must be found to build credibility, knowledge, and visibility. Enablers are counterintuitive—they are not designed to make money, but rather to create a kernel for a network of applications that will generate the profits that materials producers seek. Since they are counterintuitive, it is important that producers organize to produce them. One way to do this is to make identification of enablers the capstone activity of the research and development effort, so that more complete materials can be handed to marketers.

Market selection is useful beyond the enabler stage. Given the same value proposition, markets with lower switching costs will always be more willing to adopt a material. However, these markets are also more susceptible to attack from competitive materials.

Not all markets have simple value chains, but there are still ways to reduce switching costs. In these cases, materials producers can force quicker insertion by transferring switching costs from application manufacturers to themselves. There are many ways to do this, but the decoupling point of the value chain offers an excellent entry point. The decoupling point is the node of the value chain at which a material can be inserted with minimal further change.

Entry at the decoupling point can be technical or organizational. A technical entry mimics the properties of existing materials so that the entrant is highly compatible with all remaining elements of the chain. The mimic strategy can be easily misapplied if insufficient understanding is possessed about either the material or the application, and can result in fleeting competitive advantage unless moves are quickly made to take advantage of the unique properties of a material. Organizational entry requires acquisition or development of all the nodes ahead of the decoupling point. It provides excellent coordination and knowledge development, and shifts the burden of risk completely off of value chain elements. However, it is very expensive, and is therefore practical only in very appealing application markets.

Resolution to the Pattern of Materials Commercialization

The concepts of switching costs and network development presented in this chapter add significant resolution to the pattern of materials commercialization. Their contribution is quite simple. The progression of the major plastics from enablers to platforms to widespread substitution was a progression of knowledge, switching costs, and network development. The early, poorly understood versions of all the plastics first found applications with very low switching costs, in which they could build knowledge, gain credibility, and become visible to adjacent application markets. They then captured one of those markets—a large one—that had higher switching costs and higher visibility in other markets. Using the cash, credibility, and visibility generated by this platform application, they were able to attack other major application markets, many of which had significant switching costs. Conquering these markets ensured their long term viability.

Resolution to New Market Disruptions

The bulk of Christensen's work on disruptive technologies has focused on strategies to help new entrants beat existing competitors. While this work has been beneficial and insightful, most of it has been directed toward services and assembled products, both of which can be changed quite easily to adapt to market needs. Christensen suggests that disruption can come in two forms: new market disruption and low-end disruption[92]. New market disruptions are "so affordable to own and simpler to use that they enable a whole new population of people to begin owning and using (a) product"[93]. The markets are different enough from mainstream markets that mainstream competitors ignore them, but the entrant products quickly improve and conquer the mainstream products. Low-end disruptions are innovations that "take root at the low end of the mainstream market" and then get better until they are superior to mainstream competitors[94].

Launching new materials is quite different from both of the disruptive situations, but gives resolution to the mechanism of new market disruptions. Both entry strategies of disruptive technology model are designed to help innovators beat competitors. The insertion challenge for new materials is not to beat competing materials—it is to beat value chain obstacles. Materials are difficult to change compared to service operations or assembled products, and it is rare that incumbent materials can match the exact properties of entrants. Given the presence of a value proposition and the absence of technical difficulties, new materials will be adopted if value chain obstacles are overcome.

Christensen has always suggested that innovators should launch their wares as simple products that let people do new things, but the reason given was to avoid competitive response from incumbents[95]. The suggestions given in the present research are similar, but for fundamentally different reasons. The strategies presented here are not designed to minimize competitive response, they are designed to minimize switching costs, and therefore value chain resistance.

Because this analysis arrives at similar recommendations for different reasons than disruptive innovation theory, it provides insight into the *mechanics of disruption.* Distilled of competitive pressures, materials insertion reveals that switching costs within the value chain are minimized with simple, new products. Every product has a value chain. Although few products face the degree of value chain challenge that new materials do, it is likely that a portion of the success in disruptive technologies can be attributed to the low value chain resistance that results from inherently low switching costs in simple, new applications.

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Chapter 7: Lessons in Competition (Penetration Factors)

"Imagination is essential to visualize and to realize the potentialities of new materials—to treat them on their own terms, to recognize, in a word, the autonomy of new media"
--Paul T. Frankl, 1930

Introduction

Chapter three has shown that for a material to become commercially important, it must be inserted into many applications and must penetrate deeply into some of them. This research has shown that the factors that lead to quick insertion are different from the factors that lead to deep penetration of markets. The important limiting insertion factors are technical deficiencies and value chain obstacles—but what are the penetration factors?

Traditional materials marketing wisdom asserts that the two most important factors for large growth of a material in a given market are technical applicability and low cost. While the experience of the major plastics has shown that these factors don't necessarily lead to quick insertion, they are clearly important for competition and overall penetration. But they don't guarantee market success and certainly don't guarantee profitability, particularly if taken at face value.

Insertion of materials is rarely a competitive game, unless technical challenges and application value chains are considered competitors. Growth, on the other hand, is competitive—particularly if an entrant material is attacking an existing market. While the present research has focused on accelerating insertion of new materials into markets, some insights into competition have been gained from the histories of the major plastics.

The versatility of materials creates tremendous pressure for them to become commodities. However, the skills required for commodity competition are different from those required for materials innovation, and price pressures can quickly force the two to become mutually exclusive[1]. The best model for sustained materials innovation will sustain materials profits, as well. The histories of the biggest plastics show at least three important lessons for profitable materials competition. First, technical compatibility alone does not create a defensible position. The properties of a material must create a unique value proposition for a material to be widely accepted. Second, value chain elements can be formidable obstacles, but can also be manipulated into powerful defensive tools. Third, the concept of lowest cost is deceiving—it only tells part of the story. The safest (and most promising) competitive position is to be the lowest cost material that fits the exact needs of an application market: the lowest common denominator.

Each of these lessons will now be discussed.

Lesson 1: Advantage from Asymmetric Properties and Capabilities

The concept of asymmetric motivation is an important underlying tenet in the emerging theory of disruptive innovation. It asserts that the tendency of incumbents to flee from low-end innovations is both rational and logical. Existing businesses have a finite amount of resources, and must constantly choose how to allocate them. At any given point, incumbents can choose to move upmarket (towards higher margin products) or downmarket (toward lower margin products). However, this choice presents an "asymmetric motivation": incumbents naturally want to gravitate toward providing higher margin products to their best customers, and are motivated to allocate resources to fulfill that goal. They are not motivated to defend low-end, low-margin markets or to try to enter unattractive (meaning lower margin) new markets. In fact, they will often flee from competition in those markets.

Disruptive innovation theory says that entrants can beat powerful incumbents by deploying their innovations in such a way that it provokes incumbents to flee from competition. This is accomplished by launching into markets that are at the low-end of the existing product offering or by entering in low-margin markets that are foreign to incumbents because they are so different from existing ones[2].

The theory also asserts that the converse is true: existing companies will always defend themselves against overt attacks on attractive, high-margin markets, and will usually win. When taken as a whole, plastics seem to have followed the theory of disruption. One could say that they started out as shoddy materials that captured low-end markets such as shower curtains, costume jewelry, and hula hoops and then progressed to become important mainstays of construction, packaging, medicine, and transportation. However, if one were to stop the description there (and some authors have), the rest of the story would be missed[3]. Asymmetric motivations may have been a factor, but asymmetric properties and capabilities were at least as important. The early history of plastic pipe, now the single largest application for plastics, reveals that a competitive position can be created from the top down by offering a product that simply cannot be matched by the properties of existing materials. Asymmetric *properties* can be as defensible as asymmetric *motivations*.

Although it was used in prewar Europe, the use of plastic pipe did not begin in the United States until the early 1940s, when polyvinylidene chloride (saran) was used as a liner in steel pipes in industrial plants because of its chemical resistance[4]. By 1950, Saran had been joined by butyrate and polyethylene as a standalone pipe for use in highly corrosive environments, such as soft-drink plants, caustic pharmaceutical plants, and breweries[5]. While these were relatively small markets, they foreshadowed the attack of plastics on one of the most profitable sectors of the pipe industry—corrosion resistant applications. Replacement of corroded parts was big business in the 1950s just as it is now—damaged underground pipes were estimated to exact a $600 million toll in 1952, according to the National Bureau of Standards[6].

Almost every material will degrade under the right conditions, but certain plastics were found to be much more resistant to corrosion than metals, and they began to selectively replace metals in many high-value applications such as sour crude lines, pickle factories, and wineries[7]. They were valued for the exact same reasons as the specialty metals that were previously used—corrosion resistance, burst pressures, and service endurance. However, the properties of the plastics simply made them superior in endurance and corrosion resistance (and good enough in burst pressure); there was no way for metals to match them. Figure 7.1 shows an ABS pipe and a stainless steel pipe that had been placed in sulfuric acid demineralization for the same period of time[8].

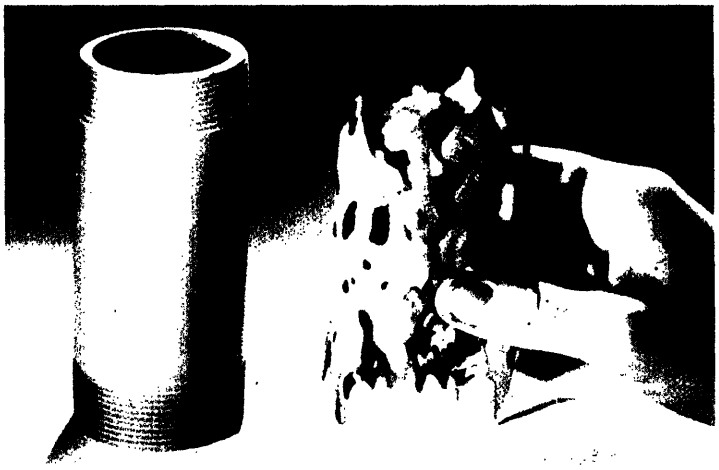

Figure 7.1: ABS vs. stainless steel in corrosion. ABS is shown on the left.

8,484,000 tons of steel and 1,964,000 tons of cast iron were used in pipes in 1952, and only around 12,000 tons of plastic pipe were sold[9]. It is likely that most of the early individual applications of plastics piping were too small to be noticed by metals producers. However, the fact remained: plastic pipes were attacking the most attractive pipe markets because of their superior properties. Plastics producers were earning very attractive returns, since their products were priced higher than competitive metal products[10]. It would be very difficult to call them low end disruptions—they were moving from the top down. An argument could be made that pipe was the lowest end product that metals producers made, but this too would be an error. The metals used in the pipes that were being replaced were very high quality. They were expensive and profitable. Any asymmetric motivation would derive from the size of the markets being attacked.

It became clear to the plastics industry that acceptance in the largest markets could only come if standards were established to maintain consistency in pipes, and it established the Society of the Plastics Industry Thermoplastic Pipe Division in 1951 to begin the largest, most overt, and most coordinated attack on an industry that plastics have ever undertaken. The Thermoplastic Pipe Division funded research with established materials testing organizations (who were in very close contact with the metals industry) to create data on bursting pressures, acceptable wall thicknesses, gas and fluid permeation, and health hazards[11,12]. With the help of this new knowledge, plastic pipe makers cooperated to create voluntary standards for their products.

The plastics industry sold over $60 million of pipe product into corrosion resistance applications in 1961, equating to around 70 million lb of resin[13]. While this was a small portion of the absolute pipe tonnage sold that year, it becomes significant when the relative density of plastics is recognized—one pound of plastics makes approximately eight times as much pipe as a pound of steel. Furthermore, 60% of that total was used in water distribution, a very important market for metal pipe. The oil field piping market had been conquered, and plastics were beginning to see use in the drain, waste, vent (DWV) market—the most important of all.

At this point, everyone could see "the writing on the wall": plastic pipes were growing, and would continue to displace metals[14]. Processors and distributors of metal pipe (including some subsidiaries of metals producers) had begun to sell plastic pipe. Disruptive theory would predict that the metals producers would respond to this overt threat to an important business. However, the direct competitive response by metals producers was minimal (the indirect competitive response will be discussed in the next section). In fact, the only direct response cited by *Modern Plastics* was a small amount of pricing pressure. The properties of plastics simply could not be matched by metals, and the capabilities required to make plastics were vastly different from those possessed by metals manufacturers.

High-end corrosion resistant applications allowed plastic pipe to develop. The quality of plastic pipe increased and prices dropped, creating an even more compelling value proposition. This value proposition was very important as ABS plastic pipe entered use in DWV applications. ABS had several appealing properties which could not be matched by metal: not only was it inexpensive and resistant to chemicals, it was light weight, tough, and could be preassembled at a factory for installation in the field. Between 1960 and 1970, ABS DWV was installed in 4 million homes[15].

PVC saw similar growth in water delivery, conduit, and even hot water applications. By 1970, PVC accounted for slightly more than half of the 692 million lb of plastics pipe that was sold[16]. At this point, plastics had achieved unqualified success in pipe by replacing metals in almost every small diameter pipe market. This success still did not provoke a direct response from metals producers—no metals producers were listed as producers of the plastics used in pipes in 1970, and the technical shortcomings of metal pipes remain even today[17].

The growth of plastic pipe has continued, and pipe is now one of the biggest outlets for plastics, accounting for 7 billion lb of PVC, ABS, and HDPE in the United States in 1997[18]. Steel pipe has been almost completely replaced for residential DWV applications, and usage of HDPE municipal pipe is well ahead of cast iron, despite its higher costs (though installed costs are lower in HDPE).

Although metal pipes are still used extensively, they have been replaced in many of the most attractive markets by plastics. Plastics attacked high-end niche markets first, conquered them, and used the skills learned in these markets to overtly attack mainstream markets. They were more expensive than metals at first, and earned attractive profits. Furthermore, they were initially valued for the same reasons that metals were. It was not until entry into irrigation and DWV markets that lightweight, easy assembly, and low cost of plastics became important penetration factors.

Disruptive theory would predict that metals producers would have created a product to counter the attack, or would have developed the capability to make the plastic themselves. Yet they did not. Materials are not easy to change, and are confined to a relatively small range of properties. The properties of plastics were (and still are) superior to those metals for many piping applications, and no amount of research performed by metals producers could change that fact. It can be said that the plastics had *asymmetric properties* with respect to metals in these applications, giving them an insurmountable competitive edge.

Pipe was not the only area in which plastics attacked and replaced metals. Plastics also grew in auto parts (including auto bodies), construction, cans (packaging), aerospace, and medical products—many of the most attractive metals markets[19,20,21,22]. Furthermore, the plastics industry grew much faster than the metals industry in the 1950s and 1960s, and plastics were big enough that they could have provided the growth necessary to sustain the trajectory of metals profits—they certainly sustained the profits of the oil and chemical companies that invested in them.

Since the properties of metals could not match those of plastics, the most practical direct response from metals producers would have been to make their own plastics. This did not occur. The underlying reason is simple: the gap in capabilities between metals production and plastics production was so large that metals companies would have been unprofitable in plastics. Although they were both process industries, the competencies required to make metals (mining, refining, smelting, rolling, etc.) were very different from the competencies required to make plastics (chemistry, catalysis, etc.). Most of the entrants in the plastics industry were companies with competencies in either basic chemicals or petroleum—competencies which were easily transferable to plastics[23]. These companies had an asymmetric advantage in capabilities, which would have made it very difficult for metals companies to compete profitably.

While asymmetric motivations are powerful, competitive advantage can also be achieved by materials in applications where they offer asymmetric properties--superior properties that cannot be matched by existing materials. This advantage is sustainable if the capabilities required to make the material are sufficiently different from those required for incumbent materials.

Lesson 2: Value Chain Elements as Strategic Tools

From the account in the previous section, one might lead one to draw the false conclusion that plastics faced no challenges in their conquest of pipe markets. Moving from specialty corrosion resistance applications to mainstream plumbing applications was wrought with challenge. Although plastic pipe saw little direct competition from metals producers, it faced tremendous obstacles from the value chains of mainstream plumbing applications. These obstacles were not serendipitous results of a new entrant—they were deliberately placed by elements of the value chain that were threatened by the onset of plastic pipe. These obstacles show the power of value chain elements as strategic tools.

Because of the damage that can be done by faulty plumbing pipes, the value chain for pipe is highly interdependent. There was (and remains) no decoupling point at which no further change would be required to adopt a new type of pipe. Any new pipe would be required to interconnect with other types of pipe at some point, and every node in the chain would need to change in order for this to happen. However, pipe distributors were a stable integration point—the nodes before the distributor could be completely different for a new product, but the nodes after the distributor would need to adapt to it. A simplified mainstream plumbing value chain, showing the relevant nodes, is shown in figure 7.2.

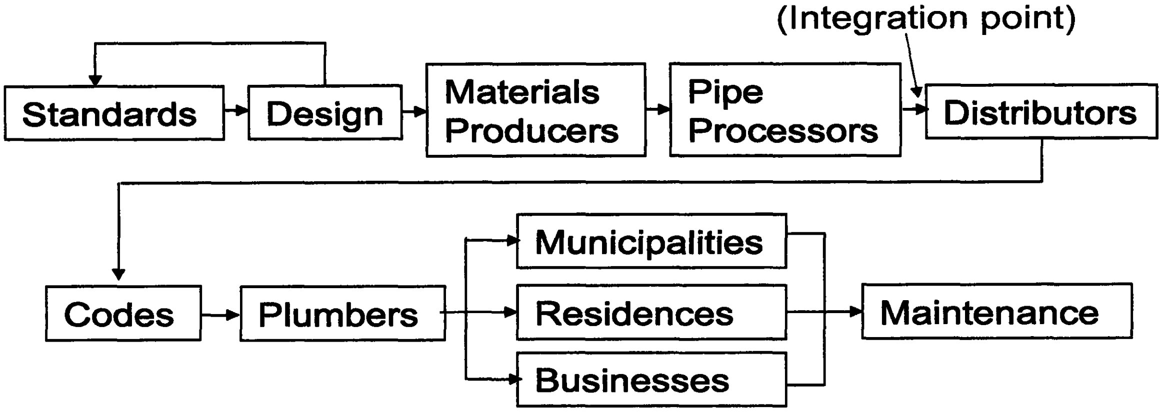

Figure 7.2: Value chain of mainstream plumbing applications.

By the time it began its attack on mainstream markets, there were three main points in the plastic pipe value proposition, all of which were appealing to municipalities, residences, and businesses[24]:

1. Most plastic pipe was less expensive than metal pipe
2. Plastic pipe was more corrosion resistant than metal pipe, so it would last longer and require less maintenance
3. Plastic pipe was much easier to install than metal pipe.

Inspection of the value chain shown above reveals that two nodes were extremely threatened by the onset of plastic pipe. Metals producers and iron pipe casters came before the integration point; they would be completely replaced by plastics producers and extrusion houses if plastic pipe were adopted. Although they were on the right sie of the intergration point, the threat to plumbers was similar. Plumbers were paid by the hour to install and maintain pipe; simpler installations and more reliable pipe infrasturctures meant fewer hours. Even worse, plumbers feared that piping might become so simple that they would be replaced altogether by the common handyman[25]!

Although metals producers showed minimal competitive response at the nodes of the value chain they directly controlled, they joined with plumbers to create a significant indirect response through a node they did not control but could influence: building codes.

The Challenge: Building Codes, Trade Adoption

Plastics coveted entry in several mainstream plumbing markets. Water delivery and drain, waste, vent (DWV) were the most desirable of these markets, but entry could only be achieved if building codes were adapted to allow the entrant materials. Previous corrosion resistant applications had not required code approval, since they were installed in controlled environments that were closely monitored such as irrigation channels, gas pipes, and industrial factories. However, water delivery and DWV applications were not monitored nearly as closely after installation; plastics pipe had to be shown to be very reliable to be installed in them. In this case (as in all cases), national, state, and local codes were the mechanism for ensuring that the standards of reliability had been met[26]. Codes are official acknowledgements of fitness for use.

The stakes were very high on both sides for the approval of plastic pipe. If code approval was given in error, it could result in heavy damages to the buildings that used the new pipe. However, if approval was not given, use of plastic pipe would be constrained to the same corrosion resistant applications it had already conquered. This result would be damaging to consumers but very appealing to metals producers and plumbing unions.

While code approval would seem to be a scientific undertaking, it was highly political. Approval boards were convened, and representatives were sent from both the plastics industry (coordinated by the SPI Thermoplastic Pipe Division) and from the opposition—plumbers unions and the Cast Iron Soil Pipe Institute, as well as other trade associations[27,28]. Plastic pipe was an entrant, so the plastics industry focused its efforts on presenting defensible scientific knowledge, including case studies and test results[29]. While the most flattering data was obviously presented, it was very difficult to overcome the propaganda that had been prepared by opposition. Since ABS was the most pressing threat in DWV applications, it was portrayed as "a defective material" that "constitutes a danger to health and life". There were seven specific charges presented at an FHA hearing in 1966, each of which (if true) could have been a major deterrent to adoption[30]:

1. ABS pipe will burn
2. ABS pipe sets off lethal quantities of hydrogen cyanide gas when burning
3. Rats can bite through it
4. Solvents used to join ABS can explode upon jarring
5. Chemicals will eat through it
6. Human waste can burn through it
7. It doesn't have durability

While there was an element of truth to the charges on flammability and toxicity, they were not health threats. The other claims were patently false.

The opposition also performed false testing in order to influence the outcome of code decisions. One incident was reported in which a test was conducted at the Local No. 1's (journeymen plumbers) Apprentice Training School in Brooklyn to prevent the New York City code board from approving ABS-DWV pipe. The results of the test (which was "rigged, and did not provide an even remotely accurate simulation of actual installation", according to an ABS representative) caused a review of the code and significant delay in approval[31].

The offensive by plumbers and metals producers stands as a brilliant example of using the value chain as a strategic tool. The adoption of plastic pipe was clearly hindered. Code approvals came very slowly: the first approvals (for ABS in DWV) were in place by 1962, and the final code battle ended in 1992 (for CPVC in hot water applications in

California)[32,33]. This allowed the metals industry and plumbers to maintain the status quo, generating profits for them that would otherwise have been taken by plastics.

There is evidence that the plastics manufacturers learned a great deal from this attack. At the time of this writing, the PVC industry is using code propaganda to defend itself against entrants in wire coating markets[34].

The Solution (part 1): Standards and Design

The code offensive placed by unions and cast iron producers delayed the acceptance of plastics, but did not stop it. The acceptance was not a natural outgrowth of the simple superiority of plastic pipe—it was the result of strategic action and concerted perseverance.

The establishment of voluntary standards was probably the single most important action taken by the plastics industry--the importance of the role of the Thermoplastic Pipe Division of the Society of the Plastics Industry (discussed in the previous section) is hard to understate. In addition to coordinating research activities, the Pipe Division created design standards which would guarantee quality, consistency, and interchangeability of plastic pipes. Since the properties of plastics were quite foreign to both end users and value chain nodes, growth could not occur unless shoddy, nonstandard pipes were eliminated. All standards created by the Pipe Division were strictly voluntary, but producers understood the need and followed them. Voluntary cooperation brought success: in its first 10 years, the Pipe Division had established eight standards with the National Bureau of Standards, seven testing standards with ASTM, and six military standards[35]. These standards covered ABS, PVC, polyethylene, and butyrate pipe—all of the commercially important varieties.

Standards were particularly important with plastic pipe because plastic required new joining techniques. Early plastic pipe papers revealed many methods of joining plastics, including threading with conventional threads, clamp-on joints, and even TIG welding[36,37]. These processes were carryovers from metal joining processes, and were not suitable for plastics. None are widely used today; plastics are generally joined with solvent adhesives and fittings, which work without tight tolerances on the composition and size of the pipes.

If standards had not been established early in the commercial life of plastic pipe, its invasion of mainstream markets would have been severely stymied. As stated in *Modern Plastics* in 1962, "without acceptable voluntary standards, there could be no workable engineering specifications; without engineering specifications, there could be no code approvals by the various regulatory agencies; and without any of these, marketing would be reduced to a dangerous hit and miss basis"[38]. The establishment of standards also allowed research to be done in a controlled manner, so that performance guarantees could be established. In short, standards allowed the plastics industry to present hard data to refute propaganda.

The Solution (part 2): Building a Track Record

The track record established by plastic pipe in applications that were not covered by codes also played an important role in persuading code committees of its fitness for use. The corrosion resistance applications mentioned in the previous section provided a great deal of this data, but corrosion resistance applications were usually tightly controlled, so they were not directly applicable. The most convincing data was supplied by the use of ABS in mobile homes.

ABS piping was first used in mobile homes in 1957[39]. It offered particular appeal to mobile home manufacturers because it could be preassembled into "trees" offsite, allowing plumbing systems to be installed in much less time (see figure 7.3). It was also light in weight, a major consideration with mobile homes. By 1965, it was used in 95% of all mobile homes and trailers (a 100,000 unit/ year market)[40]. Because mobile homes were often transported between climates and were subjected to harsh shaking and bumps during transportation, the toughness and fitness for use of ABS was thoroughly proven.

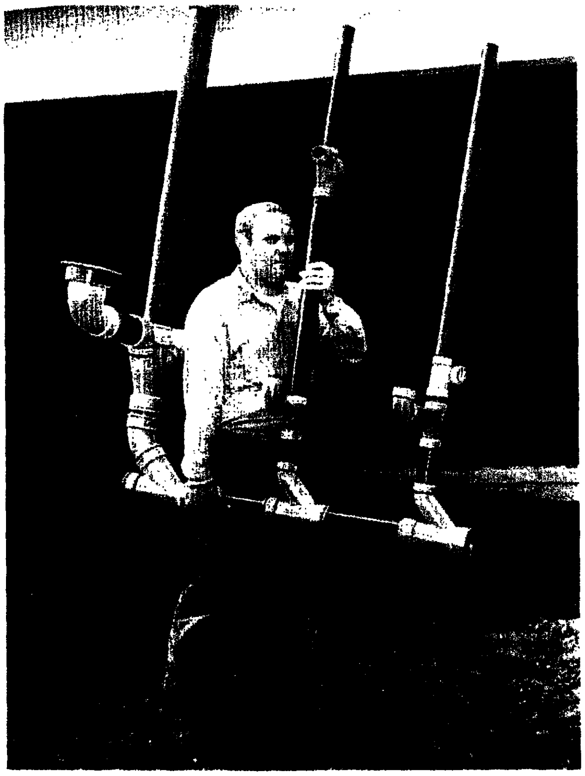

Figure 7.3: ABS pipe tree.

The experience of ABS in mobile homes was cited as a key factor for the inclusion of ABS in DWV applications in the Basic Building Code and Abridged Building Code in 1964. This was an important inclusion--it was a national code and facilitated inclusion in many local codes[41]. Over the next 10 years, ABS was included as a DWV material in most building codes. While mobile homes are still a market for ABS today, their biggest contribution was in gaining credibility for other markets[42].

Codes are not the only node of the value chain that can be manipulated. In the case of plastic pipe, they were a bottleneck in the value chain through which all growth had to pass, so they were natural candidates for manipulation. There are other examples of similar manipulation through government lobbying (PAN in soda bottles[43]), public awareness campaigns (PVC in packaging[44]), and distribution channels (HDPE in beverage bottle holders[45]). The stories all yield the same message: value chain elements can be important strategic tools. They can be used to quash new entrants or to facilitate entry into difficult markets. No matter what the end goal, value chains should always be considered in materials competition.

Lesson 3: The Lowest Cost Perfect Match

The growth of plastics has been marked by spectacular new applications and dramatic replacements of incumbent materials in existing applications. However, there are also examples of very slow replacement of incumbent materials, and of complete misapplications of plastics. All of the biggest, most enduring applications of plastics share a common trait: they are the least expensive materials whose properties coincide with all of the requirements of a material. They can be called the lowest cost perfect match for their respective applications.

For this argument to proceed, the concept of lowest cost perfect match must be clearly defined. Lowest cost perfect matches are the least expensive materials that meet the *exact* needs of an application—their properties correspond perfectly to the application requirements. In the parlance of multiattribute utility analysis, the marginal benefit for additional property features is much lower than the marginal penalty for increased cost. Likewise, the marginal penalty for removal of features is much greater than the maginal benefit for reduced cost[46]. As such, the lowest cost perfect match concept does not include the lowest cost material that *almost* meets the needs of an application, nor does it include the least expensive material that *exceeds* the needs of an application. There are many applications that are either underserved or overserved by their materials, and incumbent materials in these applications are subject to attack. Being the lowest cost perfect match is the safest position for a material.

Although being a lowest cost perfect match is the safest competitive position for a material in an application, its safety is not absolute. Lowest cost perfect matches are in a quasi-equilibrium state, which is generally stable but can be upset by shifts in technology or consumer tastes. These shifts can come in the form of lower cost materials or processes that offer equivalent properties along important dimensions, or as changes in the requirements of the application. Retaining the position of lowest cost perfect match requires constant vigilance.

A material that has not achieved lowest cost perfect match status is a stopgap, which fills some of the needs of an application until a better material is found. When the properties of incumbent materials are at disequilibrium with the requirements of applications, a tremendous opportunity exists for competitors. If competitors can match the incumbent's properties at a lower cost, they offer a compelling value proposition. If they exactly match their material to the requirements of the application at a similar cost, they also offer a compelling value proposition.

If a material is a lowest cost perfect match in an application and the needs of an application are met, its position can be taken only by a lower cost material that offers the same properties. The cost must be coupled to properties—a lower cost material that requires application compromises will not be adopted (unless the application itself exceeds the needs of its customers[47]).

Another important implication of the lowest cost perfect match concept is the fact that, since price and properties are coupled, incumbents can be attacked from the top or bottom. Inherently lower cost materials (per in^3 or per lb) can attack incumbents if their properties are improved to offer similar properties at lower cost. Inherently higher cost materials can also attack. If they offer superior properties to incumbents, it may be possible to reduce the amount of material necessary to meet the needs of an application, effectively offering lower cost. Since different materials require different processing techniques, the material cost in an application often includes processing charges. For this reason, improvements in processing techniques can also create opportunities for both lower and higher cost materials to upset incumbents.

Because the lowest cost perfect match concept is described so well in terms of marginal utility, the principles of multiattribute utility analysis are very well suited to identifying opportunities for attack. By identifying applications in which a lowest cost perfect match has not been found, substitution opportunities can be recognized. This tool has been widely applied in identifying substitution opportunities by comparing the multiattribute utility of two materials for an application[48,49,50]. In this type of comparison application, the tool is most valuable if both materials are well-established. However, if the tool is simply used for identification of applications in which lowest cost perfect matches have not been met, it is not required to compare two materials. Instead, it could be used to find the necessary properties that an attacker would need.

An examination of some of the major applications of ABS chronicles a sustained pursuit of the lowest cost perfect match.

ABS in Pipe

The entry of ABS in pipe has already been discussed. ABS pipes were (and remain) a perfect fit in mobile homes—they were lightweight, tough, climate resistant, corrosion resistant, and could be pre-assembled. They also became the least expensive way to plumb mobile homes, and have held that market since the 1950s. They are the dominant DWV pipe in mobile homes today[51].

The story in fixed foundation residential DWV applications is different. Despite its early entry in fixed residential DWV, ABS has been displaced by PVC pipe. The toughness of ABS is less important in houses that don't move—it overserves the needs of fixed foundation residential applications. On the other hand, PVC can match the corrosion resistance, ease of use, and lightweight of ABS—the important dimensions for fixed foundation applications—without matching its toughness. PVC is also priced 20-30% lower than ABS[52]. Since its properties are perfectly coupled with the requirements of the application, and since it is priced much lower than ABS, PVC is the lowest cost perfect match in fixed foundation DWV applications.

PVC is, by far, the most prolific DWV material[53]. More than 50 times more PVC pipe was sold in 2001 than ABS pipe[54].

ABS in Automobiles

ABS was the dominant plastic in automobiles from the early 1960s through the mid 1990s. The earliest use of ABS in autos was as interior trim, where it was selected over stamped metal because ABS trim pieces were "not marred by frequent foot scuffing...comfortable to the touch in either hot or cold weather... (and had) a desirable sound deadening quality"[55]. These properties could not be matched by metal, and ABS offered the further advantage of cosmetic quality that "would have been impossible to duplicate in metal without costly fabricating and finishing operations". ABS was more expensive than steel on a volume basis, but was less expensive overall because of its cosmetic properties. The properties of ABS were able to perfectly match the requirements of auto interiors at a lower cost than other alternatives, so ABS was the lowest cost perfect match in auto interiors.

ABS' dominant position in auto interiors was retained until the mid 1990s, when it began to succumb to a concerted attack from PP. PP had improved to the point where its properties could match ABS in the most important dimensions, but it was considerably less expensive[56]. Because its properties matched the needs of automotive parts at a lower cost than ABS, PP became the lowest cost perfect match, and has been capturing the associated spoils: European auto makers used nearly three times as much PP as ABS in the 2000 model year[57].

ABS in Refrigerators

The attack of ABS on HIPS was recounted in chapter six as an example of the mimic strategy, but deserves treatment here as an example of lowest cost perfect match domination. Despite repeated attempts by ABS to enter the refrigerator market, it was unsuccessful until a technological advancement ushered it in. Consumer demand for more energy efficient and smaller sized refrigerators led to the use of polyurethane as insulation, instantly matching the properties of ABS to the application. HIPS had been used as a refrigerator liner, but was dissolved by polyurethane precursors. ABS was resistant to these precursors, and was adopted because it became the least expensive material that matched the necessary properties[58]. ABS gained and maintained its dominant position until the mid 1990s, when new formulations of HIPS and PVC offered the same properties at lower cost, and began to capture some of the market[59].

Other ABS Examples

There are many other examples of ABS displacing other materials or being displaced, due mostly to changes in lowest cost perfect match positions. Higher performance engineering thermoplastics such as polycarbonate (PC) and polyphenylene oxide (PPO) began to dominate the power tool housing market in the early 1960s because they were tougher, lighter, and more colorable than the metals they replaced[60]. Fire resistant grades of ABS attacked this market in the late 1980s and early 1990s, but were quickly found to lack the strength properties necessary to compete. However, it was found that material costs could be significantly reduced by substituting ABS for part of the higher performance resins, creating an ABS blend[61]. The most popular of these blends was PC-ABS, which displaced straight PC in many applications (including power tools) by offering lower costs with very similar properties[62].

When 3.5" floppy discs and video tapes were introduced, ABS was selected as the material of choice because of its strength, toughness, and the moldability. It was the lowest cost material that met all of the needs of those markets[63]. However, both markets were very attractive to other materials, since they were growing and consumed a significant amount of material. High impact PS grades were introduced in 1990 which were able to match the properties of ABS at lower cost and were drop-in replacements. The new HIPS grades became the lowest cost perfect matches, and dominated both markets by 1994[64,65].

Conclusion

When faced with a difficult design question, skilled engineers seek to understand unique properties of the problem that might facilitate a solution. Once initial insertion is achieved, competition in materials can be approached the same way. Winning a dominant position in an application is not a trivial pursuit—it requires sustained effort and strategic action. Advantage is best gained by understanding the unique properties of materials, applications, and value chains.

Because materials are difficult to change and have limited ranges of properties, competitive advantage can be gained by introducing materials into applications where their unique properties are asymmetric to existing materials: they are superior and cannot be matched. This is especially effective if the new materials require completely different manufacturing capabilities than incumbents.

Traditional wisdom suggests that entrant materials may find these types of applications by seeking materials with similar (but worse) properties and then trying to take their markets[66]. This is sometimes a practical approach, but is generally foolish. The question is better approached from the other end—by seeking applications that might benefit from superior properties and then trying to fill their needs. By doing this, a materials producer recognizes that the value proposition of materials is visible only in the context of an application. Materials are components of the applications in which they dwell, and offer little use otherwise.

The lowest cost perfect match concept presents another problem to the approach of copying existing materials: the bar is too high. In a lowest cost perfect match situation, the properties of a material are perfectly matched to the requirements of an application. This is a safe position for incumbents because materials in the lowest cost perfect match situation are only overthrown by lower priced materials with the same properties or by shifts in the needs of their application. Superior properties of an entrant material do not gain competitive advantage over an incumbent lowest cost perfect match unless those properties can be deployed to reduce costs. While the cost reduction strategy can be appealing, it inevitably reduces margins and can lead to a downward spiral.

A superior value position can be found if applications are selected in which needs are overserved, underserved, or unserved. These applications can take advantage of the unique value provided by the new material. And if an application can benefit from the unique value offered by a material, it is unlikely that it is being served by a similar material. In the early stages of commercialization, it is better to dodge applications that are served by similar materials (because the similar materials may be in the lowest cost perfect match position), and to focus instead on identifying applications that can take advantage of unique properties.

Applications in the platform and enabler phase of materials commercialization tend to follow the model of offering a unique value proposition. Markets that value a unique material property are more likely to earn healthy profits. While there are individual companies (such as GE Plastics, DuPont, and Eastman Chemical) that have followed a strategy of targeting only applications that value unique properties, there are few important material families that have done this. Most of the biggest markets already exist, and must be attacked.

When the biggest markets are attacked, the lowest cost perfect match concept becomes very important. Materials do not win simply because they are less expensive than other materials. They win because they are less expensive *and* meet the exact needs of the application. Incumbents must be vigilant to maintain their positions, because lower cost materials can attack with improved properties, and higher cost materials can attack by de-spec-ing (removing features) or by reducing the amount of material necessary for a job.

There may be situations in which materials find that they are no longer in the lowest cost perfect match position but still desire to retain a market. In these situations, value chain manipulation can be employed to strategically increase artificial costs for entrants. Value chain obstacles can become formidable competitive tools when properly employed—they are the major source of switching costs!

Resolution to the Insertion Strategy Map

There are two major differences between new materials and established materials. The first difference is the degree of understanding possessed by materials producers and application manufacturers. The second difference is the installed base of complimentary assets to the material. If complimentary assets are assumed to be part of value chain complexity (a reasonable assumption, since complexity increases if complimentary assets must be developed), then the important factor in insertion strategy is knowledge. New materials have a low degree of understanding, while understanding is higher in established materials.

The basis of competition for new materials should be the unique properties that they offer, because unique properties create compelling value propositions to the applications that need them. Adoption based on truly unique properties actually facilitates the creation of a lowest cost perfect match position, because unique properties cannot, by definition, be duplicated.

Ideally, established materials would also compete on the basis of unique properties, but this type of competition does not always facilitate the type of growth necessary for high volume materials and is undermined by the general versatility of materials. Because of this, the lowest cost perfect match position is the basis for the majority of competition among established materials.

When these facts are recognized, it is possible to overlay them onto the insertion strategy map, adding resolution to the type of value proposition that is most appropriate for each insertion strategy. The end product is shown in figure 7.4:

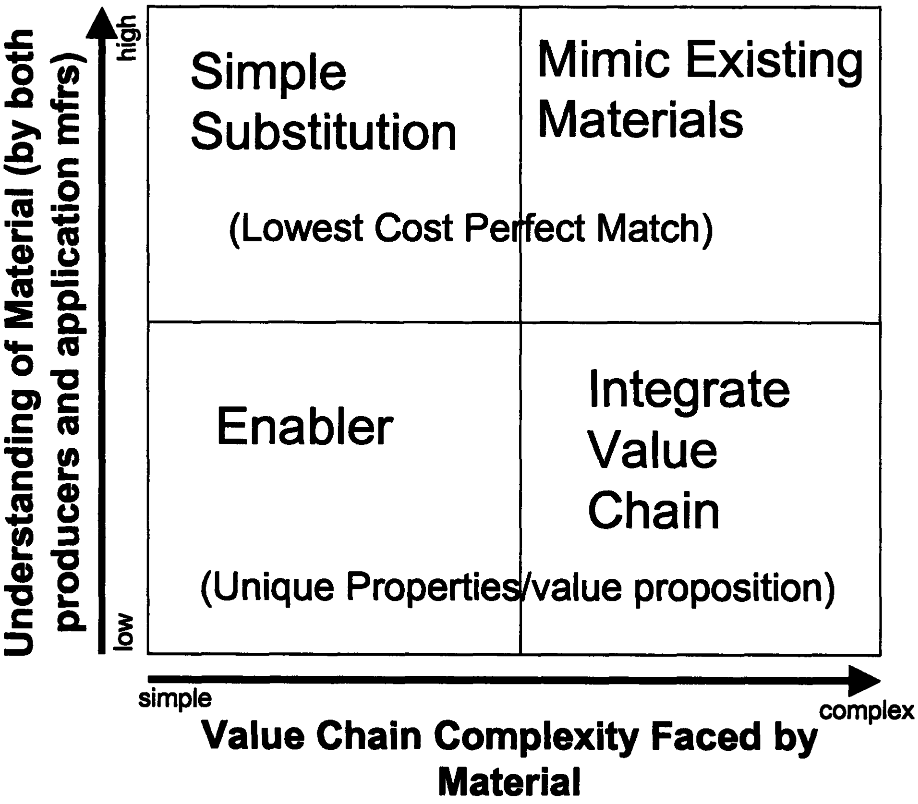

Figure 7.4: Insertion strategy map with added resolution of appropriate value proposition.

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Chapter 8: Walking Through the Shadow of the Valley of Death

Introduction

Through this point, this thesis has focused on materials commercialization from the viewpoint of materials producers. It has exposed the most important challenges of commercializing new materials, and has shown some powerful tools to manage those challenges. The most important tool is market selection, by which materials producers can avoid technical and value chain barriers. When these barriers cannot be avoided, other strategies such as forward integration, mimicking, and simple substitution can be employed. The goal of all of the insertion strategies presented here is to minimize the switching costs faced by application manufacturers who are potential adopters of a material.

The commercialization path of all of the major plastics began with enabler applications, which had simple value chains, solved new problems, and let customers and manufacturers do new things. The markets for enabler applications were generally small, but they performed the crucial tasks of generating capability, credibility, and visibility. Capability was created among the materials producers and processors to achieve the quality necessary for mainstream applications. As failure mechanisms were discovered and track records established, credibility was built to reassure applications manufacturers of fitness for use. Consumers and application manufacturers alike were also made aware of the new materials, giving them the visibility necessary to succeed.

Despite the crucial role that was played by enablers in the many of the most successful materials, launching enablers remains a counterintuitive move to most materials businesses. This is because most enabler applications are too small to generate the profits necessary to justify the investments made in materials development. However, history shows that enablers are the fastest path to profitability, and are the bridge that moves a material from development to commercialization.

The implications of the findings of this research extend beyond private enterprise into the domain of United States public policy. There is a high rate of development failure with government sponsored research— the research lab creates promising materials that fail to achieve commercialization. In fact, the failure rate is so high that the transition period between emergence of government research from the lab and commercialization has been named "the valley of death"[1]. This chapter will show that by encouraging the early development of enabler applications, governments can largely sidestep the valley of death. This will improve the commercialization potential of basic materials research, thus earning a more effective return on public investment.

In order to build a case for the development of enabler applications from basic materials research, the role of the United States government in materials development will be discussed, with a special focus on the causes of the valley of death. This discussion will be followed by three specific policy suggestions to increase development of enablers:

1) Focus current commercialization programs on enabler applications

2) Create a materials clearing house to connect buyers and sellers
3) Establish a market for materials ideas

Each of these policies will be presented in the context of potential effectiveness, cost efficiency, and benefit allocation.

Government, Materials, and the Valley of Death

There are three phases through which new technologies (including materials) must pass before achieving commercialization. First, basic research must be performed to establish the underlying ideas, theories, and principles of the technology. Basic research is primarily a knowledge generation activity. Because of this, it may or may not produce results that are useful, and it is performed on a very long timeframe—sometimes spanning decades. Both of these factors make it a very risky undertaking in the private sector[2,3].

If basic research meets technical objectives, it can pass to the second phase: applied research. Applied research is a mid-term activity in which basic research is developed into technology that can be used to solve specific problems. Applied research rarely yields end products and is also quite expensive. The general timeframe from applied research to profitability is 3-6 years, which is shorter than the timeframe of basic research, but often still too long for the private sector[4].

The third pre-commercial phase is product development, which is the realm of private enterprise. In this phase, companies transform applied research into useful products that generate profits. The general timeframe from this activity is <3 years, making it attractive for private investment.

The valley of death concept was coined to describe the most common phase of failure: applied research. The applicability of applied research is often too narrow to be interesting to the government and the timeframe to commercialization is often too long to be interesting to private enterprise[5]. This leaves promising basic research without interest, and allows it fade into oblivion.

In addition to the normal roles that government plays in facilitating commerce (patents, tariffs, interstate regulation, etc.), it plays at least three important direct roles in the development and commercialization of materials technology. Each of these roles affects the valley of death.

Government Funds Research

The most obvious role of the US government in materials development is the funding of research. In 2001, the federal government committed $44.7 billion to research activities, including over $1 billion for materials research[6]. Research funding is justified because of its potential impact—research is the basis of technological advancements which can elevate societies.

Federal research is divided into basic and applied research, with a fairly even split between the two. In 2001, $1.08 billion in federal funds were spent on materials research, with 56% going to basic research[7]. This accounted for the vast majority of US basic research in materials[8].

Because it is a steward of taxpayer funds, the government exercises its right to set research criteria, and in so doing effectively establishes the direction of the bulk of basic research that is performed at a given time. For the purposes of commercialization, the direction set by government funding is at least as important as the actual funding.

Congressional reports and commentators on the state of US research tend to blame the balance of research and development for the valley of death phenomenon, saying that failure to cross from basic research to commercialization is due to a lack of development funds[9]. However, federal budget data show otherwise. In addition to spending nearly half of the total government research budget on applied research in 2001, $35 billion was spent on *development* programs, comprising "design, development, and improvement of prototypes and new processes to meet specific requirements"[10]. Thus, 73.8% of the total federal R&D budget of $84 billion was spent on applied research and development. Although detailed figures for the development of materials are not available, the proportions are likely similar.

It is difficult to believe that the valley of death is caused by lack of federal funding. A more plausible explanation is that the that the technology being developed is so specialized that it offers little use to commercial markets, or that it is so complex and expensive that it would be prohibitively difficult to commercialize.

Government Provides Coordination and Markets for Strategic New Materials

Some of the funding agencies of basic research such as the Department of Defense, the Department of Energy, and NASA are also consumers of advanced technology. All have branches with similar missions: to ensure that their constituents have the best technology available for solving problems. This mandate extends to materials.

The development budget mentioned in the section above is used to fund these technologies. However, funding is only part of the equation. By funding various programs with specific goals, government agencies effectively coordinate development of knowledge technology, and processes so that the technology (including materials) can be used more quickly. The example of titanium presented in chapter six shows the degree of coordination that is possible in times of national need.

Government coordination can engulf both research and development. There are at least two current examples of this situation: nanotechnology and hydrogen infrastructure. The Executive Office of the President is providing a high degree of coordination to nanotechnology research through its National Nanotechnology Initiative, which "offers great promise broadly across many scientific fields and most sectors of the economy"[11]. The Hydrogen Fuel Initiative is focused on developing the technologies and infrastructure necessary to meet the country's fuel needs as oil and gas supplies dwindle.

By coordinating research and applications activities, government is able to accelerate the pace of technical development, and can accelerate the implementation of new technology in government programs. However, coordination of development does not necessarily equate to faster creation of "spillover" effects, by which society as a whole is improved. The most effective path to spillovers is the most effective diffusion technology diffusion mechanism: commercialization.

This is not to say that the materials that are developed under coordinated programs do not find niche markets—they often do. The agencies that fund and coordinate technology development also act as markets for exotic advanced materials once they are created. The marginal benefit for exotic materials is higher in weapons, energy systems, and spacecraft than in most other sectors, and the government agencies are willing to pay premium prices for those materials. The presence of this market creates pull for commercialization of nascent but promising materials, and forces producers to learn about interactions and failure mechanisms of those materials.

While government use of exotic materials creates incentives for technology development, technologies are often highly specialized and have limited commercial applicability. Furthermore, exotic government applications offer limited visibility to potential customers. These and other factors create incentives for producers of exotic materials to attempt to launch them into highly complex and exotic commercial applications akin to the government applications.

Exotic commercial applications (such as satellite antennae for carbon fiber, turbine blades for AlSiC, or supercomputer coolers for linear metallic foam) are generally highly complex and offer little visibility to mainstream markets. Furthermore, they carry extreme performance requirements, extending the transition time from government applications to commercialization.

Moving from exotic government applications to exotic civilian applications seems to a natural path, and is the traditional model for technology transfer. Companies plan to enter the most profitable top end of the market and then climb down into mainstream markets. While the prospect of cherry picking the best markets sounds compelling, this path is destined for failure with new materials unless the commercializing company has very large reserves of cash. Value chain obstacles and technical deficiencies inevitably appear, and require time, money, and effort to overcome.

In fact, the traditional model for technology transfer is a contributor to the valley of death. The most successful materials transitions from exotic government applications into civilian use have come through much simpler applications. Examples include glass fiber reinforced composites (civilian use: pleasure boats), polyethylene (civilian use: Tupperware), carbon fiber composites (civilian use: sporting goods), and teflon (civilian use: pot coating).

Government Shares Risk

In recognition that the commercial market is the most effective mechanism for the diffusion of technology, the US government has developed programs to share the risk of development of promising technologies with private companies. The most popular of these programs are the Advanced Technology Program (ATP), funded through the National Institute of Standards and Technology, and the Small Business Innovation Research Program (SBIR), funded through several agencies.

The mission of ATP is "to accelerate the development of innovative technologies for broad national benefit through partnerships with the private sector"[12]. It has provided $447 million of co-funding with the materials industry since its inception in 1990, and is a true risk-share program: participants must pay 60% of the total project cost. In keeping with the goals of government research funding, participants are selected based on scientific merit and "broad-based economic benefits"[13]. Because the ATP has been a lightning rod for political criticism (as corporate welfare), it is focused only on mid-term technology development which would be too risky for private enterprise to carry alone. ATP does not fund basic research or end product development[14]. Although ATP grants are ostensibly biased toward small business, the cost share requirement keeps most entrepreneurs out.

The SBIR program does not require cost sharing—it is designed to lift risk from small businesses, with the goal of harnessing the "entrepreneurial spirit" to develop products to meet specific national needs. SBIR grants generally have a shorter timeframe than ATP, are administered by 10 federal agencies, require no cost sharing, and are limited to companies with fewer than 500 employees. SBIR grants are executed in two phases. Phase 1 is a pure research stage, in which up to $100,000 may be granted. If Phase I shows potential, Phase II technology development grants are available for up to $750,000[15]. Phase II award winners can develop technology into marketable products.

In 1994, an outgrowth of SBIR was created called the Small Business Technology Transfer Program (STTR). STTR is similar to SBIR in structure, but has a slightly different mission. It is designed to draw small businesses and universities together to commercialize federally funded research. The SBIR and STTR programs have substantial grant authority--$1.3 billion in 2002[16].

Both the ATP and SBIR programs were designed to share the risk of developing new technologies and both seem very well suited to development of new materials. They appear to reduce the valley of death by encouraging commercialization. However, a quick survey of 1998 SBIR recipients shows that the materials technologies that are funded target highly complex applications. Titles of 1998 SBIR grants include "Synthesis of Negative Birefringence Liquid Crystals", "Fabrication of ZrC, HfC, TaC-based Firbous Monolithic Ceramics for Rocket Propulsion Systems", and "Improved Performance Double Heterostructure InGaP Heterojunction Bipolar Transistors"[17]. While not all materials grants were targeted at such complex applications (liquid crystal displays, rocket motors, and wireless microwave amplifiers[18]), these titles are representative of the group. The current research would predict that these materials developed under these contracts will find their way to the valley of death, particularly if executed by small companies that lack resources to overcome inevitable value chain obstacles.

The Case for Enablers in Materials Policy

If the goal of government funding of materials research and development is to elevate the economy and the state of society as a whole, then the valley of death must be overcome. Commercial markets have proven to be the best path to widespread diffusion of materials technologies, and government can gain greater return on its materials research investment by improving the chances that materials succeed in commercialization.

While government has been criticized for overinvesting in basic research but leaving applied research and development destitute, the data show otherwise. The applied research and development budgets are much larger than the basic research budgets. It appears that the valley of death has deep causes which cannot be overcome by simply throwing money at them; the fundamental problem with the valley of death is not lack of development funds.

The current research suggests that the traditional technology transfer model is a cause of the valley of death. At its core, the traditional technology transfer model seeks to move complex technology from complex government applications into complex commercial applications. While this natural, logical path may work for some types of technologies, it is destined for failure with new materials. The pattern of commercialization of the major plastics shows a progression from simple, new applications to complex, existing ones. This progression is supported by value chain theory which explains that application manufacturers (adopters of new materials) have very strong disincentives to switch to new materials. These disincentives stem from value chain obstacles, existing product redesigns, and risk, and are therefore scale with the complexity of an application. In the best cases, manufacturers of complex applications will adopt new materials slowly, while in the worst cases, they won't adopt them at all. Slow adoption of new materials can be a sentence to the valley of death.

The commercialization of plastics showed that value chain obstacles and technical deficiencies can be sidestepped by choosing the right applications: simple ones, with few parts and short value chains. These simple applications were able to take advantage of some of the unique properties offered by the plastics, but also allowed *material* complexity could be decoupled from *application* complexity, resulting in much faster commercialization. By any account, plastics are complex materials—their properties and structure are highly interdependent with feedstocks, production techniques, and secondary manufacturing techniques. Yet despite this complexity, all of the major plastics were deployed into very simple applications that solved new problems. These applications were called enablers.

If the traditional technology transfer model were modified to include incentives for launching new materials into enabler applications, the commercialization potential of government-funded research and development in materials would increase significantly. This would not be a natural path. It is counterintuitive to deploy exotic materials in simple applications. However, the experience of the plastics industry suggests that it would accelerate initial commercialization and would build the capability, credibility, and visibility needed to succeed in the commercial world. If past is prologue, a concerted focus on enabler applications will significantly diminish the valley of death.

Enabler applications have three common characteristics:

1. They solve new problems that can't be solved in other ways.
2. The applications are simple—they have few parts and short value chains.
3. The application markets are generally fairly small.

When taken together, it is obvious that these characteristics lead to quick adoption of a new material.

Enabler applications play important roles in market development. First, they develop production and processing capability for materials producers and application manufacturers. Second, they develop knowledge about the strengths and weaknesses of new materials. Third, they gain visibility for new materials to both potential markets and consumers. These three roles combine to reduce value chain switching costs while building credibility, thus reducing the risk borne by application manufacturers in utilizing new materials.

Arguably, if a government development project is carried through to production (in which case it would become a supply contract), then all of the enabler roles would be filled. This would essentially be a government version of value chain integration in the private sector. However, most research programs stop far short of becoming supply contracts, leaving would-be producers with the same credibility challenges and knowledge gaps that are faced with all new materials. This effectively aims their commercialization trajectory into the valley of death—but these challenges can be overcome by focusing on enabler applications.

Three Options to Encourage Enablers

Option 1: Focus Existing Risk Share Programs on Enablers

The most obvious and direct way to encourage enablers is to force existing government materials technology risk share programs such as SBIR, STTR, and ATP to seek enabler applications. This could be done by creating a mandate that new materials technology proposals be presented with a set of potential enabler applications, and that at least one of the enabler applications be developed. Exclusions would have to be made for SBIR and ATP solicitations targeted for specific solutions, but the mandate would still be fairly broad. In addition to changing development behavior, this type of mandate would have a strong effect on the mindsets of developers. Requiring applicants to consider potential enablers would push them to consider different types of applications, and would most likely lead to a higher degree of interdisciplinary thinking.

There are several potential drawbacks to such a mandate. First, the enabler requirement could stifle the creativity of proposals with respect to exotic and complex applications. However, the experience of the plastics industry showed that the most promising long-term ideas were in place well ahead of the enabler ideas—they were bluntly obvious to researchers. Second, there is a possibility that the enabler concept would not work with these types of grants, although there are few reasons why it would not.

The enabler track would seem to be very dangerous for small businesses, since a specific characteristic of enablers is that they enter small markets. This point requires clarification in the present context. Many enabler applications are too small to be profitable for major materials producers, but are more than sufficient for the small businesses that are funded by ATP and SBIR. The Hula Hoop application was too small to support the huge investment Phillip made in HDPE, but it earned $45 million for tiny Wham-O, making the two owners very rich[19]! By focusing investment on enabler applications, ATP and SBIR would increase the chances of success of awardees. The current practice of funding new materials for complex applications puts awardees in precarious commercialization positions since there is no requirement to build the credibility necessary to compete in such applications.

Efficiency and Allocation

Modifying the risk share programs would be an easy first step toward eliminating the valley of death. It would be a highly efficient use of resources, since it would require very little change in the current system. The most significant change would be the education of proposal writers and funding agencies on the purpose and characteristics of enabler applications for new materials. The allocation of benefits from the policy would be similar to allocation of current materials technology risk share programs. However, it would most likely amplify the effects by leading to more successful commercialization.

Effectiveness

While the efficiency and allocation of this policy would be good, its effectiveness at reducing the valley of death is questionable. An enabler mandate would increase the commercialization potential of materials technologies that find their way to the risk share programs, but only a small percentage of government-funded research does this. The combined budget of ATP and SBIR was ~$1.5 billion in 2002, compared to a total R&D budget of $92 billion[20,21,22]. The impact made by the enabler requirement would be significant for the recipients of share grants, but would offer minimal reductions in the overall valley of death.

Option 2: Create a National New Materials Clearing House

Traditional materials marketing wisdom suggests that applications be identified by surveying the markets of existing materials with similar properties and attacking the most attractive ones. The materials commercialization pattern and the insertion strategy matrix both show that this is not a good strategy at the beginning, because it does not lead to insertion in applications that take advantage of the unique properties of materials. In fact, finding applications that take advantage of unique properties is one of the most difficult challenges in launching enablers. The history of plastics has shown that the biggest applications were obvious to materials producers, but that enablers were not.

Since enabler applications are often new, a challenge also exists for application manufacturers to find the right material. This suggests a chicken-and-egg situation: enabler applications often can't be made without new materials, and new materials can't find enabler applications unless those applications are visible to them (read: already being made). Thus, a search problem exists, and a high degree of visibility is necessary between materials producers and application manufacturers in order for enablers to come to life. If materials producers don't see new technologies, and new technologies don't see new materials, then both may be destined for the valley of death.

There are market-based mechanisms for connecting new materials with potential buyers. Perhaps the most popular of these mechanisms are late-stage technology transfer programs (incubators) and venture capital. Both venture capitalists and incubators have a strong economic incentive to actively seek buyers—they only make money if a product is commercialized or a company sold. This incentive can lead to very aggressive solicitation of buyers, but can actually be a disincentive for commercialization of enablers. The returns necessary for venture capital are difficult to generate with small market applications, and would more likely be associated with platform-type applications. While an enabler application launch strategy has been shown to be the safest and fastest path to return on investment, it cannot promise high returns on the same timescale as a (much more risky) direct launch strategy would, if that strategy were successful. For this reason, enabler applications can be unpalatable to venture capitalists.

There are two other drawbacks to venture capital and technology transfer with respect to materials. First, materials must be in the "right" price range with respect to enabler applications—they can be more expensive but not exorbitantly so. The agent fees paid to venture capitalists and incubators could limit the applicability of new materials by forcing them out of that price range[23]. The second, more serious, problem is that incubators and venture capitalists have limited networks. In order for new materials to find enabler applications, very broad visibility into applications markets is necessary. While venture capitalists and incubators often have larger networks than materials producers themselves (network strength is a competitive advantage in the venture world), they are still fairly small when compared to the scope of all potential product applications. These market-based introduction mechanisms offer only slight improvement over serendipity.

Because of the shortcomings of the market-based mechanisms in solving search challenges, direct government intervention could help. One policy solution to the enabler search problem would be the creation of a national materials clearing house. This clearing house would act as a "market maker"--neutral party that connects buyers and sellers of new materials. It would be given a specific charge to disseminate information about the properties of all of the government-funded materials development projects.

The national materials clearing house would consist of two major parts: a materials center and an extensive database. The materials center would be staffed with materials scientists and engineers who could help application manufacturers specify materials and could help materials producers to correctly describe and characterize properties of new materials. It would offer neutral testing and technical assistance with application development. By doing this, it would be a very strong support structure for users of the database.

The database would be a mechanism by which application manufacturers could browse properties of new materials in order to select materials that might fit their needs. An effectively implemented database with the proper support structure would play three important roles:

1) It would disclose unique properties of new materials to application markets without disclosing the intellectual property necessary to make the materials
2) It would facilitate interaction between materials producers and application manufacturers
3) It would help solve technical problems.

The current US patent system plays these roles at some level. However, the patent system is designed to entice inventors to reveal underlying principles and processes of inventions so that they can be copied and built upon. In contrast, the materials database would be designed to reveal properties so that new materials could be *used.* In contrast to the patent system, it would reveal the appealing properties of new materials without revealing the underlying intellectual property, so that technology could be more quickly diffused.

The database would work best if it extended beyond new materials to include as many existing materials as possible. This would make it a central point which US application manufacturers could use as a resource in design and materials selection. Network effects with this type of database would be very important—it would attract users in proportion to the number of materials contained therein. Inclusion of existing materials would not diminish the position of new materials on the database, but rather would improve it. The properties of new materials could be compared with those of existing materials, and application manufacturers could find the optimal materials for their wares.

The database might create ancillary research benefits, as well. Materials producers could use it as an authoritative survey of available materials, and could focus efforts on creating materials with unique properties that are missing from existing materials.

In short, a national materials clearing house would provide an economically efficient forum to disseminate information about the properties of materials. However, in order to function properly, a mechanism to protect the intellectual property of both materials producers and application manufacturers would have to be created. The materials clearing house would miss a large portion of its potential value if it did not include some way to facilitate discussion between buyers and sellers in a way that would not damage the integrity and potential profitability of the ideas of either side (this would be more of a problem for smaller companies, who often cannot afford to defend their intellectual property)[24]. While the database would be a forum with the breadth and anonymity required for applications manufacturers to browse potential enabler materials without disclosing their ideas, it would not be able to provide all of the technical data necessary for efficient development of those materials. It is likely that a contractual relationship would be required at some point; standardized rules for these relationships would facilitate generation of creative applications.

As a public entity, the national materials clearing house would not only be an impartial referee, it would offer great insight into new materials because of its links to government-funded materials research projects. Its value is easily seen if it is viewed as an infrastructure project. The US government has historically been willing to invest in projects that facilitate widespread economic benefit but for which value would be too difficult to capture by a private entity (examples include highways, water systems, and power grids). The value generated by a broad and impartial national materials database would be significant, because new materials could find enabler applications and existing applications could find optimal materials for use. A national materials clearing house would be a valuable investment for society to make, but would probably be an unprofitable investment if done in the private sector.

The materials clearinghouse could be managed by a single existing organization. It seems that a national materials laboratory such as Oak Ridge or Sandia, or a university with a strong materials and IT infrastructure such as University of Illinois or Berkeley might have expertise in the necessary areas--database development, materials support, and intellectual property. They would be well suited to manage such a project.

There are several drawbacks to a national materials center. First, it would initially compete with businesses that have developed materials databases (some private databases exist, but are limited in scope to established materials)[25]. While it is likely that these businesses eventually would leverage their technology to create very advanced databases for specific sectors, they would be in direct competition with the national materials database for a time. The blow might be softened if these businesses were awarded contracts to develop the national database. The second disadvantage is strategic: it would not always be in the best interest of the security of the United States to allow all new materials to be freely viewed in a national clearing house. This effect could be mitigated by restricting access to the database, but this would undermine the effectiveness of the database by limiting the number of potential buyers. A better way to handle the problem would be to create an exemption mechanism by which new materials could opt out of the program.

Efficiency

The database portion of the national materials clearing house would be deployable on commercial software for less than $30 million[26]. Its annual maintenance costs, including support personnel, are estimated be slightly more than 35% of that number. The materials center could be supported with around $10 million/year (assuming a staff of 15 scientists and engineers). Given the total materials development budget of the federal government, this seems to be a reasonable amount to spend to reduce the number of materials in the valley of death.

If correctly deployed, the national materials clearing house would generate efficient returns by improving commercialization. It would generate direct returns in tax dollars as new materials are released into the economy. It would also generate indirect returns by increasing the return on investment in government-funded research—more research would reach society. Other indirect returns include jobs in new industries as innovative new products are developed based on materials commercialized through the clearing house.

Allocation

The fairness of allocation of benefits from the national materials clearing house depends on the viewpoint of the observer. On one hand, the obvious direct beneficiaries would be materials producers and application manufacturers. This could be problematic, because it could be seen as corporate welfare. However, the allocation of benefits is very equitable if spillover effects are considered. The ancillary effects on society of commercialization of new materials are tremendous. Jobs and taxes would be created which would be clear benefits for common citizens, but the more important effects would be improvements in the standard of living of society. While this may seem idealistic, one need only look at the impact that heat treated metals, plastics, and silicon have made on life in the 20th century to understand the basis of such a statement.

Effectiveness

If deployed with proper support structures and effectively promoted, a national materials clearing house would be a powerful tool to reduce the valley of death. It would encourage the creation of enabler applications by connecting materials producers with application manufacturers, thus launching new materials onto the path of commercialization. It would promote new ideas and interdisciplinary thinking by exposing properties of materials that were previously unexposed, leading to previously unthinkable products. Its scope and scale would be much larger than the risk-sharing projects.

Option 3: Develop a Market for Ideas

Another option to encourage creation of enablers is to provide incentives to develop a market for ideas in materials. The concept is quite simple—a market for ideas provides a profit strategy for R&D entrepreneurs in which they earn returns by selling intellectual property to larger players instead of by selling products directly to markets. Markets for ideas are valuable to both entrants and incumbents. Entrants are often small companies which lack some of the specialized assets necessary for growth, such as distribution channels, credible reputations, and manufacturing capacity[27]. On the other hand, incumbents are often large companies with organizational structures and core capabilities that are streamlined to produce materials with very consistent quality and to respond to the incremental needs of their customers; these structures rarely lend themselves toward creativity[28,29]. If entrants and incumbents in these situations come together, the entrant can take advantage of the existing assets of the incumbent, and the incumbent can gain competitive edge by leveraging the creative potential of the entrant. The end result is a situation that makes more money for both entities than could be earned if they compete[30].

Markets for ideas have emerged in many industries where a spectrum of product maturity exists. For example, the pharmaceutical industry has many products which are fully mature and compete based on low-cost and overall quality. Incumbent pharmaceutical manufacturers have developed specialized assets to distribute, promote, and manufacture their products. However, new products are the lifeblood of the pharmaceutical industry. In addition to in-house research activities, pharmaceutical companies have established a reputation that encourages development of drugs by startup firms. If these startup firms produce novel drug technologies that offer commercial promise, there is an excellent chance that the companies will be purchased by incumbent pharmaceutical giants[31]. Because of the specialized assets owned by the incumbent pharmaceutical firms, the new drugs are actually worth more to them than they would be to the start-ups if they were placed directly into the product market[32].

Another advantage of the market for ideas is that it increases the effectiveness of development expenditures. Effective users of the market for ideas can purchase intellectual property that has been proven to be useful instead of embarking on myriad internal research projects (many of which are destined to fail)[33]. In this situation, it is economically more rational for incumbents to pay a premium price for one proven technology than to undertake several risky projects on their own. This means that startups with proven technology can earn premiums well above their expenditures. If incumbents have specialized assets which increase the value of the technology, these premiums can far exceed the expected value of direct entry to the product market by startups. Thus, there are very strong incentives for entrepreneurs to prove their technology in a market for ideas.

These incentives for proving technology would encourage development of enabler applications for materials if a market for ideas were created. Researchers and developers would be driven to quickly find small applications to prove the usefulness of new materials in order to gain top dollar for their ideas. Enabler applications are *designed* to prove the usefulness of materials, and would be the best path to doing so in a market for ideas.

Unfortunately, a market for ideas has not been developed in the materials industry. While one might speculate on the reasons for this (the development of the in-house research lab, the high expense of developing materials, the quick path to commoditization of materials), experience in other industries suggests that it is correctable. Industries that have developed successful markets for ideas have several common attributes. First, new ideas tend to *reinforce* existing specialized assets and competencies in industries with markets for ideas. In general, the materials industries fit this description. To the extent that manufacturing technology, distribution channels, and corporate credibility are existing assets and competencies, most materials innovations can be seen as reinforcements to incumbents[34]. While plastics appear to be an obvious exception since they did not reinforce the existing assets and competencies of incumbent materials producers, they did reinforce the existing complimentary assets of chemical and petroleum producers. They would have been strong candidates in the market for ideas. In fact, the basic technology of polypropylene and high density polyethylene emerged from the sale of intellectual property by Ziegler, Natta, and Phillips to incumbent chemical companies[35,36].

Industries with successful markets for ideas have also developed *disclosure mechanisms,* by which entrants can disclose technology to potential buyers without fear of the buyers copying the technology without paying for it[37]. Disclosure mechanisms are already in place in the materials industry. Since the properties of materials are so intimately tied to synthesis, materials whose synthesis is not obvious are inherently protected from copying by potential buyers. Patents for materials can be very strong, and provide plenty of disclosure protection to novel materials whose synthesis is more obvious.

Perhaps the most important factor in industries with successful markets for ideas is the one that materials industries most lack: a reputation of willingness to buy ideas[38]. In the late 1990s, incumbent software, networking, and computer hardware companies created a very strong market for ideas by purchasing promising companies with equity capital. This behavior built a reputation in these industries that attracted billions of dollars in venture capital to fund thousands of startup companies, allowing incumbents to select the best technologies from a wide range of options. Unfortunately, the materials industry does not enjoy such a reputation, and is unable to reap the benefits[39].

Public policy could encourage the creation of a market for ideas in materials. Since most materials innovations can be deployed as reinforcements of the competencies of incumbents, and since disclosure mechanisms already exist, policy should focus on creating the activation energy necessary to help materials industries create a reputation as buyers of innovative materials ideas, particularly if those ideas have been proven in enabler applications. The best way to do this would be to create financial incentives for incumbent companies that participate in developing the market for ideas. These incentives could include tax credits for purchases of small companies that have produced enablers based on government-funded materials research. This type of tax credit has been shown to be an effective influence on behavior in behavior of individual consumers[40]. An alternative incentive might be increasing access to government contracts based on commercialization of new materials purchased in the market for ideas.

The risk sharing programs could also be altered to favor companies that purchase materials technology in the market for ideas. A portion of the later phase ATP and SBIR program funds could be allocated to large companies for use in purchase of smaller companies. This would shift the selection criteria from government control to private control, allowing incumbents to select from a wide variety of materials proven in enabler applications.

The national materials database could work in concert with the market for ideas. The database would facilitate the connection of buyers with sellers, and policy incentives would facilitate transactions.

Efficiency

Incentives for a market for ideas would be risky—there is no guarantee that they would work. If they did work, the effect would most likely be quite small at first, since incentives would be given to incumbents and the market would initially be supply constrained. There are not enough enabler applications of new materials to fill the pipeline for the current stock of incumbent materials producers, so efficiency would be poor. However, as the reputation of the industry improved, the industry would provide incentives for startups and entrepreneurs to begin in earnest to create enabler applications. If this end were achieved, the government investment would become very efficient. It would jumpstart a market for ideas that could become self-sustaining without incentives as incumbents gain the earnings that players in other markets for ideas have found.

Allocation

Allocation of benefits in a market for ideas is highly problematic. Any incentives would be given directly to industry, and would be designed to use small players to make large players bigger. It is likely that opponents would fail to mention the fact that small players would become richer in this scenario than they would otherwise. The only way that the allocation would be equitable is if spillover effects from increased innovation and a higher flow of new materials were explicitly recognized. These effects would be substantial.

Effectiveness

If the market for ideas were successfully jumpstarted in materials industries, it would harness the power of the market to draw new materials into society. Since government research is the main source of research and development for new materials, these materials could be expected to benefit. A much higher number of enabler applications would be created (since they would be the best path to large valuations in the market for ideas), and these enablers would help government-funded materials research to dodge the valley of death.

Jumpstarting the market for ideas would be more expensive than altering current risk share programs or instituting a national materials database. In fact, the market for ideas would work best if combined with the other two options. Adapting the risk share programs to incentivize enabler applications in early-stage SBIR and ATP grants would increase the supply of new materials. The national materials database would connect buyers and sellers of materials, both in the application markets and the market for ideas. It would facilitate efficient transactions, and would allow the market for ideas to assume its intended role as a capstone driver of materials innovation in the United States.

Conclusion

The early history of man has been classified by archaeologists into three chronological ages: the Stone Age, the Bronze Age, and the Iron Age[41]. It is significant to note that each of the Ages is named according to the materials technology that was possessed by each society. This is recognition of the impact of materials on the welfare, economies, and technologies of societies. Materials are the basis of manufactured goods, the basis of construction, and the basis of most technological advancements.

The importance of materials technology is easily observed in our society today. Casual observers have called the mid 20th century the Plastics Age, and the late 20th century the Silicon Age. Materials developments have been at the heart of many advancements in technology, and have had a huge impact on the quality of life of citizens in the developed world.

The impact of materials is not limited to advancements in technology. Materials are also key drivers of modern economy. The 1997 US Economic Census (the latest census for which data are available) shows the plastics and primary metals industries together generated $203 billion in sales, and employed 660,000 people with a $27 billion payroll. This accounted for 2.4% of the US GDP that year[42]. However, if the direct downstream products that are manufactured from plastics and primary metals are included, those numbers grow to $600 billion in sales, 3.25 million people employed, and a $108 billion payroll, and account for 7.2% of the US GDP[43]. This indicates that each materials dollar generates about 2 more dollars in direct downstream revenue. Since materials are the base products for almost all manufacturing, it is useful also to see the impact of that sector on the economy: $3.8 trillion in sales (about 46% of US GDP), 16.8 million employees, and $569 billion payroll[44].

In recognition of the impact of materials on its economy and the quality of life of its citizens, it behooves the US government to improve the commercialization potential of materials research. The first step to doing this is to explicitly recognize that investments in materials are also investments in spillover effects (which can have strong ripple effects through the economy), and to make materials commercialization a national priority. Once the priority is set, then another explicit decision should be made: to focus commercialization efforts on creating enabler applications for government funded materials research. Enabler applications have been the bridge between privately funded materials research and commercialization, and can do the same for government-funded materials.

Enabler applications should not be created by the government--they can be profitable for small companies and can improve the competitive position of large companies. Unfortunately, they are counterintuitive to the traditional tenets of technology transfer, so policy must be developed to encourage private investment in enablers. There are many potential policies for doing this, including modified risk share programs, a national materials clearing house, and a market for ideas. Each of these suggestions would work on its own, but the three together would jumpstart the entrepreneurial spirit of the materials community. An integrated national materials commercialization policy would be very compelling to potential commercializers of new materials.

Chapter 9: Changing Mindsets

Commercializing New Materials

If materials are to be commercialized faster, several mindsets must be changed. Traditional materials marketing wisdom has been developed to deal with the vast majority of materials switches, which occur between established materials in existing applications. In this situation, materials producers can easily identify potential barriers and can win business by offering a superior value proposition: lower cost or better properties than incumbents. This works because application manufacturers know exactly what to expect with established materials. Risk is relatively low since failure mechanisms and switching costs can be fully assessed prior to the switch. Application manufacturers can design around failure modes, and can calculate switching costs using common tools such as cost models. Furthermore, having full knowledge of the properties of established materials allows application manufacturers to perform utility analysis so that incremental added value can be assessed.

In this situation, the primary challenge faced by materials producers is to create a value proposition that is sufficiently superior to competitors that it overcomes the switching costs that application manufacturers face. Since supply bases are in place to deal with established materials, the material with the best value proposition will win the competition.

Traditional materials marketing wisdom would suggest that a superior value proposition also leads to quick adoption of new materials. This is not the case. New materials are different from established materials because the total costs of adoption and complete set of properties are unproven—they aren't necessarily known beforehand. Application manufacturers who adopt new materials must be willing to risk field failures and exorbitant warranty costs since the failure mechanisms of new materials are less understood than those of established materials. Because of the depth of materials in the product value chain, adoption of new materials requires application manufacturers to face potential learning and adaptation costs that can be extremely expensive. To make matters worse, supply bases are unfamiliar with new materials, and processing machinery and labor can be much more expensive than with established materials. Application manufacturers have reputations and commitments to customers, and blindly adopting an unproven material could destroy both. They would be foolish to do it without a significant qualification period.

Thus, the factors that lead to quick insertion of new materials are different from the factors that lead to large growth of established ones. A new material must provide an excellent value proposition to have any chance at adoption, but the value proposition alone is not enough. The real challenge faced by materials innovators is posed by *insertion factors:* the technical difficulties and value chain obstacles that limit the ability of application manufacturers to adopt new materials. Insertion factors are powerful and real; they set the bar for adoption very high, and often preclude the insertion of materials with extraordinarily compelling value propositions. If they are to succeed with new materials, innovators must change their mindsets away from traditional materials marketing wisdom. Instead of focusing efforts on low cost production or beating competitors, they should focus on overcoming insertion factors.

The key to shortening commercialization times of new materials (and to winning with materials innovation) is to develop capabilities to manage insertion factors so that compelling value propositions can take hold. The concept behind insertion factor management is simple: if materials are to be adopted quickly by application manufacturers, switching costs must be reduced. Chapter five showed that switching costs are driven by application value chain complexity and understanding of a material. More complex value chains are more expensive to change and require more coordination; a higher degree of understanding of a material (by both producers and application manufacturers) leads to lower learning costs, lower handoff costs between value chain nodes, and lower risk of failure. Thus, the goal is to reduce application value chain complexity and to increase understanding of a material.

There are three levers that can be pulled to increase knowledge and reduce value chain complexity. The most obvious is to make a material similar to existing materials so that it is immediately compatible with existing value chains and products[1]. While this can be a reasonable strategy for established materials, it is not good for new ones. The complexity of materials limits both the pace and range of change that is possible, so reconfiguration of a material to match the properties of incumbents is rarely an option (and is very slow when it does work). There can also be problems with value proposition—why introduce a material that is largely the same as existing ones?

The second lever is value chain integration, in which the materials producer acquires all of the nodes in the value chain up to the point that no further change is necessary to adopt a material. This strategy shifts the burdens of value chain risk and adaptation costs to the materials producer from the application manufacturer, so that adoption is much less expensive. It also allows the materials producer to control the pace of development, and can generate huge amounts of knowledge about the properties of the material. However, the enormous capital implications of forward integration limit its applicability to only the most attractive markets.

Since most materials are quite versatile—they have properties that make them useful in a wide range of applications—and are difficult to reconfigure, market selection is the best lever in most situations. Market selection allows materials producers to maximize the potential of new materials: producers can choose to deploy new materials into applications that value their unique properties, have low adoption risk, and have simple value chains. These applications are called enablers, for two reasons: they usually enable customers to do new things, and they enable materials to move forward. By selectively choosing enablers, materials producers can accelerate adoption of new materials while generating the knowledge necessary to move them other applications.

Choosing to launch new materials into enabler applications creates a conundrum for materials producers that can only be solved by changing mindsets. Because of the upfront cash required to develop a material, materials producers want big returns, fast. However, dominant design theory teaches that low risk applications with simple value chains are rarely very big—customers have established expectations for big applications, and manufacturers have usually begun to optimize the value chain to produce them. Most enabler applications are far too small to produce the returns necessary for investment in new materials. Yet enablers are crucial for growth, because they create the *credibility*, *capability,* and *visibility* necessary for success in major markets with much higher insertion factors. Without them, new materials flounder in a state of interminable testing while application manufacturers determine fitness for use. If materials producers jettison the idea that initial applications must generate fast, big profits, they can recognize enablers for what they are—stepping stones to growth. They can then selectively choose enabler applications to reduce the insertion factors faced by major market adopters. This will generate profits faster than would a direct attack on those major markets.

Enabler applications were the first step in the pattern of commercialization that was followed by all major plastics. Enablers allowed quick recognition of fitness for use, and expose failure mechanisms while creating supplier and producer capability. They also exposed the public to the materials. After a few years of enabler applications, each plastic gained a foothold in an existing application for which everyone knew (from the time of invention) it would be perfect—a platform application. In their platform applications, plastics offered very compelling value propositions based on unique material properties (all of these applications are still dominated by the same plastic today); the plastics were rarely less expensive than incumbents. Adoption of plastics in platform applications was always delayed by insertion factors, which enabler applications helped solve. Platforms were the first applications that were big enough to justify the materials development investment: they generated tremendous capability and visibility, and served as springboards for further growth.

Only after materials had been established in platforms did traditional materials marketing wisdom begin to apply, although it proved to be incomplete. From the platform applications, the major plastics attacked a wide range of existing applications. Their attacks were based on lower costs and better properties than incumbents, and their insertion time varied according to the value chain challenges and technical difficulties that they faced. The biggest applications of the biggest plastics all had a common attribute that helped them establish and maintain their competitive position: they were the lowest cost materials whose properties were aligned *perfectly* to the needs of the application. This position is called the "lowest cost perfect match", and builds on traditional materials marketing wisdom.

Being the lowest cost perfect match is the safest position a material can occupy; if a material overserves or underserves the needs of an application it is a stopgap which will lose its position. Whereas traditional wisdom would say that value proposition can stem from low cost *or* good properties, the lowest cost perfect match concept asserts that the two must be coupled. This means that simply offering a lower cost material is not enough. Simply offering a higher performance material is not enough. Successful attacks must change the lowest cost perfect match position—they must lower the overall material cost while matching the necessary properties.

Both the enabler and the lowest cost perfect match concepts require that mindsets toward deployment of materials into applications be changed. Traditional wisdom suggests that the best way to identify applications is to identify materials with similar properties and try to take their markets with lower costs or superior properties. This strategy violates the definition of an enabler—if a problem is already being solved, why use a new material to solve it again? There are cases of severely underserved applications in which improvement can be dramatic enough to meet enabler criteria, but they seem relatively rare. Chasing materials with similar properties can also lead to competition with incumbent materials in the lowest cost perfect match position; it seems common for materials innovators to frame their product in terms of existing products which *already meet the needs of customers*. Yes, the new material may work better in some aspects, but consumers may not care at all.

By changing mindsets, a better way to frame the problem of market selection emerges: selection based on the ***unique*** properties of materials. If the unique properties of materials are examined, companies are far more likely to identify enabler opportunities, and are far more likely to avoid competition with incumbent materials in the lowest cost perfect match position. In fact, they are far more likely to identify their own lowest cost perfect match opportunities.

Contributions to Innovation Theory

This research was built on a foundation of innovation theory. Materials exhibit anomalous behavior to some tenets of existing theory, and understanding the conditions causing the anomalies gives insight into theory. Simply understanding the unique aspects of the materials business gives other insights.

Because of their position in the value chain, new materials must be treated very differently than established ones. Traditional materials marketing wisdom does not apply. By separating the limiting insertion factors from the growth and penetration factors, it is possible to create a useful framework. There are few other products that face the same degree of challenge from insertion factors, but it is useful nonetheless to separate insertion and penetration factors, because it allows a systematic constraint analysis to overcome barriers.

A stream of thought is emerging in innovation around the integration and decentralization of value chains, and some interesting recommendations have been made[2,3]. A paper was recently published which suggested that forward integration to the decoupling point is the best way to introduce products[4]. While this is an important insight, the experience of the plastics industry shows that it is incomplete—it fails to recognize the conditions in which forward integration is best. Since materials are so deep in the value chain and are difficult to reconfigure, they make a very pure case study for this type of strategy and reveal the relevant conditions: value chain complexity and product understanding (by both producer and consumer). Using these conditions, the insertion strategy matrix shows that forward integration is not always the best way, but can be useful. The insertion strategy matrix is the next logical step in this stream of innovation theory.

Materials also display an anomaly to disruptive innovation theory. Disruptive theory would predict that existing materials manufacturers would have responded to the threat of plastics and that they would have ultimately have dominated the plastics business. Neither of these things occurred. The plastics industry showed that there are gaps in capability are too wide for existing manufacturers to cross, even in the face of obvious attacks on important markets. Petroleum and chemical producers, whose capabilities more closely match the capabilities necessary to make plastics, are the dominant producers of plastics. Other materials companies play only a small role, usually in distribution.

Perhaps the most obvious and important anomaly displayed by materials is their wholesale exclusion from the dominant design model: they don't follow the pattern. The reason for this is straightforward: materials are very difficult to change, and cannot be easily reconfigured to conform to the needs or desires of markets. The one material that has been shown to follow the pattern is oriented strand board (OSB), which is comprised of wood chips that can be molded into different shapes with dramatically different properties. OSB is one of the most reconfigurable materials[5].

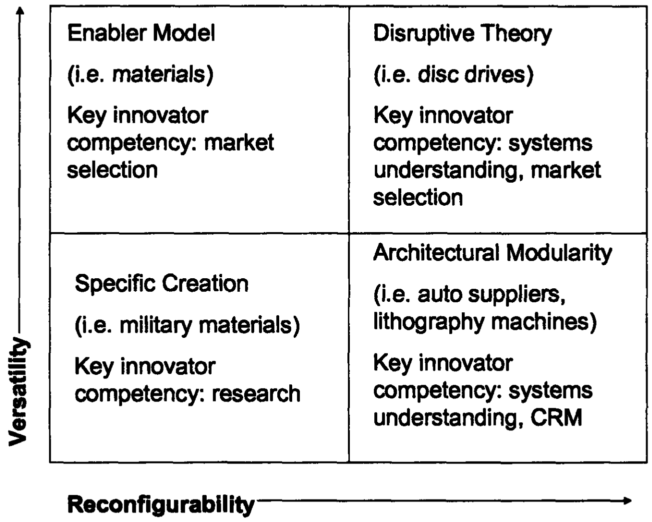
Although materials don't fit the dominant design model themselves, the applications into which materials are inserted follow a similar pattern. The materials commercialization pattern is an analog to the dominant design model. The enabler phase is similar to the fluid phase, in which materials are inserted into many applications, with the goal of generating knowledge and discovering the best potential applications. The emergence of a platform application is similar to the emergence of the dominant design, in which an application that utilizes the most desirable set of properties of a material comes to life. The widespread substitution phase of materials commercialization is similar to the specific phase of the dominant design model, since process capabilities become very important and the industry generates long term profits.

The versatility of materials and their lack of reconfigurability makes them unique among manufactured products, and these two factors combine to give great insight into innovation theory. The concept of architectural modularity in innovation theory, in which products are designed to be easily reconfigurable, has its roots in the automotive supplier and the photolithography industries[6]. Both of these industries have limited versatility—auto suppliers supply auto makers, and photolithography suppliers supply semiconductor manufacturers. Since they don't have the option of launching their products to different customers, their most important innovative capabilities are design and reconfiguration, so that they can quickly iterate products until they meet the exact needs of their customers.

Disruptive theory has roots in the disc drive industry. Disc drives are highly reconfigurable, and are fairly versatile—they can be used in many applications. Christensen's research has shown that reconfiguration was an important tool for drive makers, but that market selection (he called it market innovation) was just as important, particularly for entrants.

The complexity of materials (including both internal properties and external interactions) makes them very difficult to reconfigure—the pace of change is slow and the range of attainable properties is limited. However, they are very versatile—most can be used in a wide range of industries and applications. Since they are not easily changed to meet the needs of customers, the most important tool for materials innovators is market selection; reconfiguration plays only a small role.

There is also the possibility of products that are unreconfigurable and lack versatility. They are highly specialized, and effective, efficient research is the key capability necessary in this space. Figure 9.1 is a foursquare model with versatility and reconfigurability as the axes.



Enabler Model (i.e. materials) Key innovator competency: market selection	Disruptive Theory (i.e. disc drives) Key innovator competency: systems understanding, market selection
Specific Creation (i.e. military materials) Key innovator competency: research	Architectural Modularity (i.e. auto suppliers, lithography machines) Key innovator competency: systems understanding, CRM

Figure 9.1: Versatility vs. reconfigurability

Moving Forward

The research presented here suggests several strategic changes for the materials industry. It is the most comprehensive work done to date on materials commercialization, but it is certainly incomplete. It has uncovered questions which must be answered by further work of both practical and theoretical nature.

The strategic changes suggested by this work will not be easy to implement. Changing mindsets in organizations is notoriously difficult--particularly for companies such as materials producers who have developed deep capabilities in quality, reliability, and consistency. The attitudes and organizational structures necessary to develop these capabilities are quite different from the attitudes and structures needed for creativity. Future work should focus on identifying organizational models that can maintain consistency while fostering the creativity necessary to identify and create enabler opportunities.

The creation of models that engender both consistency and creativity may not be the biggest organizational challenge to the strategies recommended by this research. The bigger challenge may be creating mechanisms to reward enablers in the face of the large capital investments required for materials. Many ways to do this have been suggested, ranging from pulling the creation of enablers down to the R&D stage to developing a separate organization to foster small ideas[7]. However, most of these suggestions confine the job of innovation to a small group; it would be much more powerful to harness the creative power of the entire organization.

In addition to organizational models and incentive systems, early evidence suggests that simple tactical tools are necessary to help materials producers identify enabler opportunities. Although the myth that serendipity drives identification of big materials markets has been debunked by this research, serendipity appears to play a very important role in the identification of enabler applications. A more systematic method for strategic identification of enablers would be useful. This tool should be developed with the goal of using enablers to secure platform applications, and should include as many people within the organization as possible. Serendipity is facilitated by network effects.

More research should be done on value chain obstacles. Materials producers don't truly understand a material until they know what application value chains need to understand about it. A simple value proposition is not enough: winners in materials innovation will be the producers who develop the best capabilities for dealing with application value chains. Sensitivity toward value chains must be developed.

This sensitivity would be a tremendous source of competitive advantage, and might be best researched at the corporate level, in the context of organizations. The yield would be a model to carry the insertion strategy matrix to a higher level.

Developing value chain understanding will require several streams of work. The most obvious stream will create better resolution into value chain obstacles. This thesis has shown that value chain obstacles exist, that experts recognize them, and that insertion delay scales with them. In doing so, it has revealed a key question: which of the value chain obstacles is most important? Future work, with much larger samples sizes and input from supply chain management theory might be able to answer this question.

Understanding the true nature of handoffs between value chain nodes would also be useful. This research has shown that handoffs can be avoided by market selection and integration, but many markets have extremely complex value chains, making both strategies impractical. Future work focused on exposing the exact nature of information required to reduce the opportunistic behavior and environmental uncertainty that plague handoffs could be very fruitful. It could facilitate supplier specialization and could have a significant impact on the capital costs of materials innovation. It might best be done at the intersection of law, transaction cost analysis, and materials science.

This work has focused on the supply side of materials innovation, suggesting changes by materials producers to increase its potential. It would be interesting to take the opposite approach—to focus on the demand side of materials innovation by examining the adoption processes of application manufacturers. This would likely produce insight into organizational and engineering processes, and might be able to change the nature of materials research and development to include a greater degree of market pull.

The nature of competition in the materials industry needs further investigation. The nascent concept of the lowest cost perfect matach could be reinforced by development of strategic tools (multiattribute utility analysis being the best candidate) to identify lowest cost perfect match opportunities, and to identify several underserved or overserved markets. However, more interesting research could be performed on the cycle of competition in the plastics industry.

Although not quantified (and thus not reported in this thesis), the plastics industry appears to have followed a cyclical pattern of competition, in which the basis of competitive advantage shifts from product innovation to process innovation and vice-versa. Product innovation in plastics can be defined as any innovation that creates features for which customers will pay; process innovation can be defined as any innovation which reduces cost, reduces defects, or increases reliability. Both types of innovation extend markets. The basis of competition in the industry appeared to shift between these two types of innovation, with each cycle creating an elevating ante for the next one—once products improved, they never got worse; once quality improved, expectations were set among customers that were never removed. Understanding this cycle could be very important—materials producers that could predict the switch would be in a position of perpetual first mover advantage. From a standpoint of general innovation, it would offer further insight into modularity (a process innovation?) and into the relationship between dominant designs, Foster's concept of "good enough", and disruptive theory[8].

The most important question that should be explored by further research is also the most obvious: are the concepts learned from materials more generally applicable to innovation? More specifically, are they useful as tools in "technology push", or do the unique aspects of the materials business make them inapplicable? Answering this question will require a different approach than the one taken here. It will require examination of both successful and failed materials to refine the model, followed by identification and examination of a broad range of industries and technologies in which technology push is the dominant innovation diffusion mechanism.

A Final Word

The impact of materials on the quality of life of societies is hard to understate. New materials have the power to elevate standards of living, to lift economies, and even to improve the environment. However, the impact of materials is limited by their ability to be commercialized and to achieve widespread adoption. The strategies presented here can improve the commercial potential of new materials, but will require a concerted commitment on the part of managers and business leaders to drive the necessary changes of mindset.

The materials commercialization pattern is just as applicable today as it was in the time of the plastics industry. Although the most obvious materials have been discovered, materials science has created tools which can accelerate the development of ever more complex materials. Innovation of materials will continue.

Products today are more complex than they have ever been, and the value chains that make them are, too. Vertical integration is much less prevalent now than it was in the 1950s and 1960s, and value chains are often dispersed across the globe. Nodes of value chains are more specialized, speak different languages, and use more exotic equipment than ever before. Furthermore, the liability climate has become much more stringent in the past decades. The quality movement has made consumers less tolerant of product failure, and the general loosening of tort litigation has made the consequences of failure much higher. All of these factors raise the bar that materials must meet in order to be adopted into mainstream applications.

Given the pace of change in today's attractive product markets, speed of innovation is the key. Materials producers who can manage best insertion factors will reach the bar faster, and will win with materials innovation.

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Appendices

Appendix A: Actual Challenges Listed in Modern Plastics

Material	Application Category	Specific Insertion Application	Stated challenges	References	Classification of Stated Challenges
HDPE				1	
HDPE	Liquid food bottles	Milk	"Special handling problems"	2,3,4	Value chain
HDPE	Household industrial chemical bottles	Swan liquid detergent bottles	First: resin that wasn't susceptible to ESCR; then printing labels, adapting filling lines to flexible bottles, supply of bottles, better designs than competitors	5,6	Value chain
HDPE	Grocery sacks	grocery stores	proper materials blends, "fabricating equipment", shape of bag, "materials technology", "Film handling equipment", price	7,8	Value chain + Technical
HDPE	Trash and can liners	Consumers	processing settings, materials, etc./	9,10	Value chain + Technical
HDPE	pipe and conduit	water and chemical transport	joining, codes, proper application	11	Value chain
HDPE	Pails	industrial, consumer mixing bowls	cost, new molds	12	No challenge--molds had to be made for any part, regardless of plastic
HDPE	Crate and totes	quart and half gallon shipping cases	"new cases must fit into existing production facilities and be useable with wood on an interchangeable basis"; "Who'll be first?"; "Pilferage, because of the attractiveness of the cases"	13,14	Value chain
HDPE	Industrial drums	industrial 55 gallon drums	none listed	15	No challenge
Material	**Application Category**	**Specific Insertion**	**Stated challenges**	**References**	**Classification of Stated Challenges**

		Application			
LDPE					
LDPE	Food packaging film	turkey, shrimp, cream packaging	1947: printing, heat sealing, 1950:packaging machinery limitations, printing, sealing	[16]	Value chain
LDPE	Extrusion coating	multiwall bags	adherence of paper to plastic, homogenization of material--all processing challenges,	[17]	Value chain + Technical
LDPE	Non-food packaging film	bag for table cloths	1947: printing, heat sealing, 1950:packaging machinery limitations, printing, sealing	[18]	Value chain
LDPE	Stretch and shrink	Industrial pallette wrap	Technical	[19]	Technical
PET					
PET	Soft drink bottles	Pepsi 32 oz "familly bottle"	cost, production volume, high productivity machinery (also oxygen permeation--required new biaxial stretch technique)	[20]	Value chain + Technical
PET	Custom bottles	Liqupr bottles, cosmetics	cost, high productivity machinery, bottle design	[21,22]	Value chain + Technical
PP					
PP	Fibers and filaments	marine rope, outdoor furniture web	UV resistance	[23]	No challenge (introduced with poor UV quality)
PP	Consumer products	drinking tumblers, food crispers		[24]	No challenge
PP	Rigid packaging	aftershave bottles closures		[25]	No challenge

Material	Application Category	Specific Insertion Application	Stated challenges	References	Classification of Stated Challenges
PP	oriented film	shrink wrap for phono records, bundling packages	1961: "producers not yet satisfied with the quality of their resin in various applications", production problems, and machine handling, resistance to sunlight; 1967:"new technology had to be developed for extrusion, converting, and wrapping", "machines from processing and wrapping had to be altered or new ones developed", no machines to wrap apples or cigarrettes fast enough	[26],	Technical
PP	Transportation	grills, clips, etc.	none cited	[27], [28]	No challenge
PP	Appliances	dishwasher cutlery trays	none cited	[29]	No challenge
PS					
PS	Oriented film and sheet	packaging and envelope window	Problem with basic knowledge: no one knew how to biaxially orient films, heat sealing	[30]	Value chain + Technical
PS	Vending and portion cups	vending machine cups, ice cream boats	low cost processing techniques, thermoforming technology	[31]	Value chain + Technical
PS	Cassettes, Etc	8 Track tapes, cassette tapes	No cassettes before	[32]	n/a
PUR					
PUR	Furniture (padding)	furniture padding	"process is highly critical and requires experienced know how for production", cutting PUR--done by hand initially then pressed, "sensitive production problems"	[33]	Value chain

Material	Application Category	Specific Insertion Application	Stated challenges	References	Classification of Stated Challenges
PUR	Building insulation		processing methods had to be "greatly simplified", building codes for safety, structural strength	[34]	Value chain
PUR	Transportation (flexible padding)	airplane seats	cutting PUR	[35]	Value chain
PUR	Household and commercial refrigeration	refrigerators, coolers	foam-in-place processes	[36,37,38]	Value chain
PUR	Rug underlay	carpet underlay	switch from polyesters to polyethers (clearly technical)	[39]	Technical
PVC					
PVC	pipe and conduit	Chemical/pickle plants, oilfields	1954: relatively high cost, molding of pipe fittings, tight tolerances from market, misapplication failure in oilfield, standards (both size of pipe and acceptable specs.), questions about health hazards; 1960: building codes, contractor resistance, union blockages ((distribution channel problems)): 1962/1965: standards, code, joining techniques/manufacturing techniques, education of unions and plumbers, education of public, architects, contractors; 1967: codes, unions.	[40]	Value chain

Material	Application Category	Specific Insertion Application	Stated challenges	References	Classification of Stated Challenges
PVC	Siding	siding	1962: modifiers, lubricants, stabilizers, weatherability testing (material became brittle), processing equipment (machinery), "A major educating job with distributors to inform them fully on the benefits as well as the limitations of the new material" ; 1965: design limitations (particularly weatherability, impact strength, heat resistance), cost, distribution--"products must be designed for builders--adaptable to their techniques",	[41]	Value chain + Technical
PVC	Windows and doors	window tracks	"carbon copies" of metal extrusions gave poor field performance, Cte/toughness balance of material, extrusion technology(commercial standard for rigid vinyl profiles), joining corners ("largely automated" by 1965)	[42]	Value chain + Technical
PVC	Wire and Cable	Naval ships	None listed	[43]	No challenge
PVC	Extruded packaging		Extruding PVC film	[44]	Technical
PVC	Pipe fittings	Chemical piping	shape for solvent welding, standardization of pipe size, joing to metal pipes	[45]	Value chain + Technical

Appendix B: Pool applications and included data[1]

Material	Application	Industry	Year of Intro	Insertion Time	Explanation	Reference
ABS	Automotive sheet (exterior)	Trans	1964	16	ABS sheet used to make sports car body and some truck components	"Breakthrough in thermoforming: the ABS automobile body", *Modern Plastics,* February 1965
ABS	Business machine housing (telephone)	Elec	1963	15	Telephone housings	"Plastics 1963: Styrenes", *Modern Plastics,* January 1964.
Acetal	Auto parts	Trans	1960	1	Coat hooks, brake handles, shift knobs, instrument clusters	"1961 Autos: proving ground for plastics", *Modern Plastics*, November 1960.
Acetal	Plumbing valves	Const	1959	0	Internal parts in faucets	"Here are the first commercial Delrin Applications", *Modern Plastics*, November 1959.
Acetal	Steering column pins (collapsible steering columns)	Trans	1966	7	Key collapse pins on redesigned colapsible steering columns to meet safety standards	"Polyacetals move deeper into traditional non-ferrous metal markets", *Modern Plastics*, January 1967.
HDPE	Hula hoop	Consumer	1958	1	Toys for the hula hoop craze of 1958	"Bonanza for extruders", *Modern Plastics*
HDPE	Trash cans	Consumer	1959	2	Rotomolded 165 gallon containers (trash cans) for industrial use	"Why the fast growing market for BIG polyethylene containers?", *Modern Plastics*, June 1959.
HDPE	Blow molded bottles	Pack	1958	1	Blow molded detergent bottles	"New Economy in plastic bottles", *Modern Packaging*, September 1958.
HDPE	Milk jugs	Pack	1962	5	Gallon and half gallon milk jugs	"Gallon of milk in polyethylene", *Modern Packaging,* August 1962.

Material	Application	Industry	Year of Intro	Insertion Time	Explanation	Reference
HDPE	Underground wire coating	Elec	1967	11	Crosslinked HDPE for underground power applications	"The shifting markets in electronics"*Modern Plastics,* January 1968.
HDPE	HDPE fuel tanks	Trans	1977	22	Fluorinated HDPE blowmolded gas tanks for automobiles	"Transportation: pivotal year in Detroit", *Modern Plastics*, January 1978.
LDPE	HF radar wire	Elec	1943	0	Coating for wires carrying high frequency radar signal	Kline, Gordon M., "Advances in plastics during 1944", *Modern Plastics,* January 1945.
LDPE	Tupperware	Consumer	1946	3	7 Oz Tupperware "Poly-T" tumbler	"Plastics timeline tracks the evolution of an industry", *Modern Plastics*, January 2000.
LDPE	Squeeze bottles	Pack	1949	6	Unbreakable nursery bottles	Kline, Gordon M., "The year 1949 in review",*Modern Plastics,* January 1950.
LDPE	Food packaging film	Pack	1946	3	Food packaging and refrigerator bags	"Polyethylene packages in use", *Modern Pacakaging,* January 1947.
Nylon	Women's hosiery	Consumer	1940	2	Nylon stockings--64 million pair sold first year	"Plastics timeline tracks the evolution of an industry", *Modern Plastics*, January 2000.
Nylon	Car fans (auto parts)	Trans	1957	19	Engine fan for Citroen	"Plastics in 1958: SLOW START STRONG FINISH (nylon section)", *Modern Plastics*, January 1959.
Nylon	Air intakes for automobiles	Trans	1994	56	Air plenum for car engines	"Resins 1995: Highe Prices Point to Stronger Growth", *Modern Plastics*, January 1995.
PET	PET soft drink bottles	Pack	1975	8	Biaxially oriented PET 2-liter bottles for soft drinks	"The new bottle equation: GC=mrc+mPt=rH", *Modern Plastics,* April 1975.
PMMA	Highway reflectors	Industry	1938	1	Molded reflectors for highway lighting	*Synthetic Resins and Their Raw Materials*, US Government Printing Office: 1938.

Material	Application	Industry	Year of Intro	Insertion Time	Explanation	Reference
PMMA	Signs	Industry	1950	13	non-neon signs	"Application trends in 1950", *Modern Plastics,* January 1951.
PMMA	Auto lenses	Trans	1951	13	Lenses on headlights	"Plastics industry trends", *Modern Plastics,* January 1952
PC	Glazing in high vandalism areas	Const	1964	6	Tough windows	"MP Annual Review and Forecast: Polycarbonate", *Modern Plastics*, January 1965.
PC	Safety helmets	Industry	1968	10	Specfied for motorcycle helmets	"What happened in resins in 1968? What's going to happen in 1969?", *Modern Plastics,* January 1969.
PC	Bullet proof windows	Consumer	1970	12		
PC	747 windows	Trans	1970	12	Side windows on 747	"The materials picture in 1970", *Modern Plastics*, January 1971.
PC	5 gallon returnable water tanks	Pack	1976	18	Tanks for bottled water for offices	"Innovative action in packaging marks 1977 as a take-off year", *Modern Plastics*, January 1977.
Polyester	GFRP Car body	Trans	1953	11	Corvette	"Here comes the Corvette", *Modern Plastics,* September 1953.
Polyester	GFRP in aircraft and missiles	Trans	1961	19	Missile cones, skins, etc.	"Reinforced plastics", *Modern Plastics,* January 1962.
Polyester	SMC auto parts	Trans	1968	26	exterior applications--probably mirrors, etc.	"transportation: It's plastics vs. plastics now", *Modern Plastics*, January 1969.
PP	Monofilament	Consumer	1959	0	Ropes, cords, etc.	"Why the big market for polyproylene monofilaments?", *Modern Plastics*, June 1961.
PP	Washing machine	Elec	1963	4	Large agitator in washing machine tub	"Polyproylene", *Modern Plastics*, January 1964.

Material	Application	Industry	Year of Intro	Insertion Time	Explanation	Reference
PP	Disposable syringes	Consumer	1962	3	2.5 cc disposable syringes	"Why they specified Polyproylene"
PP	All PP dashboard	Trans	1997	38		*"Polypropylene", Modern Plastics,* January 1997.
PS	Foamed house insulation	Const	1947	9	Styrofoam house sheathing	"Polystyrene", *Modern Plastics*, January 1948.
PS	Wall tile	Const	1947	9	Replacement for ceramic tile in houses	"Polystyrene", *Modern Plastics*, January 1948.
PS	Radio and TV cabinets	Furn	1953	15	Cabinets for personal radios	"Polystyrene", Modern Plastics, January 1954.
PS	Thinwalled disposable cups	Consumer	1956	18	Airline-type clear PS cups	"Plastics in disposables and expendables",*Modern Plastics*, April 1957.
PS	Woodgrain PS furniture	Furn	1966	28	wood-like panels for appliances, furniture	"Styrenic materials zoom, but where's new capacity coming from?", *Modern Plastics*, January 1967.
PUR	Flexible foams (probably furniture)	Furn	1954	0	probably furniture padding first, then automobile padding	"Polyurethane and Polyester Foams", *Modern Plastics*, November 1954.
PUR	Lycra fibers for stretch clothing	Consumer	1962	1	stretchy clothes--socks, etc	heritage.dupont.com
PUR	Urethane crash pads	Trans	1965	11	interior padding in dash, etc. for crashes	"Urethane foam. . .takes off. . .and the best is yet to come", *Modern Plastics*, January 1966.
PUR	Urethane sound and temperature insulation-cars	Trans	1966	12		"Uses broaden for URETHANE foam; both rigids and flexibles set record", *Modern Plastics*, January 1967.

Material	Application	Industry	Year of Intro	Insertion Time	Explanation	Reference
PUR	Flexible urethane matresses	Furn	1954	0	matresses	"Polyurethane and Polyester Foams", *Modern Plastics*, November 1954.
PUR	Custom auto body parts	Trans	1993	48	Reaction injection molded custom body parts for aftermarket or low-volume applications	"Polyurethane formulation technologies make recycling, CFC-free foams viable",*Modern Plastics*, January 1994.
PTFE	Gaskets and seals for Manhattan project	Industry	1942	0		Funderburg, A.C.,"Makinge Teflon Stick", *Invention and Technology*, Summer 2000.
PTFE	Industrial cookware coatings	Industry	1950	8	Nonstick coatings for bakery trays	Funderburg, A.C.,"Makinge Teflon Stick", *Invention and Technology*, Summer 2000.
PTFE	Nonstick coating for home use	Consumer	1955	13	T-Fal cookware	Funderburg, A.C.,"Makinge Teflon Stick", *Invention and Technology*, Summer 2000.
PTFE	Gore tex	Consumer	1989	47	Waterproof fabric	Funderburg, A.C.,"Makinge Teflon Stick", *Invention and Technology*, Summer 2000.
PVC	Wire insulation for low temperatures	Elec	1938	0	Extruded insulation of permananent flexibility for wires	Macht, M.L., and Paine, H.W., "Themoplastic Resins", *Modern Plastics*, January 1939.
PVC	Shower curtains	Consumer	1941	3		"Thermoplastics", *Modern Plastics,* January 1942.
PVC	Color coded wire	Elec	1944	6	color coded wire for naval ships	"Plastics at War--Navy", *Modern Plastics*, January 1945.
PVC	PVC floor coverings	Const	1946	8	vinyl floor coverings--probably the industrial tiles	"Vinyl resins", *Modern Plastics*, January 1947.
PVC	Garden hose	Consumer	1946	8		"Vinyl hose can take it", *Modern Plastics*, January 1950.

Material	Application	Industry	Year of Intro	Insertion Time	Explanation	Reference
PVC	Rigid pipe	Const	1953	15	pipe for chemical plants	"Plastics vs. corrosion", *Modern Plastics,* September 1953.
PVC	Window awnings, doors, siding	Const	1959	21	Window sashes and tracks	"Tomorrow is today for vinyls in construction", *Modern Plastics*, October 1960.
Urea	Brightly colored Beetle picnic ware	Consumer	1926	0	plastic dishes	Meikle, J.R., *American Plastic: A cultural history*, Rutgers University Press, *1997. p. 77.*
Urea	Melamine dishware	Consumer	1940	1	Dishware for military and institutional applications	(first use in Navy)"Seventh Annual Modern Plastics Competition Merchandising Award: The American Cyanamid Company", *Modern Plastics*, September 1948.

Material codes:
ABS: Acrilonitirile Butadeine Styrene
HDPE: High Density Polyethylene
LDPE: Low Density Polyethylene
PET: Polyethyelene Terephthalate
PMMA: Poly (Methyl Methacrylate)/Acrylic
PC: Polycarbonate (Lexan)
PP: Polyproylene
PS: Polystyrene
PUR: Polyurethane
PTFE: Polytetrafluoroethylene (Teflon)
PVC: Polyvinyl Chloride
Urea/Melamine

Appendix C: Expert Credentials

Author's note: the experts assembled here are among the most talented and experienced people in the materials field. I am grateful for their willingness to participate in this research project.

Lawrence E. Bell
Larry Bell has been the Global Business Manager-Automotive Group at Nypro, Inc., one of the world's largest and most innovative molders of plastics, since 1998. In this position, he is responsible for developing Nypro's automotive business by understanding and predicting the plastics needs of automotive suppliers and OEMs. He has extensive experience in the automotive plastics sector, having worked as Automotive Market Segment Director at General Electric Automotive Plastics for three years and as a Business Development Manager at Freudenberg-NOK for five years. He is the inventor of two US patents for plastics in the auto industry, and is a registered professional engineer in the state of Massachusetts.

Darran Cairns, PhD
Darran Cairns is a research specialist at 3M Touch Systems Optical Division in Methuen, MA, where is responsible for the development of novel polymeric touch sensors and conductive films. Prior to joining 3M, Dr. Cairns was a Research Associate at Brown University, where he developed his reputation as a recognized authority on flexible and conformable information displays, and subject on which he has a forthcoming book. He holds a World Patent for his work on reflective strain gages and polarization sensitive devices. He is the author of 9 refereed articles and more than 20 conference proceedings.

Paul Lagace, Ph.D
Dr. Paul A. Lagace is a Professor of Aeronautics and Astronautics and of Engineering Systems at the Massachusetts Institute of Technology. He currently serves as co-Director of the Technology Laboratory for Advanced Composites (TELAC) and is a highly regarded international authority on the response and failure of composite structures. He is recognized as a national leader for the development of composite structures technology and frequently serves as an advisor and consultant to industry and government agencies.

Since joining the faculty in 1982, Professor Lagace has conducted research in the areas of mechanics, fracture, longevity, damage resistance, and damage tolerance of composite materials and their structures. He has published more than 120 papers on these topics and on general topics related to composite materials and their structures. He served for six years as president of the International Committee on Composite Materials where he was recognized as a World Fellow of Composites. He has received awards from various organizations and has delivered invited talks around the world.

Chris Magee, Ph.D
Professor Christopher L. Magee is a Professor of the Practice in the Engineering Systems Division and Mechanical Engineering at MIT and director of the Center for Innovation in Product Development. Before Dr. Magee joined MIT, he had more than 35 years of experience at Ford Motor Company, finishing as Executive Director of Programs and Advanced Engineering. In this position had global responsibility for all major technically deep areas involved in Ford's Product Development Organization, consisting of about 7,000 people located in the United States, United Kingdom, and Germany.

Early in his career, Dr. Magee made major contributions to the understanding of the transformation, structure and strength of ferrous materials. He was internationally recognized for this work and won several prestigious awards in his early 30's. Dr. Magee has led (from 1981 on) efforts at Ford to adapt systems engineering to the modern automotive design process. In addition, he was instrumental in developing new approaches to the program creation process at Ford and from 1987 through 1999 had the technical lead for all major Ford product concept efforts. He is a member of the National Academy of Engineering (since 1997), a fellow of ASM, and a participant on major National Research Council Studies ranging from design research to materials research.

Frederick J. McGarry
Fred McGarry is Professor Emeritus of Polymer and Civil Engineering at the Massachusetts Institute of Technology. He has been an integral part of polymer science at MIT since the 1950s, when he was director of the Monsanto House of the Future program and director of the Materials Research Laboratory. He is a recognized authority in toughening mechanisms and test methods for polymers and composites, having published more than 215 papers and won several awards.

In addition to his academic interests, Professor McGarry has been an active consultant to the plastics industry. He worked as a consultant to the Dow Chemical Company for 47 years, as a consultant to Goodrich Plastics for 35 years, as a consultant to Dow Corning Silicones for 35 years, and with American Cyanamid for "about 25 years". A great deal of his work was focused on rubber modified thermoplastics, although he solved problems across the entire spectrum of polymers.

Chris E. Scott, Ph.D:
Dr. Chris E. Scott is President of Material Answers, an engineering consulting firm based in Massachusetts. He specializes in polymer materials, properties, and processing. His work emphasizes thermoplastics, thermosets, blends, composite, and multicomponent formulations. He has extensive experience with manufacturing, product development, product design, and failure analysis. Dr. Scott has published extensively on the topics of polymer processing and structure relationships, sompounding and mixing in multiphase polymer systems, and structure and morphology development during polymer processing. He is the inventor on 9 US patents, author of more than 30 articles in refereed journals, author of 40 conference proceedings, and has presented more than 50 seminars to

industry and government organizations. He also has extensive experience in failure analysis of a broad range of polymer applications.

Prior to joining Material Answers, Dr. Scott has been a Managing Engineer at Exponent Failure Analysis Associates, an Associate Professor at the Massachusetts Institute of Technology, and a Senior Chemical Engineer at Eastman Chemical Company.

Appendix D: Number of Parts Definitions

Material	Application	Application boundary	Estimated Number of Parts	Source for estimation	Rating	Category
ABS	Automotive sheet (exterior)	automobile	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&& www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
ABS	Business machine housing (telephone)	Telephone	100	[illegible]	4	Large Number
Acetal	Auto parts	automobile	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&& www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
Acetal	Plumbing valves	faucets	23	Sloan EBF-85 faucet repair, available at www.sloanrepair.com	3	Small Number
Acetal	Steering column pins (collapsible steering columns)	automobile	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&& www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
HDPE	Hula hoop	hula hoop	1	hula hoop	1	Very Small Number
HDPE	Trash cans	trash can	2	trash can, lid	2	Small Number
HDPE	Blow molded bottles	Detergents (bottle, cap, detergents)	4	bottle, fluid, cap, label	2	Small Number
HDPE	Milk jugs	milk gallon	5	bottle, fluid, cap, label, seal	2	Small Number
HDPE	Underground wire coating	power wire	17	inspection, from cross sectional view of Okoguard shielded powere cable	3	Small Number
HDPE	HDPE fuel tanks	automobile	40000	Jaques Duval, automotive journalist	6	Very Large Number

Material	Application	Application boundary	Estimated Number of Parts	Source for estimation	Rating	Category
LDPE	HF radar wire	radar wire	2	wire with coating	2	Small Number
LDPE	Tupperware	tumbler	1	inspection	1	Very Small Number
LDPE	Squeeze bottles	squeeze bottle	5	inspection, from "Babies, a continuing market for plastics", MP 27, Dec 1949, p73	2	Small Number
LDPE	Food packaging film	meat products/bags	5	inspection	2	Small Number
Nylon	Women's hosiery	stockings	2	Inspection	2	Small Number
Nylon	Car fans (auto parts)	automobile	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
Nylon	Air intakes for automobiles	Automobile	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
PET	PET soft drink bottles	2 liter bottles of coke	6	pp base, pet bottles, label, cap, fluid, seal	2	Small Number
PMMA	Highway reflectors	reflectors	6		2	Small Number
PMMA	Signs	Signs	15	inspection of flourescent light in our lab	3	Small Number
PMMA	Auto lenses	automobiles	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
PC	Glazing in high vandalism areas	windows	20	inspection of lab window	3	Small Number
PC	Safety helmets	helmets	12	Inspection of helmets (available at http://www.bellracing.com/product/rmg4.htm)	3	Small Number

Material	Application	Application boundary	Estimated Number of Parts	Source for estimation	Rating	Category
PC	Bullet proof windows		20	See earlier windows	3	Small Number
PC	747 windows	aircraft	3.00E+06	caltech conference on complexity (http://www.cds.caltech.edu/conferences/1997/vecs/tutorial/Examples/Cases/777.htm)	7	Very Large Number
PC	5 gallon returnable water tanks	bottle of water	4	bottle, lid, seal, lable	2	Small Number
Polyester	GFRP Car body	automobile	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
Polyester	GFRP in aircraft and missiles	missiles	2500		5	Large Number
Polyester	SMC auto parts	automobiles	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
PP	Monofilament	Rope	5	rope, package, label, ends	2	Small Number
PP	Washing machine agitator	Washing machines	300	Estimated by counting repair parts in maytag repair book for Neptune model MAH5500BWQ--note: estimate is clearly low because maytag sells assemblies as parts	4	Large Number
PP	Disposable syringes	Syringes	8	inspection, with needle, label, packaging	2	Small Number
PP	All PP dashboard	Automobiles	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
PS	Foamed house insulation	House	50000	Estimate by Joe Musso, general contractor	6	Very Large Number

Material	Application	Application boundary	Estimated Number of Parts	Source for estimation	Rating	Category
PS	Wall tile	Wall tile	3	tiler, adhesive, labor (could be very many parts if each tile considered separately)	2	Small Number
PS	Radio and TV cabinets	TV				Large Number
PS	Thinwalled disposable cups	Cups	1	inspection	1	Very Small Number
PS	Woodgrain PS furniture	Furniture	15	inspection of coffee table	3	Small Number
PUR	Flexible foams (probably furniture)	Furniture	15	inspection of coffee table	3	Small Number
PUR	Lycra fibers for stretch clothing	Clothing	3	pieces of shorts	2	Small Number
PUR	Urethane crash pads	automobiles	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
PUR	Urethane sound and temperature insulation-cars	automobiles	40000	Jaques Duval, automotive journalist (http://www.groupeppp.com/en/index.shtml?http&&&www.groupeppp.com/en/faq/index.shtml)	6	Very Large Number
PUR	Flexible urethane matresses	matresses	1	matress	1	Very Small Number
PUR	Custom auto body parts	aftermarket body parts	5	parts, connectors, etc.	2	Small Number
PTFE	Gaskets and seals for Manhattan project	seals	3	layered seals	2	Small Number
PTFE	Industrial cookware coatings	cookie sheets	1	cookie sheet	1	Very Small Number

Material	Application	Application boundary	Estimated Number of Parts	Source for estimation	Rating	Category
PTFE	Nonstick coating for home use	pans	7	pan, handles, rivets	2	Small Number
PTFE	Gore tex	coats	15	zippers, buttons, fabric layers	3	Small Number
PVC	Wire insulation for low temperatures	wire	2	wire with coating	2	Small Number
PVC	Shower curtains	shower curtains	8	curtain, eyelets	2	Small Number
PVC	Color coded wire	wire	2	wire with coating	2	Small Number
PVC	PVC floor coverings	floor covering systems	3	tile, adhesive, labor (could be many parts if each tile considered separately)	2	Small Number
PVC	Garden hose	hose	6	inspection: hose, connectors on each end, gaskets	2	Small Number
PVC	Rigid pipe	house	50000	pipe, adhesive, connectors--many types	6	Very Large Number
PVC	Window awnings, doors, siding	windows, doors	20	inspection of window in our lab	3	Small Number
Urea	Brightly colored Beetle picnic ware	dishes	1	inspection	1	Very Small Number
Urea	Melamine dishware	dishes	1	inspection	1	Very Small Number

Appendix E: Mean Expert Ratings

Material	Application	Insertion Time (years)	Number of parts affected expert judgment	Value chain expert judgment	Exposure expert judgment	Total number of parts	Number of parts affected expert judgment (hilow)	Value chain expert judgment (hilow)	Number of Parts Affected	Value Chain	Total Number of Parts in Application	Number of Parts Affected (Hi-low)	Value Chain (Hi-low)
HDPE	Underground wire coating	11	3.00	2.58	4.25	3.00	2.50	2.75	Small Numparts Aff	Very Low VC Change	Small Number	Small Numparts Aff	Low VC Change
HDPE	HDPE fuel tanks	22	4.25	3.92	5.20	6.00	4.00	4.00	Very High Numparts Aff	High VC Change	Very Large Number	Very High Numparts Aff	High VC Change
LDPE	HF radar wire	0	3.33	3.08	3.00	2.00	3.00	3.13	High Numparts Aff	Low VC Change	Small Number	High Numparts Aff	Low VC Change
LDPE	Tupperware	3	1.20	3.67	1.17	1.00	1.00	3.00	Very Small Numparts Aff	High VC Change	Very Small Number	Very Small Numparts Aff	Low VC Change
LDPE	Squeeze bottles	6	2.42	3.25	1.92	2.00	2.00	3.25	Small Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Low VC Change
LDPE	Food packaging film	3	2.50	3.33	1.58	2.00	2.00	3.00	Small Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Low VC Change
Nylon	Women's hosiery	2	2.17	3.50	1.25	2.00	1.60	3.50	Very Small Numparts Aff	High VC Change	Small Number	Very Small Numparts Aff	High VC Change
Nylon	Car fans (auto parts)	19	2.75	3.42	3.60	6.00	2.90	3.42	Small Numparts Aff	Low VC Change	Very Large Number	High Numparts Aff	High VC Change
Nylon	Air intakes for automobiles	56	4.42	4.25	4.08	6.00	4.42	4.00	Very High Numparts Aff	Very High VC Change	Very Large Number	Very High Numparts Aff	High VC Change
PET	PET soft drink bottles	8	2.58	3.92	2.25	2.00	2.00	3.60	Small Numparts Aff	High VC Change	Small Number	Small Numparts Aff	High VC Change
PMMA	Highway reflectors	1	2.58	2.42	2.17	2.00	2.20	2.42	Small Numparts Aff	Very Low VC Change	Small Number	Small Numparts Aff	Very Low VC Change

Material	Application	Insertion Time (years)	Number of parts affected expert judgment	Value chain expert judgment	Exposure expert judgment	Total number of parts	Number of parts affected expert judgment (hilow)	Value chain expert judgment (hilow)	Number of Parts Affected	Value Chain	Total Number of Parts in Application	Number of Parts Affected (Hi-low)	Value Chain (Hi-low)
PMMA	Signs	13	3.83	3.83	2.08	3.00	3.20	3.50	High Numparts Aff	High VC Change	Small Number	High Numparts Aff	High VC Change
PMMA	Auto lenses	13	3.75	3.75	2.75	6.00	3.20	3.50	High Numparts Aff	High VC Change	Very Large Number	High Numparts Aff	High VC Change
PC	Glazing in high vandalism areas	6	3.42	3.08	3.17	3.00	3.00	2.88	High Numparts Aff	Low VC Change	Small Number	High Numparts Aff	Low VC Change
PC	Safety helmets	10	3.08	4.00	5.40	3.00	3.00	3.75	High Numparts Aff	High VC Change	Small Number	High Numparts Aff	High VC Change
PC	Bullet proof windows	12	3.67	4.25	4.33	3.00	3.20	4.00	High Numparts Aff	Very High VC Change	Small Number	High Numparts Aff	High VC Change
PC	747 windows	12	4.25	4.75	5.50	7.00	3.70	4.63	Very High Numparts Aff	Very High VC Change	Very Large Number	High Numparts Aff	Very High VC Change
PC	5 gallon returnable water tanks	18	2.75	2.75	1.67	2.00	2.40	2.75	Small Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Low VC Change
Polyester	GFRP Car body	11	5.83	5.67	5.17	6.00	5.60	5.75	Very High Numparts Aff	Very High VC Change	Very Large Number	Very High Numparts Aff	Very High VC Change
Polyester	GFRP in aricraft and missiles	19	4.67	5.00	3.50	5.00	4.67	5.40	Very High Numparts Aff	Very High VC Change	Large Number	Very High Numparts Aff	Very High VC Change
Polyester	SMC auto parts	26	4.00	4.08	3.42	6.00	4.40	3.50	Very High Numparts Aff	High VC Change	Very Large Number	Very High Numparts Aff	High VC Change

Material	Application	Insertion Time (years)	Number of parts affected expert judgment	Value chain expert judgment	Exposure expert judgment	Total number of parts	Number of parts affected expert judgment (hilow)	Value chain expert judgment (hilow)	Number of Parts Affected	Value Chain	Total Number of Parts in Application	Number of Parts Affected (Hi-low)	Value Chain (Hi-low)
PMMA	Signs	13	3.83	3.83	2.08	3.00	3.20	3.50	High Numparts Aff	High VC Change	Small Number	High Numparts Aff	High VC Change
PMMA	Auto lenses	13	3.75	3.75	2.75	6.00	3.20	3.50	High Numparts Aff	High VC Change	Very Large Number	High Numparts Aff	High VC Change
PC	Glazing in high vandalism areas	6	3.42	3.08	3.17	3.00	3.00	2.88	High Numparts Aff	Low VC Change	Small Number	High Numparts Aff	Low VC Change
PC	Safety helmets	10	3.08	4.00	5.40	3.00	3.00	3.75	High Numparts Aff	High VC Change	Small Number	High Numparts Aff	High VC Change
PC	Bullet proof windows	12	3.67	4.25	4.33	3.00	3.20	4.00	High Numparts Aff	Very High VC Change	Small Number	High Numparts Aff	High VC Change
PC	747 windows	12	4.25	4.75	5.50	7.00	3.70	4.63	Very High Numparts Aff	Very High VC Change	Very Large Number	High Numparts Aff	Very High VC Change
PC	5 gallon returnable water tanks	18	2.75	2.75	1.67	2.00	2.40	2.75	Small Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Low VC Change
Polyester	GFRP Car body	11	5.83	5.67	5.17	6.00	5.60	5.75	Very High Numparts Aff	Very High VC Change	Very Large Number	Very High Numparts Aff	Very High VC Change
Polyester	GFRP in aricraft and missiles	19	4.67	5.00	3.50	5.00	4.67	5.40	Very High Numparts Aff	Very High VC Change	Large Number	Very High Numparts Aff	Very High VC Change
Polyester	SMC auto parts	26	4.00	4.08	3.42	6.00	4.40	3.50	Very High Numparts Aff	High VC Change	Very Large Number	Very High Numparts Aff	High VC Change

Material	Application	Insertion Time (years)	Number of parts affected expert judgment	Value chain expert judgment	Exposure expert judgment	Total number of parts	Number of parts affected expert judgment (hilow)	Value chain expert judgment (hilow)	Number of Parts Affected	Value Chain	Total Number of Parts in Application	Number of Parts Affected (Hi-low)	Value Chain (Hi-low)
PP	Monofilament	0	3.17	3.17	1.33	2.00	2.40	2.40	High Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Very Low VC Change
PP	Washing machine agitator	4	3.42	2.92	2.25	4.00	3.25	3.25	High Numparts Aff	Low VC Change	Large Number	High Numparts Aff	Low VC Change
PP	Disposable syringes	3	3.20	3.20	4.20	2.00	3.00	3.50	High Numparts Aff	Low VC Change	Small Number	High Numparts Aff	High VC Change
PP	All PP dashboard	38	4.50	4.42	3.75	6.00	4.00	4.20	Very High Numparts Aff	Very High VC Change	Very Large Number	Very High Numparts Aff	Very High VC Change
PS	Foamed house insulation	9	2.42	3.00	3.67	6.00	2.38	2.60	Small Numparts Aff	Low VC Change	Very Large Number	Small Numparts Aff	Low VC Change
PS	Wall tile	9	2.33	2.42	3.08	2.00	2.25	2.20	Small Numparts Aff	Very Low VC Change	Small Number	Small Numparts Aff	Very Low VC Change
PS	Radio and TV cabinets	15	3.58	3.33	3.42	5.00	3.90	3.33	High Numparts Aff	Low VC Change	Large Number	Very High Numparts Aff	High VC Change
PS	Thinwalled disposable cups	18	2.08	2.75	1.92	1.00	1.60	2.40	Very Small Numparts Aff	Low VC Change	Very Small Number	Very Small Numparts Aff	Very Low VC Change
PS	Woodgrain PS furniture	28	3.58	4.25	3.42	3.00	3.25	3.80	High Numparts Aff	Very High VC Change	Small Number	High Numparts Aff	High VC Change
PUR	Flexible foams (probably furniture)	0	3.08	3.42	3.00	3.00	3.00	3.63	High Numparts Aff	Low VC Change	Small Number	High Numparts Aff	High VC Change

Material	Application	Insertion Time (years)	Number of parts affected expert judgment	Value chain expert judgment	Exposure expert judgment	Total number of parts	Number of parts affected expert judgment (hilow)	Value chain expert judgment (hilow)	Number of Parts Affected	Value Chain	Total Number of Parts in Application	Number of Parts Affected (Hi-low)	Value Chain (Hi-low)
PUR	Lycra fibers for stretch clothing	1	2.08	2.92	2.00	2.00	1.80	2.50	Very Small Numparts Aff	Low VC Change	Small Number	Very Small Numparts Aff	Low VC Change
PUR	Urethane crash pads	11	3.67	3.58	4.33	6.00	3.20	3.20	High Numparts Aff	High VC Change	Very Large Number	High Numparts Aff	Low VC Change
PUR	Urethane sound and temperature insulation-cars	12	2.58	3.25	2.58	6.00	2.63	3.50	Small Numparts Aff	Low VC Change	Very Large Number	Small Numparts Aff	High VC Change
PUR	**Flexible urethane matresses**	0	3.00	3.08	3.00	1.00	3.00	2.80	Small Numparts Aff	Low VC Change	Very Small Number	High Numparts Aff	Low VC Change
PUR	Custom auto body parts	48	3.33	3.83	2.42	2.00	2.60	3.50	High Numparts Aff	High VC Change	Small Number	Small Numparts Aff	High VC Change
PTFE	**Gaskets and seals for Manhattan project**	0	3.20	2.80	4.40	2.00	3.50	3.00	High Numparts Aff	Low VC Change	Small Number	High Numparts Aff	Low VC Change
PTFE	Industrial cookware coatings	8	2.42	2.92	2.08	1.00	2.20	2.40	Small Numparts Aff	Low VC Change	Very Small Number	Small Numparts Aff	Very Low VC Change
PTFE	**Nonstick coating for home use**	13	2.58	3.58	2.92	2.00	2.40	3.20	Small Numparts Aff	High VC Change	Small Number	Small Numparts Aff	Low VC Change
PTFE	Gore tex	47	3.67	4.00	2.58	3.00	3.00	3.75	High Numparts Aff	High VC Change	Small Number	High Numparts Aff	High VC Change
PVC	**Wire insulation for low temperatures**	0	2.75	3.25	2.92	2.00	2.75	3.25	Small Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Low VC Change
PVC	Shower curtains	3	2.42	2.58	1.75	2.00	2.00	2.25	Small Numparts Aff	Very Low VC Change	Small Number	Small Numparts Aff	Very Low VC Change

Material	Application	Insertion Time (years)	Number of parts affected expert judgment	Value chain expert judgment	Exposure expert judgment	Total number of parts	Number of parts affected expert judgment (hilow)	Value chain expert judgment (hilow)	Number of Parts Affected	Value Chain	Total Number of Parts in Application	Number of Parts Affected (Hi-low)	Value Chain (Hi-low)
PVC	Color coded wire	6	3.33	2.42	2.25	2.00	3.00	2.38	High Numparts Aff	Very Low VC Change	Small Number	High Numparts Aff	Very Low VC Change
PVC	PVC floor coverings	8	3.25	3.25	1.75	2.00	2.80	2.80	High Numparts Aff	Low VC Change	Small Number	Small Numparts Aff	Low VC Change
PVC	Garden hose	8	2.92	2.92	2.08	2.00	3.00	2.60	Small Numparts Aff	Low VC Change	Small Number	High Numparts Aff	Low VC Change
PVC	Rigid Pipe	15	3.75	4.08	4.42	6.00	3.40	3.80	High Numparts Aff	High VC Change	Very Large Number	High Numparts Aff	High VC Change
PVC	Window awnings doors, siding	21	3.83	4.17	3.17	3.00	3.20	3.60	High Numparts Aff	Very High VC Change	Small Number	High Numparts Aff	High VC Change
Urea	Brightly colored Beetle picnic ware	0	1.92	3.25	1.25	1.00	1.40	3.25	Very Small Numparts Aff	Low VC Change	Very Small Number	Very Small Numparts Aff	Low VC Change
Melamine	Melamine dishware	1	1.92	3.08	1.42	1.00	1.40	3.00	Very Small Numparts Aff	Low VC Change	Very Small Number	Very Small Numparts Aff	Low VC Change
	Average	**11.12**	**3.06**	**3.43**	**2.93**	**3.28**	**2.81**	**3.25**					
	Standard Deviation	*12.3361*	*0.88105*	*0.71127*	*1.19498*	*1.86183*	*0.90114*	*0.75653*					

References

References—Chapter 1

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[1] BBC report, "Making History: Bronze Age Smelting", available at www.bbc.co.uk/educatin/beyond/factshseets/makhist/makhist3_prog5a.shtml .

[2] Eagar, Thomas, "Bringing New Materials to Market", Technology Review, February/March 1995.

[3] Alternative methods, such as government adoption, have been able to bring materials to use faster than capitalism, but have done a poor job at distributing the materials into society. They are generally used in governments to solve specific military problems.

[4] Innovation papers were selected from the general body of innovation strategy literature by Kwanghui Lim (MIT Sloan Visiting Professor of Innovation Strategy), Professor Clayton Christensen (Harvard Business School), and the author. A review of the most relevant theories of innovation to materials is presented in the latter half of chapter 2. References to these and other papers are peppered throughout the thesis.

[5] The main sources of historical information were *Modern Plastics* (a monthly trade magazine that was the most important plastics industry publication until the mid 1990s) and *Synthetic Organic Chemicals* (an annual government report that chronicled the sales prices and volume of the chemical industry—including plastics—from the early 1930s to the mid 1990s).

[6] Experts include: Stan Abkowitz, Dynamet Technology (inventor of Ti-6 4-Al V); Gerry Estes, Vice President, The Lord Corporation; Thomas Eagar, Professor, MIT; Clayton Christensen, Professor, Harvard Business School, former CEO Ceramics Process Systems; Paul Lagace, Professor, MIT; Grant Bennett, CEO, Ceramics Process Systems; Eric Mayes, CEO, Nanomagnetics; Jeremy Dann, Consultant, Jump Group; Tom Ricciardelli, CEO, Selectech; Monty Alger, Director, GEAM; Fred McGarry, Professor, MIT, former industry consultant; Darran Cairns, researcher, 3M Touch Systems; Larry Bell, Director, Nypro; Chris Magee, former director, Ford Motor Company; Gaylord Smith, Director of R&D, Special Metals; The Special Metals R&D team (workshop); Chris Scott, President, Materials Solutions; Neil Jenkins, research fellow, Charles MGH; Raymundo Arroyave, research fellow, Penn State; David Roylance, Professor, MIT; GEAM research team (workshop); Randy Kirchain, Professor, MIT.

[7] The work of the MIT Materials Systems Laboratory has been very effective at understanding and modeling the value propositions of existing materials, and at predicting switches. Some of the best papers were presented in a special issue of *Materials and Society* (Vol. 13, No 3. [1989]), which was focused on markets for advanced materials.

[8] Much of the pioneering work on multiattribute utility analysis (MAUA) was performed by Richard DeNeufville of MIT; his textbook *Applied Systems Analysis, Engineering Planning and Technology Management* (McGraw-Hill, New York, 1990) is an excellent resource. The MIT MSL pioneered the use of MAUA in materials (see reference 7).

[9] While value propostion analysis techniques have a good track record with existing materials, they do poorly with new ones. Mangin, C.E., deNeufville, R., Field, F. III, and Clark, J., "Defining Markets for New Materials: Engineering Methodology with Case Application" (*Resources Policy*, 21, 3, [1995]) is an excellent example of value proposition thinking that failed with new materials. It predicted in 1995 that ceramic valves would be adopted in high performance 4 and 6 cylinder automobiles. Today, in 2004, no production engine has a ceramic valvetrain.

[10] Eagar, Thomas, personal conversation, November 2002.

[11] The American Heritage® Dictionary of the English Language, Fourth Edition
Copyright © 2000 by Houghton Mifflin Company.

[12] Porter, Michal E., *Competitive Advantage: Creating and Sustaining Superior Performance*, New York: The Free Press (1985), p 59.

[13] Vincent, B.B., "Materials science and engineering: an artificial discipline about to explode?", adapted from *Historical Studies in the Physical Sciences*, available at http://hrst.mit.edu/hrs/materials/public/bernadettespaperforhrst_files/intor(bbvhistmst).htm

[14] See MIT DMSE faculty bios.

[15] Utterback, James M., and Abernathy, William J. (1975), "A Dynamic Model of Process and Product Innovation", *Omega, the International Journal of Management Science*, Vol. 3, No. 6. pp. 639-656.

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[16] Abernathy, William J., and Clark, Kim B. (1985). "Innovation: Mapping the Winds of Creative Destruction", *Research Policy (14),* pp. 3-22.

[17] Christensen, Clayton M.(1992). "Exploring the Limits of the Technology S-Curve. Part 2: Architectural Technologies", *Production and Operations Management,* Vol. 1, 4, pp. 358-366.

[18] The author has conducted several informal surveys with groups of materials scientists by asking them what material a mechanical pencil is made from; in each case, their response has been "plastic". This reflects the fact that people don't care what material a product is made from, as long as it works.

[20] See Christensen, *The Innovator's Dilemma.*

[21] Utterback, J.M., "Innovation in Industry and the Diffusion of Technology", *Science,* Feb 15, 1974.

References-Chapter 2

[1] Most of this work has emerged from the MIT Materials Systems Laboratory.

[2] Bement, Arden Jr.; El-Rahaiby, Said K.; Campbell, Christian X. "Bringing Advanced Materials to Market, A Supplemental Report to the 1995 DOD/DOE/NASA Workshops on the US Advanced Composites Industrial Base". Ceramics Information Analysis Center Report 8. April 1995.

[3] Bement, et al.

[4] Congress of the United States Office of Technology Assessment, *Advanced Materials by Design,* Chapter 8: Industry Criteria for Investment, NTIS order #PB88-243548, 1988. Available at http://www.wws.princeton.edu/~ota/disk2/1988/8801_n.html .

[5] Committee on Accelerating Technology Transition, National Research Council, *Accelerating Technology Transition: Bridging the Valley of Death for Materials and Processes in Defense Systems,* National Academies Press, ISBN 0-309-09317-1, 2004.

[6] Bement, et al.

[7] Congress of the United States Office of Technology Assessment, *Advanced Materials by Design,* Chapter 8: Industry Criteria for Investment, NTIS order #PB88-243548, 1988. Available at http://www.wws.princeton.edu/~ota/disk2/1988/8801_n.html .

[8] Eagar

[9] Bement, et al.

[10] Congress of the United States Office of Technology Assessment, *Advanced Materials by Design,* Chapter 8: Industry Criteria for Investment, NTIS order #PB88-243548, 1988. Available at http://www.wws.princeton.edu/~ota/disk2/1988/8801_n.html .

[11] Bement, et al.

[12] Eagar

[13] US Government Thrift Savings Plan Published Information (www.tsp.gov/rates/history.html).

[14] Wang, Jiang; MIT Sloan School of Management Introduction to Finance (15.401) Notes, Fall 2001.

[15] Personal conversation with Ronald Mika, Managing Director of Bain Capital (Boston), 2001.

[16] Cochrane, John H., (2002) "The Risks and Returns of Venture Capital", National Bureau of Economic Research Working Paper, (papers.nber.org/papers/w8066).

[17] Based on various conversations with materials executives. This number obviously varies between companies.

[18] Congress of the United States Office of Technology Assessment, *Advanced Materials by Design,* Chapter 8: Industry Criteria for Investment, NTIS order #PB88-243548, 1988. Available at http://www.wws.princeton.edu/~ota/disk2/1988/8801_n.html .

[19] Field, F.R.III, ***Application of multi-attribute utility analysis to problems in materials selection,*** unpublished doctoral thesis, MIT, 1985.

[20] Cost modeling techniques are now well-known, but one of the better applications is available in Arnold, S., Hendrichs, N., Field, F.R., and Clark, J.P., "Competition Between Polymeric Materials and Steel in Car Body Applications", *Materials and Society,* Vol. 13, no3. (1989). The MIT Theses of Mssrs. Arnold and Hendrichs were both cited as sources for credible development of the cost models used in the paper. The references for the theses are: Arnold, S., *Economic Modeling of Multi-Sequential Manufacturing Processes: A Case Study of the Automobile Door,* PhD Thesism MIT, 1989. Hendirchs, N., SM Thesis, MIT, 1989.

---

[21] Mangin, C.G.E, de Neufville, R., Field, F.R. III, Clark, J., "Defining New Markets for Materials: Engineering Methodology with Case Application", *Research Policy*, Vol. 21, no. 3, 1995.

[22] For a more thorough discussion, see de Nuefville, R., *Applied Systems Analysis: Engineering Planning and Technology Management*, Chapters 18-20.

[23] Treatment taken from Mangin, C.G.E, de Neufville, R., Field, F.R. III, Clark, J., "Defining New Markets for Materials: Engineering Methodology with Case Application", *Research Policy*, Vol. 21, no. 3, 1995.

[24] Mangin, et al.

[25] Stewart, R., "Nanocomposites", *Plastics Engineering*, May 2004.

[26] Froes, F.H., "Titanium: Is now the Time?", *Journal of Metals*, November 2004.

[27] Klug, K.L, et al., "The Near Net Shaper Manufacturing of Affordable Titanium Components for the M777 Lightweight Howitzer", *Journal of Metals*, November 2004.

[28] "Still Too Exotic", *Ward's Auto Newsletter*, November 1, 2004.

[29] Schafrik, R. and Sprague, R., "Saga of Gas Turbine Materials" (3 part series), *Advanced Materials and Processes*, Mar-May 2004.

[30] Maine, E.M.A.; Ashby, M.F. "An Investment Methodology for New Materials". Materials and Design 23, 2002. PP 297-306.

[31] Maine, E.M.A.; Ashby, M.F. "An Investment Methodology for New Materials".

[32] Porter, Michal E., *Competitive Advantage: Creating and Sustaining Superior Performance*, New York: The Free Press (1985), p 59.

[33] Teece, David J., "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy", Chapter 9 in *The Competitive Challenge*, Ballinger Publishing, Cambridge, MA (1987).

[34] Personal conversation with Ronald Mika, Managing Director of Bain Capital (Boston), 2001.

[35] Maine, E.M.A.; Ashby,M.F. "Applying the Investement Methodology for Materials (IMM) to Aluminum Foams". Materials and Design 23, 2002. PP 307-319.

[36] Bement, et al.

[37] Eagar

[38] Eagar

[39] Eagar

[40] Foster, James. "Private/Public Interactions Driving Mutual Gains in Regulatory Systems". Presentation to ESD Doctoral Seminar, November 13, 2002.

[41] Personal conversation with Laura Oliphant, Intel Capital.

[42] Aircraft engine materials suppliers sometimes qualify their materials with 75,000 hour creep tests; these types of tests are required to prove safety of a metal.

[43] Eagar

[44] Personal conversation with Chris Magee, former head of Ford Materials Lab.

[45] Maine, E.M.A.; Ashby,M.F. "Applying the Investment Methodology for Materials (IMM) to Aluminum Foams".

[46] Personal conversation with Clayton Christensen, former CEO, Ceramics Processing Systems

[47] Maine, E.M.A.; Ashby,M.F. "Applying the Investment Methodology for Materials (IMM) to Aluminum Foams".

[48] Personal conversation with Steve Almeida, BMW Gallery (Norwood, MA) service representative.

[49] Lowman, Rodney W., "Life Cycle Assessment and Public Policy Development for the Automotive Industry", Presented at the Total Life Cycle Conference and Exposition, Auburn Hill, MI, April 7-9, 1997, available at http://www.americanplasticscouncil.org/apcorg/newsroom/speeches/automotive_speech.html

[50] Eagar, Thomas. MIT 3.37 Welding and Joining Lectures, Fall 2002.

[51] Personal conversation with Mike Kimber, Visteon Corporation, February 2001.

[52] Shumpeter, Joseph A. (1943). "The Process of Creative Destruction", chapter 7 in *Capitalism, Socialism, and Democracy*, Second Edition, George Allen & Unwin, Ltd., London. pp. 81-86.

[53] Utterback, James M., and Abernathy, William J. (1975), "A Dynamic Model of Process and Product Innovation", *Omega, the International Journal of Management Science*, Vol. 3, No. 6. pp. 639-656.
See also:
Utterback, James M. (1994). *Mastering the Dynamics of Innovation.* Harvard Business School Press, Boston.

---

[54] Ibid.

[55] Ibid.

[56] Liebowitz, S.J. and Margolis, S.E., "Network Externalities (Effects)", *The New Palgraves Dictionary of Economics and the Law,* MacMillan, 1998.

[57] Yang, Yi-Nung, "An Introduction to Network Externalities", first chapter of unpublished doctoral thesis, Utah State University, 1997.

[58] Liebowitz, S.J.m and Margolis, S.E, "The Fable of the Keys", *Journal of Law and Economics,* April 1990.

[59] Christensen, C.M., *The Innovator's Dilemma,* HarperBusiness, 2000.

[60] Ibid.

[61] Ibid.

[62] Christensen, C.M. and Raynor, M.E., *The Innovator's Solution,* Harvard Business School Press, 2003.

[63] Beattie, S., Dahn, J.R., "Electrodeposition of a Combinatorial Library of Binary $Cu_{1-x}Zn_x$ Alloys", 204th Meeting, The Electrochemical Society.

References—Chapter 3

[64] Eppinger PD process, IDEO process, Windchill processes, etc.

[65] Porter's Five Forces is a popular example of a market assessment tool; however, more convincing evidence of the variety of available tools can be found by performing a websearch on "market analysis", which returns more than 9 million responses.

[66] Abernathy, William J., and Clark, Kim B. (1985). "Innovation: Mapping the Winds of Creative Destruction", *Research Policy (14),* pp. 3-22.

[67] Tushman, Michael L., and Anderson, Philip (1986). "Technological Discontinuities and Organizational Environments", *Administrative Science Quarterly,* Vol. 31. pp. 439-465.

[68] Henderson, Rebecca M., and Clark, Kim B. (1990). "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms", *Administrative Science Quarterly,* 35, pp. 9-30.

[69] Christensen, C. Raynor,M., Verlinden, M., "Skate to Where the Money Will Be", *Harvard Business Review,* November 2001.

[70] Utterback, James M., and Abernathy, William J. (1975), "A Dynamic Model of Process and Product Innovation", *Omega, the International Journal of Management Science,* Vol. 3, No. 6. pp. 639-656.

[71] See also Utterback, James M. (1994). "Dominant Designs and the Survival of Firms", Chapter 2 in *Mastering the Dynamics of Innovation.* Harvard Business School Press, Boston. pp. 22-55.

[72] Ibid.

[73] Although not presented here, the author tested Utterback's statement by examining the pattern of the number of firms. Utterback was correct: it was very different.

[74] Examples include *Makromolecule, The Journal of Polymer Chemistry ,The Journal of Polymer Processing, etc.*

[75] *Plastics News,* a weekly newspaper, was introduced in 1990 and has since displaced *Modern Plastics* as the primary source of information for the US plastics industry. *Modern Plastics* is now positioned as "the Global Plastics Magazine", and has all but eliminated in depth coverage in favor of simple descriptions of emerging market trends and challenges.

[76] Kline's title and a short description of his life can be found on the website of the Plastics Hall of Fame, available at http://www.plastics.com/halloffame.php?hof=kline&menu=ind_manage .

[77] United States Tariff Commission, *Census of Dyes and of Other Synthetic Organic Chemicals 1930,* US Government Printing Office, Washington (1931).

[78] See Meikle, Jeffrey L., *American Plastic: A Cultural History,* Rutgers University Press, 1997.

[79] The approach of examining only successful innovations is well established—see for example Utterback, J.M Successful Industrial Innovation: A Multivariate Analysis," *Decision Sciences,* Vol. 6, No. 1, January 1975, pp. 65-77.

[80] "Resin supply at the crossroads", *Modern Plastics,* January 1999.

[82] "Resins Report: United States", *Modern Plastics,* January 1999, pp. 72-75.

---

[83] See Mangin, C.E., de Neufville, R., Field, F. III, and Clark, J., "Defining Markets for New Materials", *Resources Policy,* 21, 3, 1995.
[84] "Gallon of Milk in Polyethylene", *Modern Packaging,* August 1962.
[85] "New economy in plastic bottles", *Modern Packaging,* Sep 1958.
[86] "Big Push on Plastics", *Modern Packaging,* October 1959.
[87] "New Champ of detergent bottles: high-density PE", *Modern Plastics*, August 1959.
[88] "Sure. Film markets are big, but is there any potential left?", *Modern Plastics,* January 1972.
[89] "Plan your line for the payoff in Extruding film grocery bags", *Modern Plastics,* April 1973.
[90] "What's really happening in paperlike HDPE film?", *Modern Plastics*, March 1978
[91] "Plastics get rid of the garbage", *Modern Plastics, D*ec 1971
[92] "Futures for plastics pipe", *Modern Plastics,* March 1954.
[93] "Why the fast growing market for BIG polyethylene containers? *Modern Plastics,* June 1959.
[94] "Beverage cases: Coming market for HDPE", *Modern Plastics*, August 1961.
[95] "Why the fast growing market for BIG polyethylene containers?", *Modern Plastics,*, June 1959.
[96] Ibid.
[97] "Polyethylene packages in use", *Modern Packaging,* January 1947.
[98] "Great Packaging Discoveries 7-Extrusion Coating", *Modern Packaging*, August 1959.
[99] "Polyethylene packages in use", *Modern Packaging,* January 1947.
[100] Boskirk, R.L. (ed.), "Film sets the pace in low density PE, but what's ahead for film?", *Modern Plastics*, July 1970.
[101] "The new bottle equation: GS+mrc+NPt=rH", *Modern Plastics,* April 1975.
[102] "Beyond the soft drink bottle: New markets in sight for PET*", Modern Plastics*, April 1978.
[103] Resins 1980, *Modern Plastics*, January 1980.
[104] "Why the big market for monofilaments?", *Modern Plastics,* June 1961.
[105] "Polypropylene upgrades housewares", *Modern Plastics,* December 1959.
[106] "Polypropylene", *Modern Plastics*, January 1964.
[107] "Polypropylene: where is it going?", *Modern Plastics,* August 1961.
[108] "Polypropylene", *Modern Plastics*, January 1960.
[109] "1961 Autos: proving ground for plastics", *Modern Plastics*, November 1960.
[110] "Polypropylene", Modern Plastics, January 1960.
[111] "Polystyrene films in use", *Modern Packaging,* September 1958.
[112] "Plastics in disposables and expendables", *Modern Plastics,* April 1957.
[113] "Biggest hit in tape packs: polystyrene, to the tune of 19 million lb. in '68", *Modern Plastics,* June 1969.
[114] "Polyurethane and polyester FOAMS", *Modern Plastics,* November 1954.
[115] "Polyurethanes on the way", *Modern Plastics*, August 1955.
[116] "Polyurethanes on the way", *Modern Plastics*, August 1955.
[117] "New direcctions for plastics applications", *Modern Plastics*, January 1957.
[118] "The Urethanes Grow Up--part 2", *Modern Plastics*, April 1959.
[119] Bushnell, C.E., "Thermal Insulation: where foams fit in", Modern Plastics, October 1963.
[120] "Flexible foams--past and future", *Modern Plastics*, September 1955.
[121] "Plastics vs. corrosion", *Modern Plastics,* September 1953.
[122] "Tomorrow is today for vinyls in construction", *Modern Plastics, O*ctober 1960.
[123] "Tomorrow is today for vinyls in construction", *Modern Plastics, O*ctober 1960.
[124] Macht, M.L. and Paine, H.W., "Thermoplastic Resins", *Modern Plastics*, January 1939.
[125] "1949. . .and the Future", Modern Plastics, January 1948.
[126] "Futures for PLASTICS PIPE", Modern Plastics, March 1954.
[127] US patent 2155243: Electrical Cable.
[128] "Polypropylene Fibers 1998-2003", Chemical Market Resources Inc., available at http://www.cmrhoutex.com/cmr/multi-clients/polypropylene_fibers_1998-2003.htm .
[129]"Bonanza for extruders", *Modern Plastics*
[130] Kline, Gordon M., "Advances in plastics during 1944", *Modern Plastics*, January 1945.
[131] "Latest engineering thermoplastic--injection moldable POLYESTER", *Modern Plastics*, June 1967
[132] "Why the big market for polypropylene monofilaments?", *Modern Plastics*, June 1961.
[133] Bunn, H.S., "Thermoplastics (in Plastics Progress in 1939)", *Modern Plastics*, January 1940.
[134] "Polyurethane and Polyester Foams", *Modern Plastics*, November 1954.

---

[135] Macht, M.L., and Paine, H.W., "Thermoplastic Resins (in Plastics Progress in 1938)", *Modern Plastics*, January 1939.
[136] Kline, Gordon M. "The Year in Review", *Modern Plastics*, January 1949.
[137] "Here are the first commercial applications of Delrin", *Modern Plastics*, November 1959.
[138] Sembera, K.W., "Evolution and Analysis of the Toothbrush", *ASME Mechanical Advantage*, March 2001.
[139] Funderburg, A.C.,"Makinge Teflon Stick", *Invention and Technology*, Summer 2000.
[140] *Synthetic Resins and Their Raw Materials*, US Government Printing Office, Report no 131. 1938.
[141] "First Polycarbonate Applications", Modern Plastics, December 1958.
[142] "The first year of war--and the next", *Modern Plastics*, January 1943.
[143] See Wilson, G.D., "Polyethylene: The Early Years", *The Development of Plastics*, Mossman, S.T.I. and Morris, P.J.T, Ed., London, Royal Society of Chemistry, 1994. p71.
[144] Utterback, James M., and Abernathy, William J. (1975), "A Dynamic Model of Process and Product Innovation", *Omega, the International Journal of Management Science*, Vol. 3, No. 6. pp. 639-656.
[145] Kline, G.M., "Advances in plastics during 1945", *Modern Plastics*, January 1946.
[146] Bayer, Otto, "Polyurethanes", *Modern* Plastics, June 1947; cited in Kline, G.M., "Advances in plastics during 1947", *Modern Plastics*, January 1948.
[147] "Polyurethane and polyester foams", *Modern Plastics*, November 1954.
[148] "Foam-Stuffed Tubbable Toy", *Modern Plastics*, November 1954.
[149] Ibid.
[150] Information on acrylic highway reflectors taken from *Synthetic Resins and Their Raw Materials*, US Government Printing Office, Report no 131. 1938.
[151] Photo from Smithsonian Archives, available at americanhistory.si.edu .
[152] Conversation with Gerry Estes of the Lord Corporation, September 2003.
[153] Conversation with Monty Alger, Director, GE Noryl Research and Development, June 2004.
[154] www.mantex.co.uk/samples/glo-3.htm
[155] "New Economy in plastic bottles", *Modern Packaging*, September 1958.
[156] "Polyethylene packages in use", *Modern Pacakaging*, January 1947.
[157] "The new bottle equation: GC=mrc+mPt=rH", *Modern Plastics*, April 1975.
[158] "Molded polypropylene: Sears' choice for luggage", *Modern Plastics*, November 1960.
[159] De Bell, J.M., "Thermoplastics (in Advances in Plastics During 1940)", *Modern Plastics*, January 1941.
[160] "The battle is on in FLEXIBLE FOAMS", *Modern Plastics*, September 1957.
[161] De Bell, J.M., "Thermoplastics (in Advances in Plastics During 1941)", *Modern Plastics*, January 1942.
[162] "TOUGH NEW THERMOPLASTIC", *Modern Plastics*, September 1955.
[163] "1961 Autos: proving ground for plastics", *Modern Plastics*, November 1960.
[164] Meikle, J.A., *American Plastic: A Cultural History*, Rutgers University Press, 1997. p 142.
[165] Funderburg, A.C.,"Makinge Teflon Stick", *Invention and Technology*, Summer 2000.
[166] De Bell, J.M., "Thermoplastics (in Advances in Plastics During 1940)", *Modern Plastics*, January 1941.
[167] "Modern Plastics Annual Review and Forecast: Polycarbonate", *Modern Plastics*, January 1965.
[168] "Plastics timeline tracks history of an industry", *Modern Plastics*, January 2000.
[169] It can be argued that Teflon replaced cooking oil.
[170] "Plastics timeline tracks the development of an industry", *Modern Plastics*, January 2000.
[171] "Polyethylene grabs the spotlight", *Modern Plastics*, September 1955.
[172] "A bonanza for extruders", *Modern Plastics.*
[173] Ibid.
[174] HDPE attracted more entrants early in its life than any other plastic—at least 12 companies had announced plans to produce it in 1955—before any material had been sold!! ("Polyethylene grabs the spotlight", *Modern Plastics*, September 1955).
[175] "Polyethylene grabs the spotlight", *Modern Plastics*, September 1955
[176] "Big push on plastics", *Modern Packaging*, October 1959.
[177] "New economy in plastic bottles", *Modern Packaging*, September 1958.
[178] Ibid.
[179] "Big push on plastics", *Modern Packaging*, October 1959.
[180] "New champ of detergent bottles: high density PE", *Modern Plastics*, August 1959.
[181] Ibid.

---

[182] "Big push on plastics", *Modern Packaging*, October 1959.
[183] "Production hits 6.7 billion lb", *Modern Plastics*, January 1962. Claim based on calculation taken from "Big puch on plastics", that 22 oz. detergent bottles required 1/10 lb. of HDPE each.
[184] Front Cover Photo, *Modern Plastics*, August 1959.
[185] "Production hits 7.8 billion lb., sales hit 7.4",*Modern Plastics*, January 1963.
[186] "Bleaches move to plastics", *Modern Packaging*, January 1961.
[187] Ibid.
[188] The enablers were definitely not large enough to justify investment, but some of the platforms may have achieved commodity status too quickly to make money, either.
[189] The materials that did not get new entrants (PPO, polyimide, Kevlar, etc.) tend not to grow very large; however, causality is very difficult to prove.
[190] Inventors.about.com—washing machine history..

[191] Association of American Appliance Manufacturers, quoted in Modern Marvels: History of the Washing Machine, available at www.historychannel.com.
[192] Weith, A.J., "Phenolic Resins", *Modern Plastics*, January 1942.
[193] "What's ahead for 1946?", *Modern Plastics,* January 1946.
[194] "Looking toward 1948", *Modern Plastics*, January 1948.
[195] "Progress in plastics", *Modern Plastics,* January 1953.
[196] "Resins UP a Billion Pounds!",*Modern Plastics*, January 1956.
[197] "Plastics in 1958: SLOW START STRONG FINISH", *Modern Plastics,* January 1959.
[198] "Production hits 6.7 billion lb.", *Modern Plastics*, January 1962.
[199] "Applications 1963: a year of significance", *Modern Plastics,* January 1964.
[200] "Plastics 1964: soaring growth. . .dynamic complexity. . .new directions", *Modern Plastics*, January 1965.
[201] Ibid.
[202] "What a year this has been", *Modern Plastics,* January 1966.
[203] "Plastics outpace appliance growth better than 3 to1", *Modern Plastics,* January 1968.
[204] "Markets for plastics held up nicely, thank you", *Modern Plastics,* January 1970.
[205] "Plastics sales reach new high as market penetration deepens", *Modern Plastics*, January 1967.
[206] "The statistics for 1971", *Modern Plastics*, January 1972.
[207] HDPE usage in agitators is common knowledge—see Encarta encyclopedia.

References—Chapter 4

[1] "In Search of Serendipity: Bridging the Gap that Separates Technologies and New Markets", Wharton Managing Technology Internet Series.
[2] "Biggest hit in tape packs: polystyrene, to the tune of 19 million lb in '68", *Modern Plastics,* June 1969. pp. 68-69.
[3] "Polyethylene grabs the spotlight"-- *Modern Plastics,* September 1955, pp 85.
[4] Ibid.
[5] "What are the prospects for the paper-like blown PE films?", *Modern Plastics*, May 1970.
[6] "Who Needs Coextrusion?", *Modern Plastics*, June 1968 (Note: HDPE coextrusions were being used for other sacks--not practical for liners until the biaxial problem was solved).
[7] "Polyethylene grabs the spotlight"-- *Modern Plastics,* September 1955, pp 85.
[8] Ibid.
[9] "Beverage cases: Coming market for HDPE", *Modern Plastics,* August 1961.
[10] "Polyethylene grabs the spotlight"--*Modern Plastics*, October 1955, p 100.
[11] Wilson, G.D., "Polyethylene: The Early Years", The Development of Plastics, Mossman, S.T.I. and Morris, P.J.T, Ed., London, Royal Society of Chemistry, 1994. p71.
[12] Ibid.
[13] ibid.
[14] US Patent 3095677: Method of Packaging Articles
[15] US Patent US3778214: Apparatus for preparing a biaxially oriented thermoplastics bottle.
[16] Ibid.

---

[17] US Patent US4376851: Solid Polymer of Olefins and Production of Such Polymers.

[18] Ibid.

[19] ibid.

[20] ibid.

[21] Ottolenghi, M. and Crespi, C., "What's with polypropylene", *Modern Plastics*, March 1958.

[22] Ibid.

[23] US Patent US2412187: Process and Apparatus for Producing Continuous Sheet of Biaxially Oriented Organic Polymer.

[24] US Patent US 28005790: Plastic Containers and Packaging Thereof.

[25] "Biggest hit in tape packs: polystyrene, to the tune of 19 million lb. in '68", *Modern Plastics*, June 1969, p. 68.

[26] "Polyurethane and polyester FOAMS", Modern Plastics, November 1954.

[27] "Polyurethanes on the way", *Modern Plastics*, August 1955.

[28] "Polyurethanes on the way", Modern Plastics, Aug 1955

[29] Ibid.

[30] Ibid.

[31] "The 'Hard' Vinyls", *Modern Plastics*, April 1952 (reference to American discovery of German uses of PVC during war, including pipes).

[32] US Patent 2682236: Construction Unit.

[33] US Patent 2753603: Plastic Window Frame.

[34] US Patent 2122805: Production of Thermoplastic Polymerization Products.

[35] Macht, M.L. and Paine, H.W., "Thermoplastic Resins", *Modern Plastics*, January 1939.

[36] "1948. . .and the Future", *Modern Plastics*, January 1949.

[37] "The 'Hard' Vinyls", *Modern Plastics,* April 1952 (reference to American discovery of German uses of PVC during war).

[38] “Maine, E.M.A., and Ashby, M.F., “An investment methodology for materials”, *Materials and Design* 23 (2002) p. 297-306.

[39] Mangin, C., De Neufville, R., Field, F. III., Clark, J., “Defining Markets for New Materials”, *Resources Policy* 21 (1995), pp. 168-178.

[40] "Gallon of Milk in Polyethylene", *Modern Packaging*, August 1962.

[41] "New economy in plastic bottles", *Modern Packaging*, September 1958.

[42] "One way or another, HDPE will make it in retail bags", *Modern Plastics*.,July 1975.

[43] "What's really happening in paperlike HDPE film?",*Modern Plastics*, March 1978. (same thickness, similar cost/lb, higher density=higher cost).

[44] Gloor, W.E., "Why biaxially oriented pipe?", *Modern Plastics*, June 1960. (note: price difference was implied, because the author concluded that the reason for biaxial orientation was to reduce cost to make the material more competitive with metal).

[45] "Why the fast growing market for BIG polyethylene containers?", *Modern Plastics*, June 1959.

[46] "Beverage cases: Coming market for HDPE", *Modern Plastics*, August 1961.

[47] "Why the fast growing market for BIG polyethylene containers?", *Modern Plastics*, June 1959.

[48] "Costs of plastics in comparison to other materials", *Modern Plastics*, February 1950.

[49] "Film and Sheeting Sales", *Modern Plastics*, February 1959.

[50] "Great Packaging Discoveries 7-Extrusion Coating", *Modern Packaging*, August 1959.

[51] "Costs of plastics in comparison to other materials", *Modern Plastics*, February 1950.

[52] "Film and Sheeting Sales", *Modern Plastics*, February 1959.

[53] Lower price suggested by comparative PE film prices at the time of introduction.

[54] "The new bottle equation: GS+mrc+NPt=rH", *Modern Plastics,* April 1975.

[55] "Beyond the soft drink bottle: New markets in sight for PET", *Modern Plastics,* April 1978.

[56] "Why the big market for monofilaments?", *Modern Plastics*, June 1961.

[57] "Polypropylene upgrades housewares", *Modern Plastics,* December 1959.

[58] "Polypropylene", *Modern Plastics* resin review, January 1964.

[59] "Polypropylene", *Modern Plastics* resin review, January 1962.

[60] "Polypropylene", *Modern Plastics* resin review, January 1960.

[61] "Polypropylene", *Modern Plastics*, January 1960.

[62] "Polystyrene films in use", *Modern Packaging*, September 1958.

---

[63] "Plastics in disposables and expendables", *Modern Plastics*, April 1957.

[64] "Biggest hit in tape packs: polystyrene, to the tune of 19 million lb. in '68", *Modern Plastics,* June 1969.

[65] "Polyurethanes on the Way", *Modern Plastics,* August 1955.

[66] "Markets in the making for rigid foams", *Modern Plastics,* October 1957.

[67] "The Battle is ON in Flexible Foams", *Modern Plastics,* September 1957.

[68] "New directions for plastics applications", *Modern Plastics*, January 1957.

[69] "Flexible foams--past and future", *Modern Plastics*, September 1955.

[70] "A realistic look at plastics in building: Rigid PVC", *Modern Plastics,* February 1965.

[71] "Tomorrow is today for vinyls in construction", *Modern Plastics,* October 1960.

[72] *Modern Plastics* cost chart, January 1958.

[73] US Government published rubber prices; the state of rubber technology was well beyond that of PVC, and processing costs were undoubtedly lower.

[74] "Plastics Trends in Packaging", *Modern Plastics*, June 1963.

[75] "Biggest hit in tape packs: polystyrene, to the tune of 19 million lb. in '68", *Modern Plastics,* June 1969.

[76] Cost was explicitly listed as a factor in grocery sacks, pails, PET bottles, PET Custom bottles, PVC pipe, and rigid PP packaging.

[77] "POLYPROPYLENE upgrades housewares", *Modern Plastics,* December 1959.

[78] "Beverage cases: a coming market for HDPE", *Modern Plastics*, August 1961.

[79] "Polypropylene", *Modern Plastics* resin review, January 1960.

[80] "1961 Autos: proving ground for plastics", *Modern Plastics*, November 1960.

[81] "Polypropylene", *Modern Plastics* resin review, January 1964.

[82] "Why the fast growing market for BIG polyethylene containers?", *Modern Plastics*, June 1959.

[83] Stretch-blow molding was an entirely new processing technique that allowed biaxial stretching of PET so that oxygen molecules would not diffuse away.

[84] Microcool Technology was started by the author, based on research done for his master's thesis in Materials Science at MIT. Its failure was the impetus for this work.

[86] Musso, C.M., Rassey,L.W., "Microcool: Enabling Electronics Advancements", (business plan) April 2002.

[87] Eagar, T.W. and Musso, C.S., "Creation of Anisotropic Continuous Strand Metal Matrix Composite Material", ONR Proposal, submitted November 1999.

[88] Ciarlo, Livermore, 2001.

[89] Musso, C.S., "Development and Manufacture of Continuous Strand Metal Matrix Composites", unpublished Master's thesis, MIT, 2002.

[90] http://www.intel.com/technology/itj/q32000/articles/art_4.htm

[91] Histrory of Nanomagnetics came from three sources, listed in this and the next two references: www.nanomagnetics.com,

[92] Personal interview with Shantanu Bhagwat, a member of the board of directors of Nanomagnetics.

[93] Personal interview with Eric Mayes, CEO, Nanomagnetics.

[94] Hoinville, J., Bewick, A., Gleeson, D., Jones, R., Kasyutich, O., Mayes, E., Nartowski, A., Warne, B., Wiggins, J., Wong, K., "High density magnetic recording on protein derived nanoparticle", *Journal of Applied Physics,* 93, 7187-7189, 2003.

[95] "System cleans up almost any water", Stars and Stripes, June 21, 2004.

[96] Selectech story taken from personal interview with Tom Ricciardelli, Selectech CEO

[97] www.selectechinc.com

[98] See Christensen, C. M. and Raynor, M., *The Innovator's Solution*, Harvard Business School Press, 2003, p. 34.

[99] Farrell,J. and Saloner, G., "Standardization, Compatability. and Innovation", *Rand Journal 16*, Spring 1985. Cited in Liebowtiz, S.J., and Margolis, S.E., "The Fable of the Keys", *Journal of Law and Economics*, April 1990.

References—Chapter 5

[1] See www.Accelrys.com for details.

[2] "Polypropylene: where is it going?", *Modern Plastics,* August 1961.

---

[3] "Polyethylene grabs the spotlight", *Modern Plastics,* September 1955.

[4] "Bonanza for extruders", *Modern Plastics, find date.*

[5] *Facts and Figures of the US Plastics Industry,* Society of the Plastics Industry, 1995.

[6] Porter, Michael E., *Competitive Strategy,* New York: The Free Press (1980); quoted in "Switching Costs", Fisher School of Business supply chain management papers.

[7] Porter, Michal E., *Competitive Advantage: Creating and Sustaining Superior Performance,* New York: The Free Press (1985), p 59.

[8] Sussman, J., "Collected Views on Complexity in Systems", MIT ESD Working paper 2003-01.06.

[9] In addition to the two instruments reported here, the experts were asked to rate the applications, on a scale of 1-7, according to the risk faced by the application manufacturers in adopting the new material. However, the experts and the author judged this to be a very unreliable instrument, because the experts were unfamiliar with the changing legal liability climate in the 1950s-1990s. The instrument may be fruitful if restructured to provide a basis for understanding this climate, or if given to legal experts instead of materials experts.

[10] This may sound simplistic, but part count is a very common heuristic for determining cost and challenges of making a product. In fact, an important metric for lean, six sigma, and design for manufacturing techniques is step/part count reduction.

[11] The National Plastics Museum in Leominster, MA, does have a few of the original examples of the applications mentioned, but not enough for proposed analysis to be meaningful.

[12] Others materials engineers consulted include Professor Thomas Eagar, Raymundo Arroyave, and Joel Williams, all of the MIT Welding and Joining group.

[13] Moses, J. cited in Sussman, J., "Collected Views on Complexity in Systems", MIT ESD Working paper 2003-01.06.

[14] Cost of insertion may be a very effective and tractable proxy for measuring degree of change required in a value chain; exploring this relationship could be a fruitful area for future work.

[15] Estimate provided by Paul Lagace (MIT Professor of Aeronautics) in personal conversation.

[16] Obstfeld,M., Cumby, R., Huizinga, J., "Two-Step Two-Stage Least Squares Estimation in Models with Rational Expectations", NBER Technical Paper No. 11, March, 1981.

[17] Hoole, R., "Can You Reduce Your Supply Chain Complexity?", *PRTM's Insight Magazine,* May 2004.

[18] Porter, Michael E., *Competitive Strategy,* New York: The Free Press (1980); quoted in "Switching Costs", Fisher School of Business supply chain management papers.

[19] Wernerfelt, Birger, "Brand Loyalty and Market Equilibrium", *Marketing Science,* Vol. 10 No.3 (Summer 1991) p. 229.

[20] Klemperer, Paul, "Markets with Consumer Switching Costs", *The Quarterly Journal of Economics,* Vol. 102, No2, (May, 1987), 375-394.

[21] Ibid.

[22] Note that in this definition of value, improvement can be made either by reducing costs or by adding features (improving performance). It is unlikely that feature improvement will appeal to all consumers, but price reduction would appeal to rational ones.

[23] Personal conversation with Steve Cook, Dell Operations Director, January 2002.

[24] Rinfliesch, Aric and Heide, Jan B., "Transaction Cost Analysis: Past, Present, and Future Applications", *Journal of Marketing,* Vol. 61 (Oct 1997), 30-54.

[25] Ibid.

[26] See Christensen, Musso Research Technology Review paper, also Utterback/Abernathy 1975, and Henderson/Clark, 1989.

[27] Rinfliesch, Aric and Heide, Jan B., "Transaction Cost Analysis: Past, Present, and Future Applications", *Journal of Marketing,* Vol. 61 (Oct 1997), 30-54.

[28] Williamson, Oliver E., *The Economic Institutions of Capitalism: Firms, Markets, Relational Contracting.* New York: The Free Press (1985) p. 47.

[29] Donovan, Michael R., "Supply Chain Management III: Cracking the Bullwhip Effect", available at www.rmichaeldonovan.com.

[30] Utterback, James M. (1994). "Dominant Designs and the Survival of Firms", Chapter 2 in *Mastering the Dynamics of Innovation.* Harvard Business School Press, Boston. pp. 22-55

References—Chapter 6

[1] Definition provided by Jeff Whatcott, Senior Vice President, Macromedia.

[2] Scott, John, "Rational Choice Theory", in *Understanding Contemporary Society: Theories of The Present*, edited by G. Browning, A. Halchi, N. Hewlett, and F. Webster; Sage Publications, 2000.

[3] Personal conversation with Dr. Thomas Allen, Professor of Management at the MIT Sloan School of Management.

[4] Gobasu, Hakan and Wu, S. David, "Lead Time Coordination Between Marketing and Operations in an Internal Market", Working Paper, Manufacturing and Logistics Institute, Department of Industrial and Systems Engineering, P.C. Rossin College of Engineering, Lehigh University.

[5] Strong, A.B., *Plastics : Materials and Processing*, Columbus: Prentice Hall Publishing, 1996. P. 487-489.

[6] Eagar, Thomas, "Bringing New Materials to Market", Technology Review, February/March 1995.

[7] "Porsche Builds Composite Tennis Racquets", Porsche Press Release, November 23, 1998 (available at http://composite.about.com/)

[8] Based on information collected by author during visits to R^3 Composites, Sandy UT; Boeing Composites, Seattle, WA; Bombardier Aerospace Service Center, Windsor Locks, CT.

[9] Rinfleisch, Aric and Heide, Jan B., "Transaction Cost Analysis: Past, Present, and Future Applications", *Journal of Marketing*, Vol. 61 (Oct 1997), 30-54.

[10] Christensen, C.M., Musso, C.S, Anthony. S.D, "Maximizing Returns from Research", *Research-Technology Management,* July-August 2004.

[11] Ibid.

[12] von Hippel, E. and Tyre, M., "How Learning by Doing is Done: Problem Identification in Novel Process Equipment", *Research Policy,* vol. 24, 1, 1995.

[13] Personal conversation with Thomas Eagar, 2002.

[14] "Here are the first commercial Delrin applications", *Modern Plastics*, November 1959.

[15] Kline, G.M., "Polyacetal resin—a new engineering material", *Modern Plastics* technical section, December 1957.

[16] Alsup, R.G. et al, "The Effect of Solvents on High molecular Weight, Stable Acetal Resins", in Journal of Applied Polymer Science, 1-2 (1959).

[17] Kern, V.W., Cherdron, H. "Der Abbau von Polyoxymethylenen", in Makro,Chem. 112 (1960).

[18] Oner, M. and White, D. "Investigation of the degradation of commercial polyoxymethylene copolymer in water service applications", in Polymer Degradation and Stability 40 (1993).

[19] Broutman, L.J. and Kamyowski, G.W., "Surface Embrittlement of Polyacetals in Chlorinated Water", ANTEC '94 Conference Proceedings, Society of Plastics Engineers (1994).

[20] Stivala, S. et al., "Mechano-chemical degradtion of polyacetal fittings in potable water applications", ANTEC '94 Conference Proceedings, Society of Plastics Engineers (1994).

[21] Kemmer, F. (ed), The NALCO Water Handbook, 2nd ed., New York: McGraw-Hill. P. 2.2, 2.3 (1988)

[22] Bregar, B. "Settlement looms over PB pipe battle", Plastics News 7-37 (13 Nov. 1995).

[23] Bregar, B. "Settlement looms over PB pipe battle", Plastics News 7-37 (13 Nov. 1995).

[24] von Hippel, E. and Tyre, M., "How Learning by Doing is Done: Problem Identification in Novel Process Equipment", *Research Policy,* vol. 24, 1, 1995.

[25] Allen, Thomas J. "Distinguishing Science from Technology" Human Side of Managing Technological Innovation, Ralph Katz, Ed. Oxford University Press, pp. 307-319.

[26] Personal communication with Richard Maloney, maintenance manager at ADM Cocoa, Mansfield, MA.

[27] Personal communication with Professor Fred McGarry, MIT Polymer Scientist, 2001.

[28] Personal communication with Gerry Estes, Vice President, Lord Corporation.

[29] Liebwotiz, S.J., Magolis, S.E., "Network Externalities (Effects)", in The New Palgrave's Dictionary of Economics and the Law, MacMillan, 1998.

[30] Systems-scale effects explained in David, Paul A. (1985). "Clio and the Economics of QWERTY", Economic History Vol. 75 No. 2, AEA Papers and Proceedings.

[31] Singer, P., "In the Materials Age, What Happens to Economies of Scale?", *Semiconductor International,* 7/1/2004.

---

[32] Utterback, James M., and Abernathy, William J. (1975), "A Dynamic Model of Process and Product Innovation", Omega, the International Journal of Management Science, Vol. 3, No. 6. pp. 639-656.

[33] Herstatt, C. and Von Hippel, E., "From Experience: Developing New Product Concepts Via the Lead User Method: A Case Study in a 'Low Tech' Field", *Journal of Product Innovation Management*, 9, 1992.

[34] Thomke, S. and von Hippel, E., "Customers as Innovators: A New Way to Create Value", *Harvard Business Review,* April 2002.

[35] Von Hippel, E., "Perspective: User Toolkits for Innovation", *Journal of Product Innovation Management,* July 2001.

[36] Von Hippel, E. and Katz, R., "Shifting Innovation to Users Via Toolkits", MIT Sloan School of Management Working Paper 4232-02, April 2002.

[37] "Plastics in 1958:SLOW START, STRONG FINISH", *Modern Plastics*, January 1959.

[38] "Resins UP a Billion Pounds!", *Modern Plastics,* January 1956.

[39] Greer, J., "Phillips' ties to Hula Hoop brings rich history to Conoco marriage", *Houston Business Journal*, November 20, 2001.
http://inventors.about.com/gi/dynamic/offsite.htm?site=http://www.phillips66.com/about/hula.html.

[40] "POLYETHYLENE Grabs the Spotlight", *Modern Plastics,* September 1955.

[41] Thomas L. Cubbage, then VP of chemicals at Phillips, quoted in "Hula Hoops Craze Helps Create Market for Marlex", Official Phillips Petroleum Company History.

[42] "Over 4 billion pounds!", *Modern Plastics*, January 1957.

[43] Ibid.

[44] Ibid.

[45] Hula Hoops Craze Helps Create Market for Marlex", Official Phillips Petroleum Company History.

[46] "Richard Knerr & Spud Merlin", Lemelson-MIT Program Inventor of the Week Archive, August 1997.

[47] Hula Hoop picture courtesy of Wham-O company, available at http://www.wham-o.com/content/hulahoop.html .

[48] Lori Lynn Lomeli holds the world record for hula hoping—she has successfully twirled 82 hoops at once. Picture courtesy of her website, http://www.hula-hoops.com/ .

[49] "Bonanza for Extruders", *Modern Plastics*, November 1958.

[50] Ibid.

[51] In fact, the original idea for hula hoops came from Australia, where bamboo was used.

[52] Hula Hoops Craze Helps Create Market for Marlex", Official Phillips Petroleum Company History.

[53] From encyclopedia article wikipedia.com

[54] "Bonanza for extruders", *Modern Plastics*, November 1958.

[55] Hula Hoops Craze Helps Create Market for Marlex", Official Phillips Petroleum Company History.

[56] "Bonanza for extruders", *Modern Plastics*, November 1958.

[57] "Plastics in 1958:SLOW START, STRONG FINISH", *Modern Plastics*, January 1959.

[58] Richard Knerr & Spud Merlin", Lemelson-MIT Program Inventor of the Week Archive, August 1997.

[59] Hounshell, D.A., Smith, J.K.,*Science and Corporate Strategy:DuPont R&D, 1902-1980*, Cambridge University Press (1988), p. 259.

[60] Meikle, J.L., *American Plastic: a cultural history*, Rutgers University Press (1997), p. 137.

[61] *Statistical Abstract of the United States* (Washington: US Government Printing Office, 1939), p 812. (Quoted in Hounshell, p.257).

[62] Meikle, p.137.

[63] Hounshell, p. 260-265.

[64] Meikle, 137.

[65] Hounshell, 265.

[66] Hounshell, 272.

[67] Los Alamos National Laboratory Chemistry Division element pages, available at http://pearl1.lanl.gov/periodic/elements/22.html.

[68] "Salient Attractive Characteristics of Titanium Alloys are Outlined", article in American Metals Market, January 20, 1951.

[69] Abkowitz, Stanley, "The Emergence of the Titanium Industry and the Development of the Ti-6Al-4V Alloy: Collections and Recollections", JOM Monograph Series, Volume 1, a publication of the Minerals, Metals, and Materials Society (1999).

[70] Ibid.

---

[71] Ibid, p. 14.
[72] Richard Simmons (president emeritus of Allegheny Ludlum) reported the first application of titanium in aircraft to be the wing tanks of the Dougls DC-7 aircraft, introduced May 1953 (introduction date supplied by Boeing-McDonnell Douglas history, available at http://www.boeing.com/history/mdc/dc-7.htm). Simmons quoted in Abkowitz, p. 14.
[73] "Looking toward 1948", *Modern Plastics*, January 1948.
[74] Dow and Monsanto led the way in defending the reputations of plastics with national campaigns. See "1948. . .and the future", *Modern Plastics,* January 1949.
[75] Personal communication with Paul Lagace, MIT Professor of Aeronautics and Astronautics.
[76] Pitcher, A.E. (president of Plastics Materials Manufacturer's Association), letter to the editor, *Modern Plastics,* January 1942.
[77] Pitcher, A.E. (president of Plastics Materials Manufacturer's Association), letter to the editor, *Modern Plastics,* January 1943.
[78] "The first year of war—and the next", *Modern Plastics,* January 1943.
[79] Kinnear, Ronald (president, Society of Plastics Industry), letter to the editor, *Modern Plastics,* January 1943.
[80] Carman, F.H., "How plastics have gone to war", *Modern Plastics,* January 1943.
[81] Kline, G.M., "Advances in plastics during 1944", *Modern Plastics,* January 1945.
[82] "The first year of war, and the next", *Modern Plastics,* January 1943.
[83] Ibid.
[84] Ibid.
[85] De Bell, J.M., "Thermoplastics (in Advances in Plastics During 1940)", *Modern Plastics*, January 1941.
[86] "Close to 4 Billion Pounds!", *Modern Plastics* , January 1957.
[87] "Over 4 billion pounds", *Modern Plastics*, January 1958. (implied—MP said that tougher PS was needed for further penetration in refrigerator liners).
[88] "Production tops 7.8 billion pounds. . .sales hit 7.4", *Modern Plastics*, January 1963.
[89] "Plastics top 5 1/2 billion-pound mark", *Modern Plastics,* January 1960.
[90] "Prices firm up. . .markets expand. . .volumes soar", *Modern Plastics*, January 1964.
[91] "Plastics outpace appliance growth better than three-to-one", *Modern Plastics*, January 1968.
[92] Christensen, C.M. and Raynor, M.E., *The Innovator's Solution,* Boston: Harvard Business School Press, 2003. p 44.
[93] Ibid.
[94] Ibid, p. 46
[95] Ibid. p. 50

References—Chapter 7

[1] The basis of commodity competition is process innovation, which is focused on reducing costs, improving reliability, and increasing consistency. The skills required are highly operational in nature, and seem quite different from the creative and developmental skills required for innovation of materials. There are emergent organizational models in which the two coexist, but they have serious drawbacks, and usually result in domination of one side by the other.
[2] Christensen, C.M, Rayner, M., "How Can We Beat Our Most Powerful Competitors", Chapter 2 in *The Innovator's Solution*, Boston: Harvard Business School Press, 2003.
[3] See note on plastics in table 2-2 of *The Innovator's Solution.*
[4] "Plastics Pipes Invade New Markets", *Modern Plastics*, March 1950.
[5] Ibid.
[6] "Plastics vs. corrosion", *Modern Plastics,* September 1953.
[7] "Plastics pipe invades new markets", *Modern Plastics,* March 1950.
[8] "6000 miles of pipe", *Modern Plastics*, July 1957.
[9] "Futures for PLASTICS PIPE", *Modern Plastics,* March 1954.
[10] Ibid. (see section on PVC in oil fields).
[11] Ibid (see "Potentials and Cautions).
[12] "Plastics pipe: a new plateau", *Modern Plastics,* August 1962.
[13] Ibid.

---

[14] Ibid.
[15] "Pipe confounds doubters. . .up 25% in '70", *Modern Plastics,* September 1970.
[16] Ibid.
[17] United States Tariff Commission, *Synthetic Organic Chemicals*, 1970.
[18] "United States Resins Report.", *Modern Plastics,* January 1998.
[19] "Automotive Plastics: 1956",*Modern Plastics,* March 1956.
[20] "Plastics' stake in building", *Modern Plastics*, September 1958.
[21] "A Time for Decisions", *Modern Packaging*, April 1962.
[22] "Breakthrough for polypropylene", *Modern Packaging,* September 1963.
[23] Major players included Dow, DuPont, Phillips, Koppers, Monsanto. All had previous experience in plastics.
[24] "Tomorrow is today for VINYLS in construction", *Modern Plastics*, October 1960.
[25] "The plastics pipe industry is booming, but...", *Modern Plastics,* October 1967.
[26] "A new look at plastics pipe", *Modern Plastics*, May 1965.
[27] "Who writes the building codes?", *Modern Plastics*, April 1977.
[28] "The plastics pipe industry is booming, but...", *Modern Plastics,* October 1967.
[29] "A new look at plastics pipe (part 1), *Modern Plastics,* May 1965.
[30] "The plastics pipe industry is booming, but...", *Modern Plastics,* October 1967
[31] Ibid. .
[32] "Plastics pipe: a new plateau (part 2)", *Modern Plastics*, September 1962.
[33] "Materials '90", *Modern Plastics* , January 1990.
[34] Personal communication with research center of major plastics manufacturer (name cannot be released because of legal concerns).
[35] "Plastics pipe: a new plateau", *Modern Plastics*, August 1962.
[36] "Plastics Pipes Invade New Markets", *Modern Plastics*, March 1950.
[37] "Plastics vs. Corrosion", *Modern Plastics*, September 1953.
[38] "Plastics pipe: an new plateau (part 2)", *Modern Plastics,* September 1962.
[39] "A new look at plastics pipe (part 1)", *Modern Plastics,* May 1965.
[40] Ibid.
[41] "A new look at plastics pipe (part 1)", *Modern Plastics,* May 1965.
[42] Author experience as mobile home installer, 1988-1993.
[43] Personal communication with Frederick J. McGarry, MIT Professor of Materials Science.
[44] "Brakes on growth in store for 1988", *Modern Plastics,* January 1988.
[45] "Beverage cases: coming market for high-density PE", *Modern Plastics,* August 1961.
[46] See de Neufville, R., *Applied Systems Analysis, Engineering Planning and Technology Management*, McGraw Hill, 1990.
[47] Applications often exceed the needs of their customers. This is the basis of disruptive attack.
[48] Arnold, S., Hendrichs, N., Field, F.R. III, Clark, J.P, "Competition Between Polymeric Materials and Steel in Car Body Applications", *Materials and Society*, vol. 13, no. 3, 1989.
[49] Mangin, C.G.E., de Neufville, R., Field, F.R. III, Clark, J., "Defining Markets for New Materials: Engineering Methodology with Case Applications", R*esources Policy,* vol.21, no.3, 1995.
[50] Hong Ng, L., Field, F.R. III, "Materials for Printed Circuit Boards: Past Usage and Future Prospects", *Materials and Society*, vol. 13, no. 3, 1989.
[51] Personal communication with plumbing drafter, Champion Homes.
[52] Prices taken from 2004 Charlotte Pipe and Foundry Company price list "Plastic Pipe for Drainage and Pressure Applications".
[53] Based on poundage usage listed in "United States Resins Report.", *Modern Plastics,* January 1999.
[54] "Plastic pipe market share in North America", *Plastics News,* May 27, 2003.
[55] "Automotive Plastics: 1956", *Modern Plastics*, March 1956.
[56] Personal communication with Larry Bell, Director of Automotive Business, Nypro, Inc. March 2004.
[57] "Engineering plastics in the European auto industry", *Plastics News,* October 8, 2003.
[58] "Prices firm up. . .markets expand. . .volumes soar", *Modern Plastics*, January 1964.
[59] "Key markets post solid gains in 1993.", *Modern Plastics*, January 1994.
[60] "Plastics 1964: soaring growth. . .dynamic complexity. . .new directions", *Modern Plastics*, January 1965.

---

[61] “Resins 1992: Supply Patterns are Changing”, *Modern Plastics,* January 1992.
[62] See resin tables in “Resins ’98: Sea change in supply”, *Modern Plastics*, January 1998.
[63] "Resin sales rise toward 61.5 billion lb.", *Modern Plastics*, January 1991.
[64] "1991 Resin sales took a step back.", *Modern Plastics,* January 1992.
[65] "A year of robust growth, rising costs.", *Modern Plastics*, January 1995.
[66] See Maine, E.M.A.; Ashby, M.F. “An Investment Methodology for New Materials”. Materials and Design 23, 2002. PP 297-306.

References—Chapter 8

[1] United States House Committee on Science, “Unlocking Our Future: Toward a New National Science Policy”, report to Congress, September 24, 1998.
[2] Allen, Thomas J. “Distinguishing Science from Technology” *Human Side of Managing Technological Innovation*, Ralph Katz, Ed. Oxford University Press, pp. 307-319.
[3] Utterback, J.M., “Innovation in Industry and the Diffusion of Technology”, *Science,* New Series, Feb. 15, 1974.
[4] Fong, G.R., “Repositioning the Advanced Technology Program”, *Issues in Science and Technology,* Fall 2001.
[5] United States House Committee on Science, “Unlocking Our Future: Toward a New National Science Policy”, report to Congress, September 24, 1998.

[6] National Science Foundation, Division of Science Resources Statistics,*Federal Funds for Research and Development: Fiscal Years 1970–2003,*Arlington, VA (NSF 04-335) [August 2004]

[7] Ibid.
[8]

[9] See “Unlocking Our Future” and “Repositioning ATP”.

[10] National Science Foundation, Division of Science Resources Statistics, *Federal Obligations for R&D and R&D Plant Expected to Reach Over $105 Billion in FY 2004,*Arlington, VA (NSF 04-331) [July 2004]

[11] Marburger, J.H. and Daniels, M.E., “FY 2005 Interagency Research and Development Priorities”, Memorandum from Executive Office of the President, June 5, 2003.
[12] Stanley, M.G., “The Advanced Technology Program in Partnership with NIST and the Nation”, Executive Briefing, available at http://www.atp.nist.gov/atp/presentations/atp_overview/overview.pdf .
[13] Ibid.
[14] Fong, G.R., “Repositioning the Advanced Technology Program”, *Issues in Science and Technology,* Fall 2001.
[15] From United States Small Business Administration SBIR/STTR page, http://www.sba.gov/sbir/indexsbir-sttr.html.
[16] “SBIR/STTR Four Course Overview”, available at http://www.sba.gov/sbir/SBIRSTTR_3CourseFullOverview.ppt
[17] “SBIR Awardees for Fiscal Year: 1998”, Small Business Administration, available at http://www.sba.gov/gopher/Innovation-And-Research/Awd98/awd98all.txt .
[18] “HBT Amplifier Gains from InGaP Technology”, *Microwaves and RF,* December 2003.
[19] Hula hoop reference
[20] “SBIR/STTR Four Course Overview”, available at http://www.sba.gov/sbir/SBIRSTTR_3CourseFullOverview.ppt
[21] “FY 2002 Appropriation for National Institute of Standards and Technology”, *FYI: The American Institute of Physics Bulletin of Science Policy News*, November 19, 2001.
[22] National Science Foundation, Division of Science Resources Statistics, *Federal Obligations for R&D and R&D Plant Expected to Reach Over $105 Billion in FY 2004,*Arlington, VA.
[23] This problem is probably much more important in widespread competition than in the enabler phase, but it is worth mentioning.
[24] Personal communication with Stan Abkowitz, Dynamet.

---

[25] These databases are very popular in plastics. Examples include Matweb and IDES Prospector.

[26] Personal communication with Oracle Database representative Bryan Wise, 17 Oct 2004.

[27] Gans, J.S. and Stern, S., "The Product Market and the Market for "Ideas": Commercialization Strategies for Technology Entrepreneurs", *Research Policy,* February 2003.

[28] Foster, R.N., 1986. Innovation: The Attacker's Advantage. Summit Books, New York

[29] See Christensen, C.M., *The Innovator's Dilemma,* Harper Business, 1997.

[30] Gans, J.S. and Stern, S., "The Product Market and the Market for "Ideas": Commercialization Strategies for Technology Entrepreneurs", *Research Policy,* February 2003.

[31] Ibid.

[32] For more discussion on this subject, see , Cheeseborough, H.W., and Teece, D. J., "When is Virtual Virtuous? Organizing for Innovation", *Harvard Business Review* (January-February 1996).; the integration literature of Williamson is also helpful—see Williamson, Oliver E., *The Economic Institutions of Capitalism: Firms, Markets, Relational Contracting.* New York: The Free Press (1985);

[33] Christensen, C.M., Talk on disruptive technologies, given to the MIT Leaders for Manufacturing Program, Spring 2002.

[34] Gans, J.S. and Stern, S., "The Product Market and the Market for "Ideas": Commercialization Strategies for Technology Entrepreneurs", *Research Policy,* February 2003. This paper has been cited several times in this section; the author considers it one of the finest papers on innovation ever written.

[35] Ottolenghi, M. and Crespi, C., "What's with polypropylene", *Modern Plastics,* March 1958.

[36] McGrew, F.C., The polyolefin plastics field—present technical status", *Modern Plastics,* March 1958.

[37] Gans, J.S. and Stern, S., "The Product Market and the Market for "Ideas": Commercialization Strategies for Technology Entrepreneurs", *Research Policy,* February 2003.

[38] Ibid.

[39] The author has been in the materials science department at MIT for five years, including the latter part of the Internet/venture capital boom. Here, in the best university in the country for materials science and a hotbed of markets for ideas, talk of a market for ideas for materials has never been heard by the author. There is some venture capital activity in materials, but the liquidity event is never a sale to a materials producer. It is a sale to an applications manufacturer or long term entry into the product market. It should be noted that electronic materials might be an exception, but again, they were sold to application manufacturers.

[40] Gompers, P.A., and Lerner, J., "What Drives Venture Capital Fundraising?", Harvard Business School working paper 9899, August 1998.

[41] BBC report, "Making History: Bronze Age Smelting", available at www.bbc.co.uk/educatin/beyond/factshseets/makhist/makhist3_prog5a.shtml .

[42] US Economic Census, available at www.census.gov, NAICS codes 325211, 331.

[43] Ibid, NAICS codes 332,3261,325211,331.

[44] Ibid, NAICS codes 31-33.

References—Chapter 9

[1] This is the most obvious because it is so prevalent in the assembled products and software industries.

[2] Cheesborough, H.W., Teece, D. J., "When is Virtual Virtuous? Organizing for Innovation", *Harvard Business Review*, January-February 1996.

[3] Christensen, Clayton M.; Raynor, Michael, and Verlinden, Matthew. "Skate to Where the Money Will Be", *Harvard Business Review*, November 2001.

[4] Christensen, C.M., Musso, C.S., and Anthony, S.D., "Maximizing Returns from Research", *Research Technology Management,* July-August 2004.

[5] Montrey, H. and Utterback, J.M, "Current status and future of structural panels in the wood products industry", *Technological Forecasting and Social Change*, August 1990.

[6] Abernathy, W.J., and Clark, K.B. . "Innovation: Mapping the Winds of Creative Destruction", *Research Policy (14),*1985..

[7] Christensen, C.M., *The Innovator's Dilemma*, Harper Business, 1997.

[8] Foster, R. N. "The S-Curve: A New Forecasting Tool", Chapter 4 in *Innovation: The Attacker's Advantage,* Summit Books, Simon and Schuster, 1985.

References—Appendix A

[1] "Gallon of Milk in Polyethylene", *Modern Packaging,* August 1962.
[2] "New economy in plastic bottles", *Modern Packaging,* Sep 1958.
[3] "Big Push on Plastics", *Modern Packaging,* October 1959.
[4] "New Champ of detergent bottles: high-density PE", *Modern Plastics,* August 1959.
[5] "Sure. Film markets are big, but is there any potential left?", *Modern Plastics,* January 1972.
[6] "Plan your line for the payoff in Extruding film grocery bags", *Modern Plastics,* April 1973.
[7] "Sure. Film markets are big, but is there any potential left?", *Modern Plastics,* January 1972.
[8] "Plan your line for the payoff in Extruding film grocery bags", *Modern Plastics,* April 1973.
[9] "What's really happening in paperlike HDPE film?", *Modern Plastics,* March 1978
[10] "Plastics get rid of the garbage", *Modern Plastics, D*ec 1971
[11] "Futures for plastics pipe", *Modern Plastics,* March 1954.
[12] "Why the fast growing market for BIG polyethylene containers? *Modern Plastics,* June 1959.
[13] "Beverage cases: Coming market for HDPE", *Modern Plastics,* August 1961.
[14] "Why the fast growing market for BIG polyethylene containers?", *Modern Plastics,,* June 1959.
[15] Ibid.
[16] "Polyethylene packages in use", *Modern Packaging,* January 1947.
[17] "Great Packaging Discoveries 7-Extrusion Coating", *Modern Packaging,* August 1959.
[18] "Polyethylene packages in use", *Modern Packaging,* January 1947.
[19] Boskirk, R.L. (ed.), "Film sets the pace in low density PE, but what's ahead for film?", *Modern Plastics,* July 1970.
[20] "The new bottle equation: GS+mrc+NPt=rH", *Modern Plastics,* April 1975.
[21] "Beyond the soft drink bottle: New markets in sight for PET*",* *Modern Plastics,* April 1978.
[22] Resins 1980, *Modern Plastics,* January 1980.
[23] "Why the big market for monofilaments?", *Modern Plastics,* June 1961.
[24] "Polypropylene upgrades housewares", *Modern Plastics,* December 1959.
[25] "Polypropylene", *Modern Plastics,* January 1964.
[26] "Polypropylene: where is it going?", *Modern Plastics,* August 1961.
[27] "Polypropylene", *Modern Plastics,* January 1960.
[28] "1961 Autos: proving ground for plastics", *Modern Plastics,* November 1960.
[29] "Polypropylene", Modern Plastics, January 1960.
[30] "Polystyrene films in use", *Modern Packaging,* September 1958.
[31] "Plastics in disposables and expendables", *Modern Plastics,* April 1957.
[32] "Biggest hit in tape packs: polystyrene, to the tune of 19 million lb. in '68", *Modern Plastics,* June 1969.
[33] "Polyurethane and polyester FOAMS", *Modern Plastics,* November 1954.
[34] "Polyurethanes on the way", *Modern Plastics,* August 1955.
[35] "Polyurethanes on the way", *Modern Plastics,* August 1955.
[36] "New direcctions for plastics applications", *Modern Plastics,* January 1957.
[37] "The Urethanes Grow Up--part 2", *Modern Plastics,* April 1959.
[38] Bushnell, C.E., "Thermal Insulation: where foams fit in", Modern Plastics, October 1963.
[39] "Flexible foams--past and future", *Modern Plastics,* September 1955.
[40] "Plastics vs. corrosion", *Modern Plastics,* September 1953.
[41] "Tomorrow is today for vinyls in construction", *Modern Plastics, O*ctober 1960.
[42] "Tomorrow is today for vinyls in construction", *Modern Plastics, O*ctober 1960.
[43] Macht, M.L. and Paine, H.W., "Thermoplastic Resins", *Modern Plastics,* January 1939.
[44] "1949. . .and the Future", Modern Plastics, January 1948.
[45] "Futures for PLASTICS PIPE", Modern Plastics, March 1954.

References—Appendix B-E

[1] References for applications listed in appendix tables.