The Critical Role of Manufacturing-Process Innovation on Product Development Excellence in High-Technology Companies

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ABSTRACT

Few managers of high-technology companies view manufacturing-process development as primary source of competitive advantage. For the last two decades trends have shown an increasing number of high-tech industries outsourcing manufacturing completely to third-party contractors or joint-venture partners. In doing so, companies have tried to avoid the risks of investing in expensive manufacturing plants and losing focus on product research and development (perceived as their true source of advantage). Research on the pharmaceutical industry, over the period between 1985 and 1995, suggests that such thinking is often costly and potentially dangerous to the competitive health of high-tech companies. Studies highlighted a pattern where companies that built organizational capabilities to support innovative, fast, efficient and effective process development, could introduce new products more quickly, with higher yields and controlled processes that gave them a significant cost advantage over competitors. And, surprisingly, they often required less capital investment and fewer development resources than their more conventional competitors.

The discovery of this pattern in pharmaceuticals, an industry in which product innovation is paramount, stimulates us to look at other high-technology industries for similar patterns.

This thesis explores a framework to understand how manufacturing-process innovation can be a hidden advantage to high-tech companies competing on the basis of product innovation. It also provides examples of companies, in a variety of high-tech industries, which exhibit a pattern similar to the one found in the pharmaceuticals and have accrued tremendous advantages by treating process development as an integral part of the product development cycle.

Thesis Supervisor: Edward B. Roberts
Title: David Sarnoff Professor of Management of Technology

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Dedication

To my wife Monica,
Her commitment to my dreams and me can never be compensated for…
I am grateful to her for not allowing me to forget
the other important things in life.
I will always love her.

To our children, Carolina, Alejandro, and Ignacio,
Who make it all worthwhile!

To my parents,
Who were the most important teachers and role models
during much of my own development.

To my colleagues at Schlumberger,
Who have made possible for me to live my deepest beliefs at work,
and to be part of the Schlumberger adventure.

> *"To have an independent mind,*
> *To think for oneself,*
> *Not to follow fashions,*
> *Not to seek honor or decorations,*
> *Not to become part of the establishment"*
> *By Marcel Schlumberger*

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Chapter 1: Introduction

Academics and practitioners alike increasingly recognize the competitive power of new product development. In the last decade alone, a flood of articles and books has been written on how to make product development cycles both faster and more effective. MBA and executive-level courses on new product development proliferated. Major consulting firms have made product development a staple of their client services, while hundreds of "boutique" consultancies now specialize in managing product development. Across a wide range of industries, it would be hard to find senior managers who are not actively trying to improve their companies' product development performance. For the last few years, efforts to improve product development have received the kind of resources and attention that productivity and quality improvement received during the 1980s.

The development of new manufacturing process technologies, however, has generated much less excitement among academics and practitioners, let alone the public at large. Partly because we, as consumers, often come into direct contact with innovative new products in our daily lives but rarely glimpse the manufacturing processes hidden behind factory walls. But there are deeper reasons. During the 1990s, there was a growing perception that manufacturing was no longer a necessary strategic competence, at least for companies that competed in technologically dynamic environments. Process development and manufacturing superiority have come to be viewed as strategic competencies in precisely those "mature" industries in where U.S., European, and increasingly even Japanese companies find themselves at a comparative disadvantage relative to rivals from newly industrialized countries. Indeed, since the 1990s, many U.S. companies turned to new product development as a way to compete against offshore rivals with stronger manufacturing competencies.

In an effort to focus resources on core competencies, many companies in industries such as computers, pharmaceuticals, biotechnology, and electronics have been increasingly turning over manufacturing of entire products, not just components, to third-party contract manufacturers. A growing number of senior executives in high-tech industries appear to agree with William Joy, cofounder of Sun Microsystems, who said, “The creative path of design is going to add value . . . [Because manufacturing prowess can be bought from any number of vendors], intellectual property is the asset for the 1990s”[1], and with a magazine article from 1994, that citing numerous examples of how innovative companies successfully outsourced production, concluded, “In the new economy, the most successful 'industrial' companies will often be those that don't make their own products”[2].

This dichotomy between “high-tech” industries, where R&D capabilities predominate, and more “mature”, manufacturing intensive industries is very apparent in the academic literature. If we review leading texts on manufacturing strategy (e.g. Hayes, Wheelwright, and Clark 1988), several examples and cases from “mature” industries are presented, but relatively few from technologically dynamic ones. Similarly, research on manufacturing productivity, quality, flexibility, and process innovation has tended to focus on technologically mature environments.

Likewise, the strategic role of manufacturing is barely mentioned in discussions of high-tech competition (e.g. Scherer 1992). Here the focus tends to be on the determinants of R&D performance as measured by patents, number of innovations, R&D productivity, or lead times to launch new products. Beyond rectifying deficiencies in manufacturing performance through better communication between R&D and plants, and through adopting design-for-manufacturability practices and philosophies, there is little discussion of how strong process development capabilities might lead to better competitive outcomes or might enhance a company's product development performance.

1.1 Thesis Business Context

It is hard to argue with the principle that different types of capabilities may be important in different industries and that managers should focus on those activities offering the greatest competitive leverage. Yet the perception that superior manufacturing competency fails to contribute to (or may even hinder) product development performance may mask a deeper reality: lurking behind many new product introductions is the development of complex, novel, and enormously costly production technologies. The latest generations of computer memory chips, for example, require production facilities costing more than $2 billion but with useful economic lives of just a few years. Moreover, the true value of these processes lies not just in the physical aspects (the buildings, tooling, and machinery), but also in the intellectual capital (information about tool designs, reaction conditions, assembly sequences, and quality assurance methods) created by scores of process development scientists and engineers. It comprises knowledge difficult to observe and imitate.

“Even some relatively low-tech new product introductions can require the development of highly sophisticated process technologies. Gillette engineers, for example, spent seven years, $75 million in R&D, and $125 million in capital to develop the manufacturing process for the Sensor razor system. The novel product design required the development of an entirely new process technology for making the cartridge heads, including a laser spot-welder that could operate at unprecedented speeds"[3].

From high-tech to low-tech environments, commercializing innovative and complex product designs often requires the development and successful implementation of innovative process technologies. How quickly and effectively a company can develop and implement such process technologies increasingly shapes the overall cost, timeliness, and results of new product introductions, and the overall competitive success of the company. Process development, then, can be the hidden leverage in product development performance.

Although many companies still regard manufacturing as a bottleneck (rather than a contributor to) in product development, most recognize that their manufacturing organizations should not remain passive observers of the development process. They discontinued the old approach of R&D "throwing designs over the wall" into manufacturing and have adopted multiple approaches to ensure that the designs of new products are compatible with existing manufacturing capabilities. Despite these improvements, the manufacturing organizations still play a fairly passive role, as they are considered to have accomplished their goals when they do not complicate and impede the product development "too badly".

But there is a growing number of companies that have recognized that their manufacturing organizations have to play a much more proactive role in the product development process and that manufacturing can play a critical role on enhancing their overall innovative capabilities. They have found that manufacturing excellence, commonly viewed as critical only in more mature industries, such as steel and commodity chemicals, where low cost is the primary differentiator, also provides strategic leverage in high-tech industries, where cost is not the highest competitive priority.

1.2 Thesis Summary

This thesis explores a framework to understand how manufacturing-process innovation can be a hidden advantage to high-tech companies competing on the basis of product innovation. The framework was developed around the "virtuous pattern" observed in the pharmaceutical and biotechnology industries (Pisano and Wheelwright 1995; Pisano 1997), where companies that built organizational capabilities to support innovative, fast, efficient and effective process development, could introduce new products more quickly, with higher yields and controlled processes that gave them a significant cost advantage over competitors. And, surprisingly, they often required less capital investment and fewer development resources than their more conventional competitors.

This thesis then examines a group of companies, in a variety of high-tech industries, in order to identify the same "virtuous pattern" characteristics and to gain management insights on how to develop manufacturing-process capabilities and to unlock its potential in achieving a higher product development performance. The examination is focused on making a compelling case for the critical and strategic role of manufacturing-process innovation and development, and on highlighting management practices to develop these process capabilities. Based on actual situations, the case studies and notes portray a set of management dilemma related to process development, the rich environment in which process development takes place, and the associated management challenges.

1.3 Thesis Outline

The next chapter of the thesis reviews the literature in industrial innovation in general, and manufacturing-process innovation in particular. Then the study on the pharmaceutical industry carried by Pisano and Wheelwright in the 1990s (Pisano and Wheelwright 1995, Pisano 1997) is reviewed. Finally, the literature on learning curve, and product development are briefly reviewed to outline their application in process development.

The third chapter presents a capabilities-based Manufacturing-Process Innovation Framework that effectively explores the determinants of process development performance, its critical role on enhancing product development performance and the management challenges in linking both process and product development activities.

The fourth and fifth chapters present two case studies to gather exploratory data about the framework and the associated management challenges. Given the time and resources available to the author, statistical analysis and investigation of phenomenon boundaries were not possible; the focus is on illuminating elements of the framework. The sixth chapter follows on the same objectives of the two previous chapters but is not presented in a case study format. The data presented in all three chapters comes largely from relevant literature and documentation publicly available; and it is confirmed by a series of interviews with management (16 managers were interviewed, with interviews ranging from 1 to 2 hours), and observations from visits to manufacturing and product development facilities (6 facilities were visited, in four different states in the U.S.).

Finally, the seventh chapter provides some conclusions and recommendations for management.

Chapter 2: Literature Review

This chapter will begin by reviewing the literature on industrial innovation in general, and then manufacturing-process innovation in particular. A fair amount of research has been undertaken since the late 1970s on the first topic (Abernathy 1978, Van Hippel 1988, Utterback 1994, Christensen 1997, Christensen and Raynor 2003), while academic research on manufacturing-process innovation and development is fairly recent and not prolific (Pisano and Wheelwright 1995, Pisano 1997, and Hayes, Pisano, Upton and Wheelwright in 2005). These later work provide the foundations and structure for the concepts and ideas discussed on this thesis.

The chapter will continue with a review of the study on the pharmaceutical industry and its context.

And finally, the chapter will conclude with a brief review of the literature on learning curve and product development, ant their application to process development.

2.1 The Product Life Cycle Model

The idea that process development becomes increasingly important as industries mature dates back to the work of Abernathy and Utterback in 1978, who developed the product life cycle of innovation (see figure 2.1). Their model posited that during the early phases of a product's life, when its basic concepts were still being formed, the rate of product innovation would exceed that of process innovation. Once producers and consumers have gained enough experience with alternative versions of the product, a "dominant design" would emerge and opportunities for radical product innovation would begin to recede. At that point, competitors would shift to producing similar designs at lower cost and firms would focus on process innovation. Thus according to the product life cycle model, process innovation becomes important only later in the life of an industry.

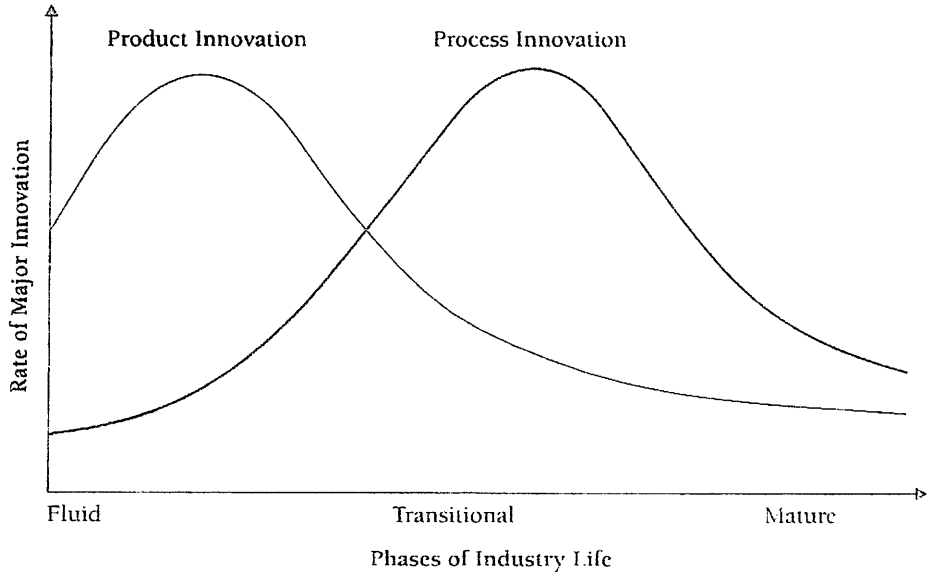


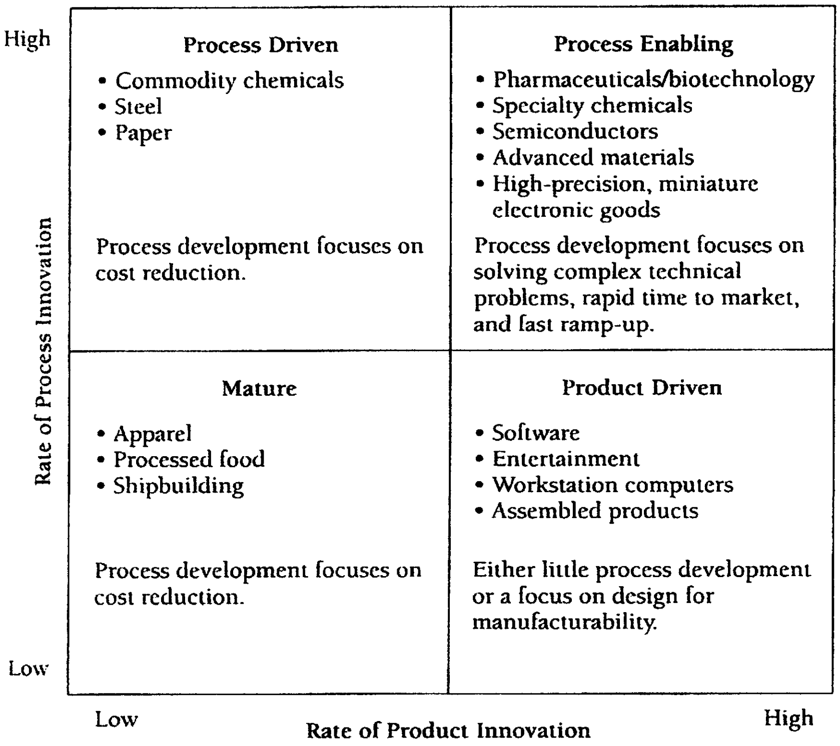
Figure 2.1 – The product life cycle of innovation

The product life cycle model provides a plausible logic that helps to explain patterns of innovation in several industries (Utterback 1994). It also draws attention to the critical competitive impact of the emergence of a dominant design, and provides some insight into why established firms in mature industries tend to experience difficulties adapting to radical product or process innovation (Christensen 1997). Yet the assumptions of the model are not always applicable. First, it focuses on cost reduction as the primary goal of process innovation, implying that firms have an incentive to develop new processes only in the intermediate phases of an industry's life, after opportunities for new product innovation have been depleted and production volumes are sufficiently high to justify standardized equipment. Such potential competitive advantages as time to market and rapid production ramp-up are ignored. Second, there is an implicit assumption that the organizational competencies required for product innovation are fundamentally different from those competencies required for process innovation. Abernathy noted, "[... progress in high-volume established products, and production processes...] They are much different from those needed to achieve a high rate of major product innovation"[1]. Finally, the model assumes that process innovation is not needed to enable product innovation. Indeed, investments in process technologies are often viewed as a potential hindrance to further product innovation, by causing firms to hesitate to introduce new products that make existing process technologies obsolete, and thus need to be avoided early on (Pisano 1997).

Yet there are many firms where strong product and process development capabilities not only coexist peacefully, but also complement each other. In biotechnology, semi-conductor, advanced materials, and pharmaceutical industries, new products cannot be commercialized without breakthroughs in process technology. "Intel Corporation, as an example, is able to continually introduce ever higher-performing microprocessors because it has built strong capabilities to develop and scale-up the complex manufacturing processes required to produce these sophisticated devices"[2].

Examples like the ones mentioned above suggest the need for a broader view of the role of process development. It is necessary to understand how process development capabilities can be valuable outside the environment of mature cost-driven industries and how it can proactively contribute to, rather than conflict with, a firm's ability to compete on the basis of product innovation.

The relationship between process and product innovation matrix (see Figure 2.2, Pisano 1997) provides the broader view and highlights the role of manufacturing-process development in different types of industries.



Rate of Process Innovation	Low Rate of Product Innovation	High Rate of Product Innovation
High	**Process Driven** • Commodity chemicals • Steel • Paper Process development focuses on cost reduction.	**Process Enabling** • Pharmaceuticals/biotechnology • Specialty chemicals • Semiconductors • Advanced materials • High-precision, miniature electronic goods Process development focuses on solving complex technical problems, rapid time to market, and fast ramp-up.
Low	**Mature** • Apparel • Processed food • Shipbuilding Process development focuses on cost reduction.	**Product Driven** • Software • Entertainment • Workstation computers • Assembled products Either little process development or a focus on design for manufacturability.

Figure 2.2 – The relationship between process and product innovation matrix

The two left quadrants of the matrix represent the transitional and mature phases of the product life cycle model, where there is a low rate of product innovation. At the transitional phase, process innovation is still very active (upper-left, process driven), while at the mature phase, process innovation also slows down (lower-left, mature). In both quadrants, the role of manufacturing is to improve productivity and to adopt more efficient process technologies.

The lower-right quadrant (product driven) represents the fluid phase, where product innovation is rampant but process technologies are relatively stable. In this quadrant, the role of manufacturing is to ensure that the designs of the products are compatible with existing capabilities.

It is the upper-right quadrant (process Enabling), where both product and process evolve rapidly, that is ignored by the product life cycle model. In this quadrant, the capability for fast, efficient and quality process development has direct impact on the commercial success of new products. Product and process capabilities evolve rapidly, must be carefully synchronized and, far from being in conflict with one another, are mutually dependent. The capabilities required for innovative manufacturing-process development in this quadrant, and their role in achieving excellence in product development, are the focus of this thesis.

2.2 Process Development Capabilities

Academic research on manufacturing-process development (Pisano and Wheelwright 1995, Pisano 1997, and Hayes, Pisano, Upton and Wheelwright in 2005) is consistent in pointing out that although process development has proved over time to be able to reduce manufacturing costs, its real power lies in how it helps firms to achieve faster time to market, more rapid and smoother production ramp-up, and a stronger proprietary position.

Faster time to market

The benefits of reducing product development lead times are well known and broadly covered by the academic literature and business press. Many firms have adopted approaches that employ overlapping product and process design cycles and shown that, managed properly, it facilitates significantly shorter development lead times than does a traditional sequential approach (Clark and Fujimoto 1991). However, very little attention is given to reducing the time required for process development, despite the obvious fact that reducing it may translate into shorter overall product development lead-time. In situations where process technologies are complex and need to be customized, process development can be a constraint for product launch; shortening the product development lead-time depends directly on the ability to speed up process development.

Firms also find that for process design to be successfully carried out in parallel with product design, a much more flexible process development capability is required (Clark and Fujimoto 1991). The traditional sequential approach allows process developers to work around a relatively fixed set of specifications; under simultaneous engineering, they have to be able to respond quickly to a continuous flow of information about evolving product specifications.

There are finally more subtle ways on how process development can influence product development lead times. "For example, in contexts such as pharmaceuticals, semiconductors, and automobiles, some process development must take place before functional prototypes or representative product samples can be fabricated. Slow process development at this stage can delay and prolong prototyping lead times, which, in turn, delays the entire project. Similarly, a process that is incapable of producing sufficient quantities of test materials can severely restrict a firm's ability to conduct needed tests"[3].

Rapid ramp-up

When a product is first manufactured, it can take some time (e.g. in the automobile industry, it may take six months or more before a factory produces a new model at full-scale production volume) for manufacturing performance (in terms of cost, productivity, capacity, quality, yields) to reach the projected levels. This period, known as ramp-up, occurs mainly for two reasons. First, as operators become familiar with a process, they become more effective at carrying the necessary production tasks. Second, it is during this period that many processes problems are identified and fixed. "To a large extend, ramp-up speed is a function of the quality of the process technology, which, in turn, is determined by process development"[4].

Rapid ramp-up is valuable for three reasons. First, the faster a firm can ramp-up production, the quicker it can begin to earn revenues from the new product and recoup its development investments. Second, and more strategic, a rapid ramp-up enables a firm to achieve faster market penetration, broader market acceptance, and to begin accumulate high-volume production experience that should lead to future lower production costs. And finally and more basic, the faster the ramp-up, the faster resources can be freed to support other product development activities.

Stronger proprietary position

"Survey data from Levin et al. (1987) suggest that only in industries such as chemicals and pharmaceuticals do product patents play any significant role in protecting intellectual property. Even where patents do provide protection, long lead times between the discovery of the patentable technology and its commercialization may mean that patent protection expires relatively early in (or even before the start of) the product's commercial life"[5].

Innovative process technologies are one way for firms to extend the proprietary position of a product. Product designs that are complex and difficult to manufacture can create opportunities to use proprietary processes as a barrier to imitation. Competitors may be able to reverse-engineer a product, but can still face difficulties in trying to manufacture the product at competitive cost and quality levels. "The [Gillette] Sensor has proven to be one of the most successful products in Gillette's history and a major driver of its earning growth in recent years. Yet despite licensing of the Sensor's product patents, no generic versions of the Sensor have reached the market. The complex manufacturing process (which was not shared with others) has proven a major barrier to entry"[6].

2.3 Process Development Strategic Value

Firms in general recognize that shorter product life cycles, increasingly hard-to-manufacture product designs, and growing technological parity are all changing the competitive forces in high-tech industries. These relatively recent issues are changing the nature of competition in high-tech industries (see Figure 2.3, Pisano 1997).

Globalization and the digital revolution are on the background of each one of these issues and ensure that the trend will continue or even accelerate.

Customization is also another issue that poses challenges to product development. Firms need to have manufacturing-process capabilities that provide a response to customization, without lowering quality, adding cost or slowing delivery; those that proactively develop these capabilities, can improve significantly their position in the market. "Consider McNeil Consumer Products' gel-cap version of Tylenol. A distinctive manufacturing process provided an easy-to-swallow product; and because the process was proprietary, the product was the only one it its class with that feature. As a result, the gel cap strengthened Tylenol as a brand"[7].

Shorter product life cycle

The combination of intense competition and rapid technological changes lead to ever-shorter product life cycles. Although managers in high-tech firms are aware of this trend, they do not recognize its implications to manufacturing-process development. Indeed, many firms use the shortening of product life cycles as the reason to outsource manufacturing and concentrate on product R&D (Pisano and Wheelwright 1995). Yet, shorter product life cycles raise the importance of being first to market and rapid ramp-up, key benefits of having strong manufacturing-process development capabilities.

"Semiconductor fabrication facilities incur weekly depreciation costs running into the million of dollars. This is one reason why yield improvement and rapid ramp-up play such a critical role in semiconductor manufacturing. In these contexts, the strategy of commencing commercial production with poorly developed or unstable processes and improving over time is too costly. Long before the plant gets to the bottom of the learning curve, the technology may be obsolete and the firm may find itself at the top of a new learning curve. In environments with short product development life cycles, the capability to develop highly efficient processes before launch is a strategic imperative"[8].

Harder to manufacture

In rapidly changing markets (e.g. semiconductors), the use of proven technologies in developing new products is conservative and no longer viable. In order to gain even a small temporary market advantage, firms must work at the technological frontiers, creating a significant challenge to their process development and manufacturing capabilities. "For example, in flat-panel displays (the type used on notebook computers), size increases, improvements in clarity, and the addition of color – all critical product characteristics in the eyes of customers – have required companies to push the envelope of semiconductor process knowledge and process control. In such environments, practices such as design for manufacturability simply are not practical. The product technology, by its very nature, is difficult to manufacture"[9].

Although firms should always strive to avoid unnecessary product design complexity, those with strong manufacturing-process development capabilities have more freedom to develop new products than those that have no option other that to stick to simple-to-manufacture designs.

Growing technological parity

Broad access to basic technological know-how, highly mobile knowledge workforce, and relatively weak intellectual property protection in many industries are some of the key factors encouraging the rapid diffusion of technological know-how across countries and companies.

This growing parity in design capability makes it almost impossible for firms to sustain competitive advantage on the basis of performance and functionality. Despite the criticality of these attributes, technological parity basically raises the importance of faster time to market, rapid ramp-up, and proprietary manufacturing-process ("because manufacturing processes take place behind factory walls, manufacturing technologies often are harder to imitate than product technologies and therefore offer a more sustainable source of competitive advantage"[10]).

"As technology becomes more public and less proprietary through easier imitation, then strength in manufacturing and other capabilities is necessary to derive advantage from whatever technological advantages an innovator may possess"[11].

	Driving Forces		
	Growing Technological Parity	Product Complexity	Shorter Product Life Cycles
Competitive Implications	Difficult to sustain advantage on product functionality or performance alone	Costly/uncertain development	Rapid obsolescence of physical and intellectual capital
Source of Advantage	First to market; rapid market penetration; barrier to imitation/entry	Sophisticated technical problem-solving capabilities; capability to push the envelope of both product and process technology	Short development lead time; rapid market penetration; lower fixed development and manufacturing costs
Potential Strategic Contribution of Process Development Capabilities	Rapid process development increases time to market; fast manufacturing ramp-up supports market penetration; process technology enhances customer acceptance; proprietary process technology used as barrier to imitation	Rapid process development reduces risk and complexity of development by allowing later start; strong problem-solving capabilities provide technical degrees of freedom for product design	Rapid process development facilitates quick time to market; rapid manufacturing ramp-up supports market penetration; efficient process development increases returns to R&D; development of processes that economize on capital expenditures increase return on net assets (RONA)

Figure 2.3 – Process development strategic value

2.4 Study On The Pharmaceutical Industry

Research in the health care and pharmaceutical industry carried between the 1985 and 1995 period (Pisano and Wheelwright 1995) identified a set of companies that had made process development a priority and achieved a sustainable competitive advantage.

Until the 1990s, process development in pharmaceutical companies was characterized by five basic practices: "When developing a new drug, delay significant process R&D expenditures until there is a reasonable certainty that the product will be approved for commercial launch; process R&D is successful when it stays off the critical path for the launch of the new product; once a product is on the market and demand begins to grow, the primary task of manufacturing and process engineering is to bring on-line additional physical capacity; whenever possible, locate manufacturing in a tax haven, even if it is far from R&D and process development; consider investments in process improvements later in the patent life of a product when the threat of generic competition becomes imminent"[12]. Given the fact that only one out of 10,000 new compounds discovered in laboratory became a commercial drug, the rationale was compelling; also until then, the majority of drugs were relatively easy to manufacture and manufacturing costs were often less than 10% of revenues. This set of practices worked for many years and the industry enjoyed high profitability and growth rates (see Figure 2.4, Pisano 1997).

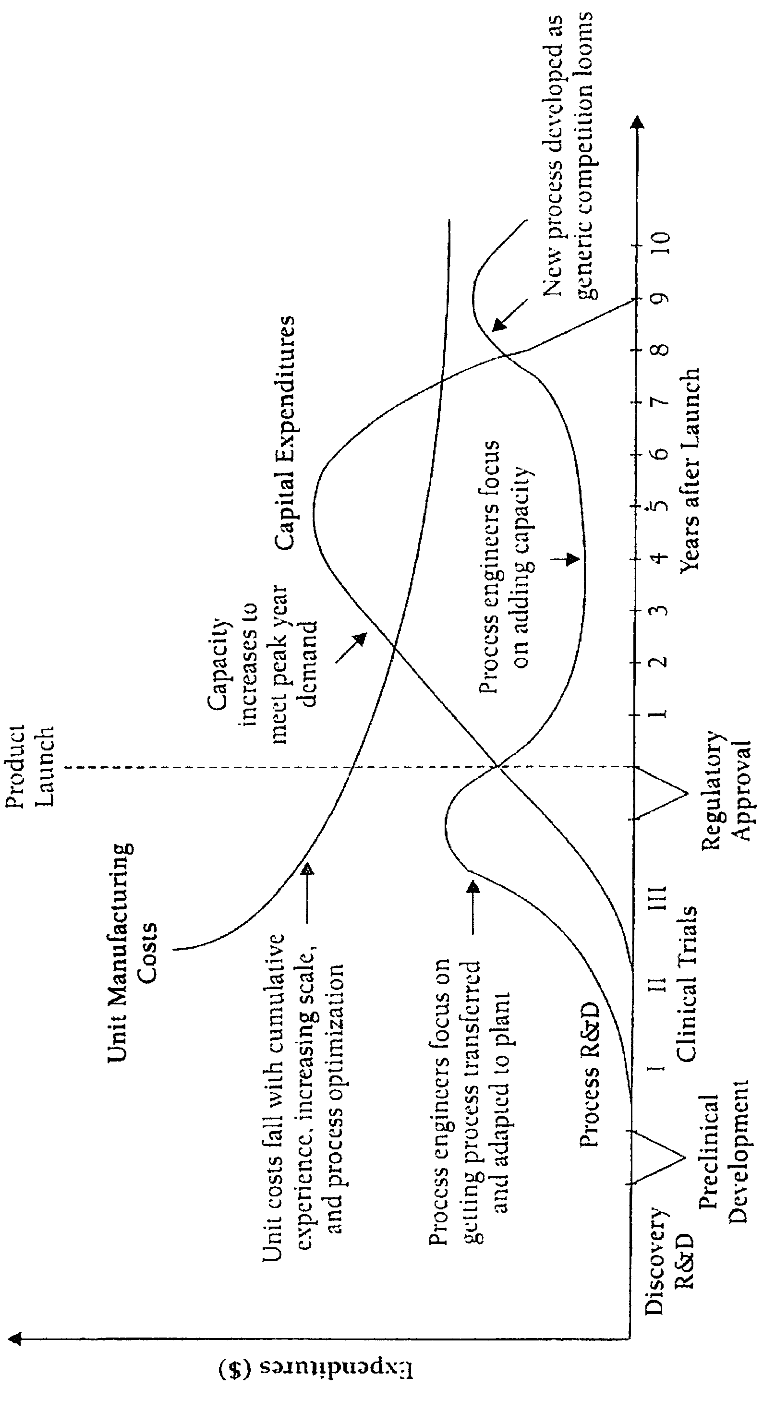


Figure 2.4 – Traditional approach to process R&D

By 1995, pharmaceutical companies found themselves squeezed by the shorter product life cycles, less pricing flexibility, and higher costs. The expansion of health maintenance organizations with their tremendous bargaining power, the increased competition from generics, and direct competition from similar patented branded drugs, all put an enormous pressure on pricing. The increasing regulatory requirements and the complexity of the new compounds increased considerably the cost of developing and manufacturing a new drug. "… the cost of developing a new drug increased to $ 359 million in 1992 (taking into account the cost of the many compounds that never made it to market), up from $ 120 million five years earlier. The cost of manufacturing these pharmaceuticals also is increasing. In the early 1990s, manufacturing costs represented 20% of sales, up from 10% in the early 1980s. At 20% of sales, manufacturing costs on average now exceed R&D costs"[13].

The challenge faced by the pharmaceutical companies was far more complex than a shift of emphasis from product innovation to lower costs. Product innovation in this industry is paramount. The key challenge became how to manage process development in order to dramatically decrease manufacturing costs while continuing to excel at product innovation and development (see Figure 2.5, Pisano 1997).

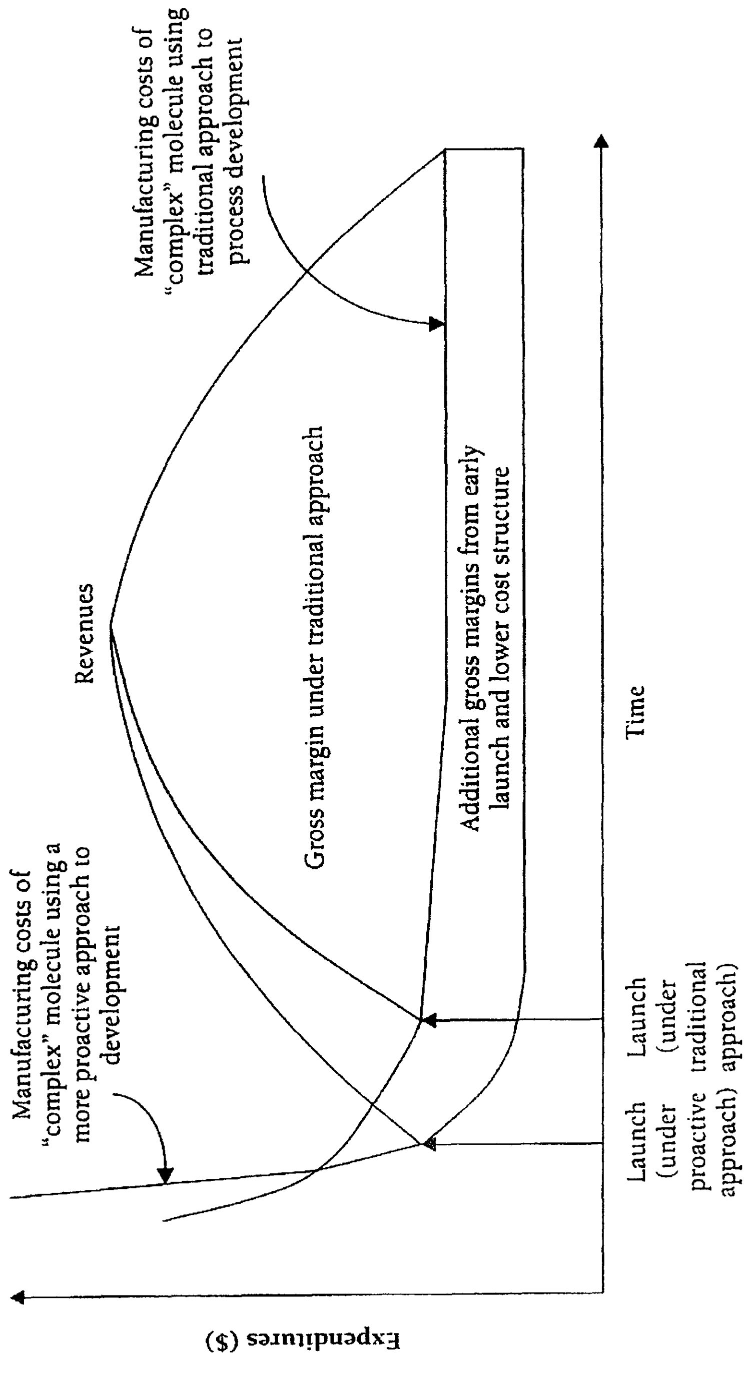


Figure 2.5 – Superior process development over product life

On a specific pharmaceutical industry study, data was systematically collected on 23 process development projects, from a total of 11 different companies, including approximately 200 people interviewed from the participating R&D sites and manufacturing plants in the United States and Europe (Pisano 1997). The study positively confirmed the critical role of process development in reducing manufacturing and capital expenditures, in reducing product lead-time, and as an enabler to product innovation.

Real leverage came from aggressive pursuit of process-technology changes rather than focus on operating existing technology to increase volume and capacity utilization. One company was able to reduce manufacturing costs by 85% during a 12 years period of producing a typical antibiotic (see Figure 2.6, Pisano and Wheelwright 1995), due to more than 80 projects on manufacturing process, half one them were major process improvements requiring significant capital expenditures and engineering resources (e.g. improving equipment designs, altering the basic chemistry of the process). With process development, the improvements were far greater than the ones obtained via the effects of cumulative experience on costs.

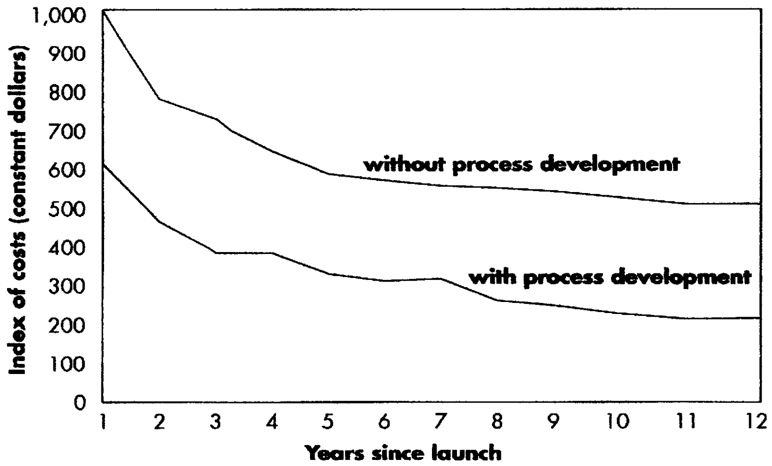


Figure 2.6 – Impact of process development on cost improvement

The most striking result of the process improvements at this company was a reduction in the capital expenditure needed to meet demand (see Figure 2.7, Pisano and Wheelwright 1995). The bars on the chart refer to the number of reactors (each costing $7 million) required to meet the 1994 demand had the process yields stopped improving in that year. Had no process development been undertaken and yields not improved dramatically, the company would have needed 120 reactors (instead of 17) and incurred more than $700 million of additional capital expenditures.

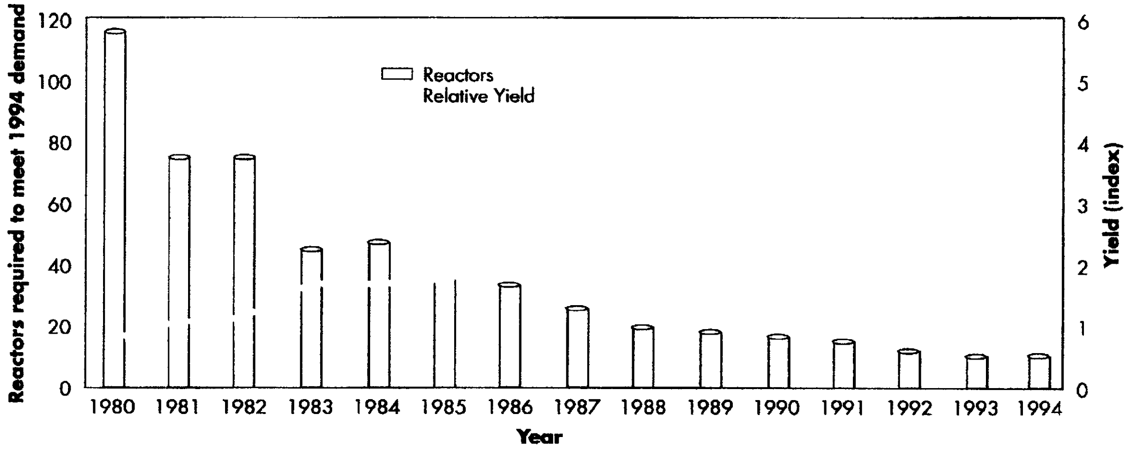


Figure 2.7 – Impact of process development on capital expenditures

The total spending on process development did not influence process-development lead times, but the timing and focus of such spending did. In projects for chemical-based pharmaceuticals, correlation was found between intense process research activity at an early stage and more rapid process development; but in biotechnology projects no such correlation was observed (see Figure 2.8, Pisano and Wheelwright 1995). The reason was that chemical-process technology rest on very mature knowledge base and process developers used laboratory results to anticipate many potential production problems and then results could be validated in a pilot plant; while in biotechnology, because the technology was novel, laboratory results were not so good indicators and doing more process research did not appear to shorten the lead-time.

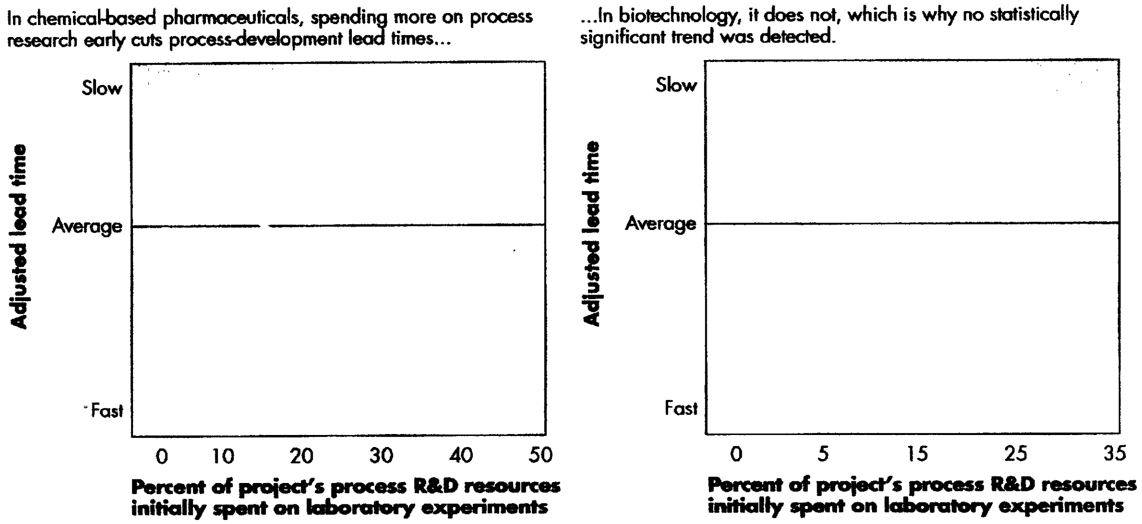
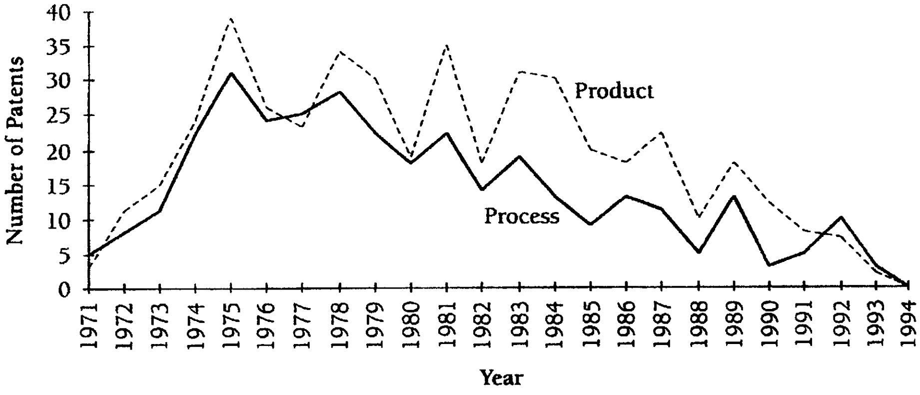


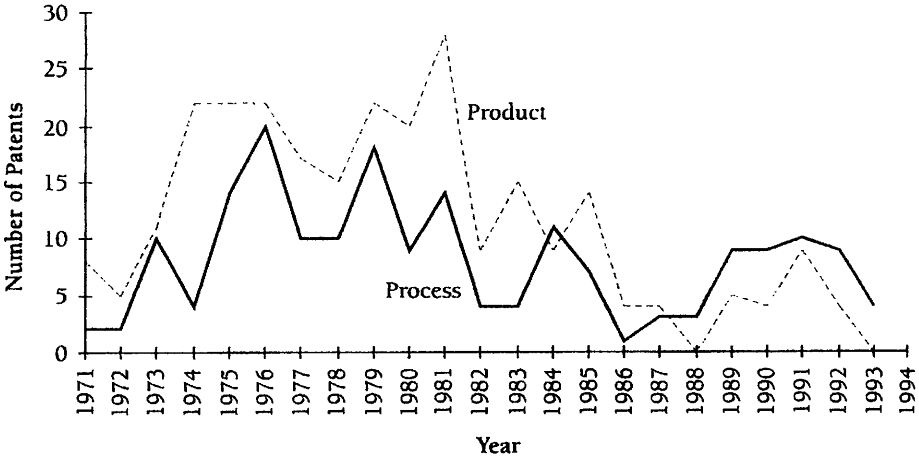
Figure 2.8 – Impact of process research on process development lead times

The distribution of product and process patents for two classes of antibiotics developed in the early 1970s (see Figure 2.9, Pisano 1997) clearly showed the role of process innovation early in the life cycle of a new drug and the highly complementary relationship with product innovation (contradicting Abernathy and Utterback's product life cycle model). "Because the basic inventions of genetic engineering were made in the early and mid-1970s and no products had been manufactured using these methods before, little was actually known about how to manufacture these proteins on a larger scale"[14]. Consistent with interviews with scientists, the distribution showed that novel classes of drugs required the invention of novel process technologies, and that process development could be a critical enabler of product innovation.

(a) Beta Lactam Inhibitors



(b) Cephalosporin Antibiotics



Source: Data compiled from patent records, U.S. Department of Commerce, Patent and Trademark Office.

Figure 2.9 – Complementary relationship between product and process development

No single approach to how process development should be organized was found to consistently provide advantage. Informal relationships and approaches to managing projects were identified as more important than the formal structures and procedures.

2.5 The Learning Curve

There is an enormous amount of empirical evidence that manufacturing performance improves with cumulative experience. As workers gain knowledge of a process, they become better in executing it. Cumulative experience generates data needed for problem identification and solving, and also induces improvements through product and process design changes, production equipment enhancements and workers training. One of the underlying themes in existing literature is that only through time or experience (and the corresponding data) an organization can identify and solve problems.

The assumption that manufacturing performance improvement requires actual production experience neglects the impact of process development activities that happen before a process is used in a plant. Also, and accordingly, it is interesting to note that in the learning curve literature the earliest point for tracking process improvement is the start of commercial production, and activities before it are not covered (the initial manufacture performance is a given). The learning curve framework does not address the trade-offs between higher development cost versus lower production costs, the improvement of the initial manufacturing cost, and the balance and optimization of learning before and after commercial production starts.

2.6 Product Development

The literature on product development provides a foundation for understanding process development, as both activities share common characteristics. Product and process development are problem-solving activities, require a high degree of cross-functional integration, and require an ability to probe future user needs.

“Despite similarities, process development presents distinct challenges having to do with the organizational nature of processes. The primary task of product development is to create a detailed characterization of the product and to fully capture information about the design in such media as blueprints, CAD drawings, formulas, specifications, mock-ups, and models. A product design embodies significant information about manufacturing. Indeed, this linkage has become much more explicit with the growing adoption of design-for-manufacturability practices. However, although a well-specified product design might allow a sufficiently skilled person to build a replica of the product, it does not contain explicit instructions for producing large quantities economically. For instance, skilled technicians can construct very accurate prototypes of automobiles using blueprints and CAD drawings, but these may cost up to $1 million each and take several weeks to construct”[15].

The critical component of process development is the creation and implementation of operating procedures and organizational routines needed to control a set of actions required for production. Unlike products, processes do not exist outside an organizational context, and the capabilities created by process development become an integral part of the organization.

Chapter 3: Manufacturing-Process Innovation Framework

This chapter explores the determinants of process development performance. There are several challenges to this task. First, process development does not occur in isolation but takes place within product development. Second, process development is intertwined with a firm's manufacturing and operations strategies. Third, the required process development capabilities are largely determined by a firm's competitive position. Finally, process development is organizationally complex and spans multiple functions.

In order to explore effectively such a complex set of topics, a capabilities-based perspective of process development will be used. "This framework is based on the notion that process development is a capability-creating activity involving the translation of technical knowledge into operating routines"[1].

3.1 The Context

The traditional distinction between product and process innovations, viewing process development R&D as quite distinct from product R&D, is quite appropriate for mature industries settings, where process R&D is often carried out unrelated to any change in product technology.

In settings where product and process technology evolve together (upper-right quadrant of Figure 2.2), process development cannot be understood in isolation but as a part of the total product development process. The recent product development literature has emphasized the importance of integrating product and process design (e.g. concurrent engineering, cross-functional teams, and design for manufacturing) but remains focused and limited to the coordination aspects of the product and process design.

Process development is a technically and organizationally complex activity and occurs in a much richer context than is generally described in the concurrent engineering literature (see Figure 3.1, Pisano 1997).

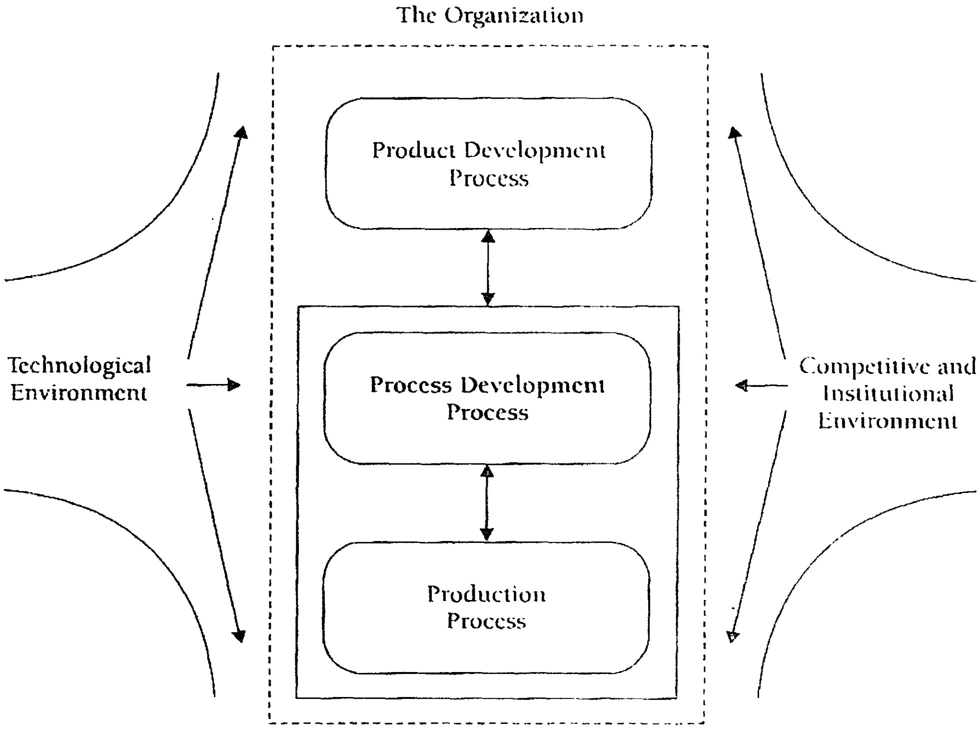


Figure 3.1 – Process development in context

The competitive and institutional environments in which firms operate largely determine the objectives that process development has to achieve (speed, efficiency, yields, cost, etc…). "Changes in everything from effective patent lives to the systems through which health care is supplied have been fundamentally altering the process development capabilities required to thrive in the pharmaceutical business"[2].

Available technical knowledge, both internal and external, play a critical role in framing problems, generating and testing solutions, and ultimately, determining and implementing the chosen solution. The ability to exploit available knowledge, and to adapt to its dynamic landscape, is critical to high performance in process development.

When process development occurs within the context of product development, choices of product design and technology set the technical agenda for process development, as well as choices on timing of events and information flow. But it should be noted that process development capabilities have the potential to influence the product development process ("… an organization with the capability to rapidly develop a pilot-scale manufacturing process – as did BetaGene – may be in a better position to make larger test batches that are more representative of commercially manufactured product than an organization that can produce only a few laboratory prototypes at an early stage…"[3]).

The output of the process development activity is a new or improved production process (a set of technical knowledge, organizational capabilities and operating processes needed to create a product). Beneath this direct link, however, there a several subtle interactions that influence the effectiveness of process development (e.g. integration of new and existing processes, constraints imposed by existing processes, operational feasibility, learning from cumulative experience). Although process development must be integrated across all the three interfaces previously discussed (i.e. competitive and institutional, technological, and product development), the linkage with product process is particularly critical in order to achieve high performance.

3.2 The Framework For Process Development

A framework for viewing process development from a capabilities-based perspective (see Figure 3.2) not only highlights the multiple relations through which process capabilities are built, implemented, and evolve, but also clarifies the roles of process development and production experience in enhancing a firm's capabilities.

The lower half of the diagram focuses on how process development projects and production experience contribute to the evolution of the production capabilities. Process development projects, in this case, are defined as attempts to create new architectures rather than incremental improvements; and are likely to be associated with a new product launch or introduction of a next-generation process for an existing product. Process development focuses on anticipating and attempting to solve problems that might arise during production (e.g. in specifying the assembly sequence for a new product, process engineers model the process to identify bottlenecks, small scale pilot runs simulate future production and identify tasks that might be difficult to carry out). Because these problem-solving activities take place before actual production starts, they are referred to as "learning before doing". Once production starts, additional improvements occur as workers become familiar with the process and their tasks. Production experience brings information on problems and improvement opportunities, which can be addressed through changes in the process, the product design, worker skills or equipment used. We refer to these problem-solving activities as "learning by doing".

The upper half of the diagram focuses on how process development and production experience contribute to enhance a firm's process knowledge base. The same way that production performance hinges on the organization's production capabilities, process development performance rests on the firm's knowledge base (e.g. process engineers who set the specifications of a production equipment draw from their own and the firm's collective knowledge about what types of solutions worked well in the past). Each process development project adds to the firm's stock of knowledge (which can be used on current and future projects), in addition to the creation of new production capabilities previously discussed. It should be stressed that this knowledge is not purely technical, but also covers the organizational and managerial aspects, which further enhance development capabilities.

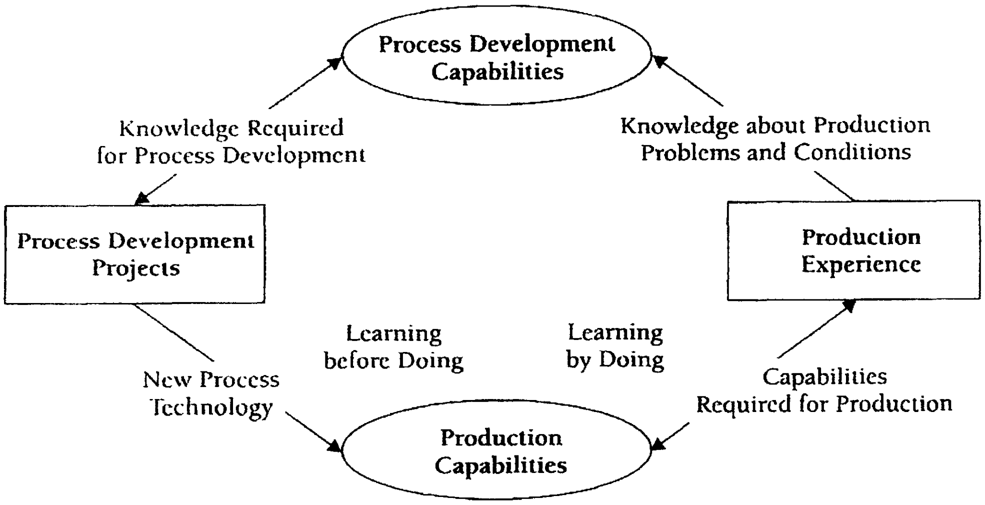


Figure 3.2 – Framework for process development

Both process development projects and production experience have dual roles as users and producers of capabilities and create direct feedback through "learning by doing" effects. Similar to production experience enhancing production capabilities, process development projects enhance the firm's process development capabilities. And there are also the "learning before doing" effects; process development projects represent the learning that takes place before the start of commercial production. Also, prior product experience generates information that contributes to future process development projects.

3.3 Management Challenges

The context (see Figure 3.1) and framework for process development (see Figure 3.2) are useful to frame the challenges facing an organization that needs to develop a new process and then transfer it into a manufacturing setting.

The process encompasses input specifications, sequence of tasks, equipment to be utilized, parameters at which the equipment must be operated, expected intermediate outputs, controlling mechanisms and quality checks throughout. In simple terms, it is similar to a cooking recipe; and as anyone that has tried out a new recipe for the first time can attest, the jump from having the recipe to creating the cake can be challenging.

The cooking recipe analogy highlights two issues in process development and transfer. The first is that transferring a process from the lab to the plant is complex because the relevant details cannot be all clearly communicated in writing. As a result, most companies routinely deploy "technology transfer teams" to ensure that face-to-face communication supplement the process documentation. The second issue, and one that even more organizations tend to struggle with, is that the process ("the right recipe") is contingent on manufacturing conditions and scale. It is not uncommon to hear cases of processes that worked well in small-scale pilot runs to later fail when attempted at full scale under real conditions. The problem here is often that the process was not actually designed to run at full scale, under normal conditions, using the typical workers; a better technology transfer does not solve this type of problem.

The critical challenge of process development is to develop and transfer to manufacturing, in a timely and efficient manner, a process that can produce the desired product and also achieve the desired performance (in terms of costs, quality, reliability, etc.) under real operating conditions.

There are three types of management decisions that address this challenge and that affect significantly the process development performance: integrating approaches to product and process development, timing of process transfer into manufacturing, and degree to which process technology choices are centralized.

Integrating product and process development

Process development does not occur in isolation but takes place within product development, and the most challenging process development projects are those addressing a new product. Also, the integration of product and process design activities is organizationally and technically challenging. And finally, both process and product design happen in a dynamic context; as product designers gain more information from product test, experiments and market feedback, product design evolves and induces changes on the process design.

It is no surprise, then, that the interface between product and process design is the greatest source of tension in a new product development and the cause of some many new products failing commercially.

In order to deal with the integration of product and process development, companies utilize three approaches: integrated development teams, design for manufacturing methodologies, and prototyping activities.

Development teams that include both process developers and manufacturing experts are now widely used. There is enough evidence that these integrated cross-functional teams lead to better product development performance (in terms of lead time, productivity and quality) than the more functionally oriented approach (Clark and Fujimoto 1991, Cusumano and Nobeoka 1998). In order for the cross-functional approach to work properly, it has to be underpinned by strong leadership, adequate resources and clear competitive priorities strategy (e.g. functionality has priority over lower cost).

Design for manufacturing approaches have been widely used since the 1980s and all strive to implement a methodology where manufacturing issues are incorporated into the design process, leading to lower manufacturing costs without sacrificing product quality, development time, and development cost (Ulrich and Eppinger 2004). Some basic examples are design rules that ensure compatibility of product design with manufacturing capabilities (e.g. specifications require tolerances that can be achieved by plant equipment), and reduction of manufacturing complexity of product (e.g. rules that promote product design that contains less parts, easier to assemble). Design for manufacturing is one of the most integrative practices in product development and requires the contributions of most members of the development team. In order for these approaches to work properly, a detailed understanding of the linkages between design choices and manufacturing performance, and to be performed throughout the product development process (begins with concept phase), are a must.

Prototyping is used to gain feedback on technical and marketing aspects of a certain product design. Prototypes enrich the communication between design and process engineers, and help to integrate the perspectives of the different functions represented on the product development team. “A simple physical model of the form of a product can be sued as the medium through which the marketing, design, and manufacturing functions agree on a basic design decision”[4].

Prototypes can reduce the risk of costly iterations during the product development cycle by detecting problems earlier on; but its anticipated benefits in reducing risk must be weighted against the time and money required to build and evaluate the prototype (see Figure 3.3, Ulrich and Eppinger 2004).

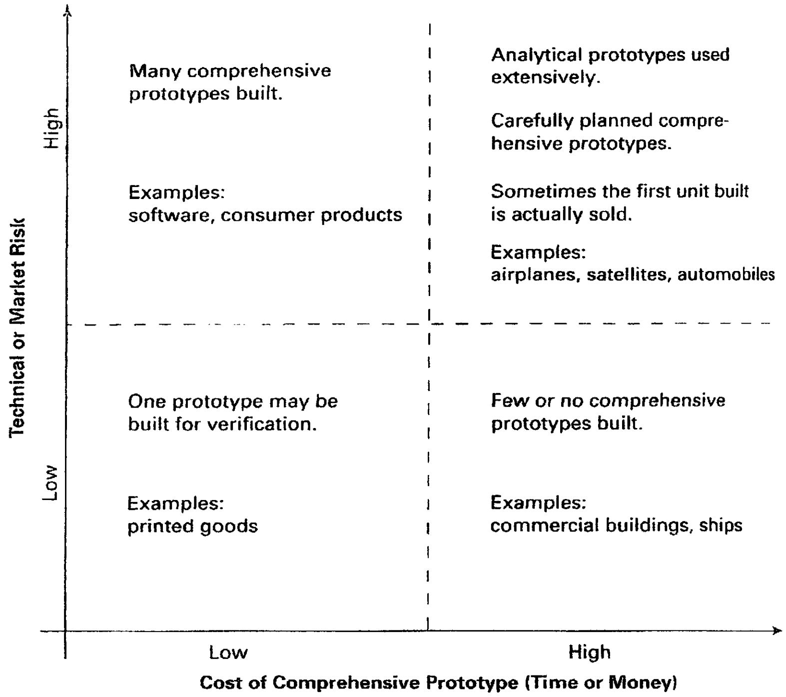


Figure 3.3 – Decision for use of prototype

Prototypes have also the potential to expedite other development steps (e.g. mold design) and remove tasks from the critical path (e.g. software test in wire-wrapped boards).

In the vast majority of companies, prototyping (particularly physical prototypes that incorporate most of the attributes of a product) activities happen under the engineering function charged with designing the product, and as a result, prototypes are often built in specialized departments using methods, equipment, and workers, that are all very different from the ones that will be used for commercial production. The problem with this approach is that it provides no feedback about future production issues and the possible process design and manufacturability problems are only revealed very late on the development cycle (typically when a pilot production run is made). One way to address this problem is to build prototypes using a process that closely resembles the commercial production environment, which in most cases is difficult and costly. The understanding of the key elements of the commercial production environment is critical to make the later approach feasible (e.g. BMW 7-Series project in the early 1990s, very well documented).

Timing the transfer of new process into manufacturing

Deciding when a process technology is transferred from product development into manufacturing is a subject of intense debate in most organizations. Some argue that the process should be largely error-free by the time it is transferred, and as such, should be transferred fairly late in the development cycle; others, that it is simply impossible to anticipate all the problems that will occur during production, and as such, the process should be transferred as early as possible. There is no right answer to this debate. The timing of a process technology transfer is contingent on several factors, but mainly on the experimentation strategies used (from theory to plant) and learning capabilities employed ("learning before doing" versus "learning by doing").

"Despite differences in the ways new processes are developed in different industries, the problem-solving approaches used have certain similarities"[5]. Process developers use problem-solving techniques as they narrow the gap between what is known about the process and its likely performance, and what needs to be known in order to achieve the desired performance. Experimentation lies at the heart of this iteration.

Process development experimentation takes many forms and occurs under a variety of conditions. One way to characterize different experiments is along the dimension of representativeness of the final production environment (see Figure 3.4, Pisano 1997).

Representativeness of Final Production Environment	Locus of Experimentation	Learning Mode
High	Full-scale commercial factory	By Doing
↑	Pilot plant located at production site	↑
	Pilot plant located at development site	
↓	Laboratory	↓
Low	Computer-aided simulation	Before Doing
	Theory, algorithms, heuristics	

Figure 3.4 – <u>The locus of experimentation</u>

Experiments take place along a continuum of settings, from purely theoretical calculations and computer-aided simulations to pilot runs conducted in a plant.
Some companies prefer a more "lab-focused" approach to experimentation and tend to allocate a greater share of their process R&D budget to build capabilities in simulation and to carry out more laboratory experimentation. These companies have the expectation that the key process problems will be identified and resolved in previous simulations and laboratory tests, and as such, tend to transfer the process to manufacturing relatively late in the development cycle ("learning before doing" approach). Other companies prefer a more "operations-focused" approach and tend to allocate a greater share of the budget to process engineering at the production site and to build large-scale pilot facilities that are nearly identical to full-scale production sites ("learning by doing" approach).

The key trade-off between the experimental modes is the cost versus the value of the feedback per experiment. Simulations and laboratory experiments are typically far less expensive than pilot runs in a full-scale commercial factory; however, they do not always provide good predictions on how the process will behave when used under normal operating conditions. The choice between a more "lab-focused" or a more "operations-focused" approach must be largely dependant on the knowledge base underlying the process technology (see Figure 3.5, Pisano 1997).

"Where underlying cause-effect relationships are well known and there is relatively complete knowledge of the future operating environment, one may know enough about the critical variables and their behavior to design highly representative laboratory experiments or simulations that provide reasonably accurate predictions of expected commercial performance"[6]. An example commonly used is process engineers using software models that simulate process flows and bottlenecks accurately enough to design a facility layout.

In contrast, when the theoretical or practical knowledge of the effects of scale and other environmental factors are limited, and critical variables cannot be modeled accurately ahead of time, feedback from simulations or small-scale pilot experiments will be less predictive of the problems and performance to be experienced when the process is transferred into full-scale commercial operating conditions. In these cases, evaluations of the process need to be done under conditions as close as possible to actual operating conditions.

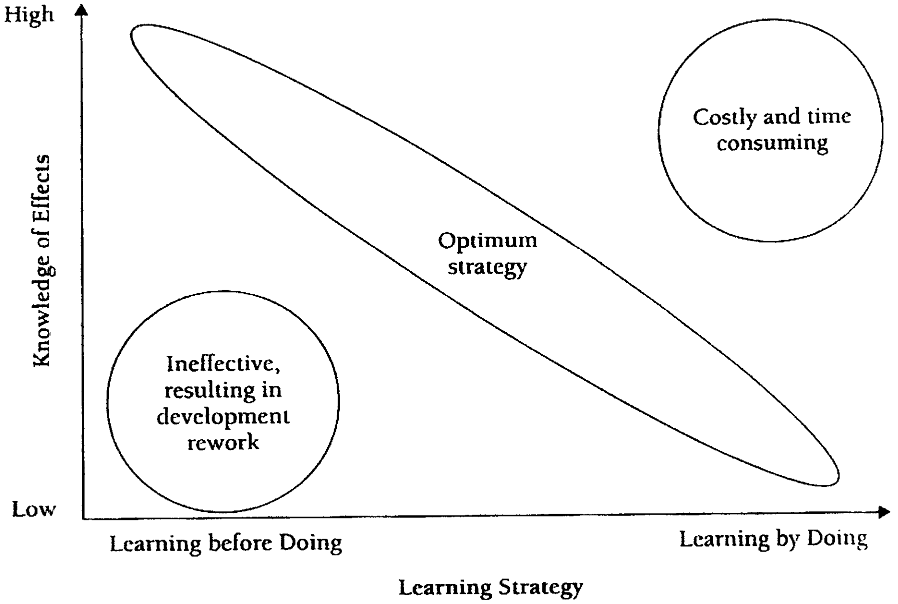


Figure 3.5 – Learning strategy

Centralized versus decentralized process development

The degree to which process development choices are centralized versus decentralized is another issue of great contention in many companies. Under an extreme form of the centralized approach, process technologies are selected and developed by a central group, and the operating units responsible for a given product are then essentially mandated to adopt a uniform standard process technology, with very limited discretion to modify it. Under the extreme decentralized approach, each operating unit is given a high degree of freedom in choosing, developing and modifying the processes used, with very little coordination or sharing across different units.

There is no single approach that works equally well for all companies under all circumstances. Each of the approaches, centralized and decentralized, has its advantages and disadvantages. The centralized approach can achieve a critical mass of technical talent necessary to stay on the cutting edge of process technology development, eliminate redundant development efforts across the different operating units, and enable the implementation of standardized process technologies in markets where customers require a high degree of consistency but still the flexibility of sourcing from any operating unit (e.g. Intel's Copy-Exact strategy). The decentralized approach can enable local process development and engineering that are likely to be more responsive to needs of its particular environment and customers, reduce the process risk due to the increased variety of process experiments carried out by the different operating units, and allow a faster and more effective transfer of process technology into the operating units as they are collocated.

The choice comes down to a firm's specific operational and competitive strategies; and issues like the importance of local market and operating conditions differences, the degree to which the process can be optimized prior to transfer to the operating units, and the transition mode between consecutive generations of process technology, largely determine the best one to follow.

In some markets there is a tremendous competitive advantage in being able to guarantee that the process technology being used across multiple operating units is exactly the same, particularly for products which process and product technologies are highly interdependent. "The Copy-Exact approach made it possible for Intel to use the same process technology at plants around the world to supply global customers with a highly consistent product"[7]. In other markets, differences in culture, work habits, unions and regulation can be important factors for local modifications to the process design. The use of highly sophisticated automated equipment may be justified in regions with high wages and strong technological infrastructure, while more labor intensive processes may be better in low wages and less technologically developed regions. A reasonable course of action is to develop centrally those aspects of the process where economies are associated with standardization, and allow local choice for others.

A centralized approach is better suited to cases where the process technology can be developed right the first time, otherwise there is the risk of having a non-optimal process affecting all operating units at the same time. "This was Intel's rationale for investing heavily in facilities and capabilities that enabled it to develop optimal processes before launching a new product. Its "Technology Development Fabs" are essentially full-scale replicas of its commercial manufacturing facilities, allowing Intel to fully test out a new process in a setting nearly identical to the commercial production environment, and to identify and resolve problems before transferring it to the plant network"[8]. If significant "learning by doing" is expected, experimentation by autonomous operating units is recommended.

A centralized approach is better suited when performance improvements (productivity, quality, reliability, etc.) are driven by the implementation of a completely new generation of process technology. When there are opportunities for multiple incremental improvements to the process after its transfer, the centralized approach can be costly in terms of the lost opportunities, and the decentralized approach is better suited.

Chapter 4: Case Study Pratt & Whitney

4.1 Background

Founded in 1925, Pratt & Whitney was the aircraft engine subsidiary of United Technologies Corporation. Pratt & Whitney was among the world's largest manufacturer of commercial, general aviation and military aircraft engines. Pratt & Whitney provided overhaul and repair services, spare parts, and fleet management services for the engines it produced and other commercial and military jet and gas turbine engines. Pratt & Whitney products were sold principally to aircraft manufacturers, airlines and other aircraft operators, aircraft leasing companies and the US and foreign governments. By the end of 2003, Pratt & Whitney had over 16,000 large commercial jet engines installed serving 600 domestic and foreign customers, 11,000 military engines serving 27 government armed forces, and 33,000 small commercial engines serving 800 airlines and 8,000 operators.

Pratt & Whitney had three potential sources of revenue coming from the large commercial jet engines business segment: initial sale of an engine, spare parts, and overhaul and component repair services. The company was willing to discount heavily on the first source, partly to lock in lucrative long-term contracts on the second and third sources; besides being highly profitable, maintenance contracts provided stable and long-term revenue and earnings streams that sheltered the company from the large variations in jet engines sales.

Pratt & Whitney competed with General Electric and Rolls-Royce Plc for jet engines contracts from the airlines and big commercial aircraft manufacturers (primarily Boeing and Airbus). Historically, this arrangement led to intense price wars, prompting many observers to contend that the industry could support only two engine makers. In order to avert price wars, the three companies typically entered into exclusive supplier contracts with aircraft manufacturers to become the sole provider of jet engines for a specific aircraft model. The three companies also entered into joint venture agreements to share expensive development cost of a commercial jet engine (as much as $2 billion in 2002).

The $31.1 billion global jet engine manufacturing industry operated as an oligopoly in 2002, with General Electric's jet engine division as the largest player with 55%, followed by Pratt & Whitney with 24%, and Rolls Royce's Aerospace unit with 21%.

4.2 Business Context

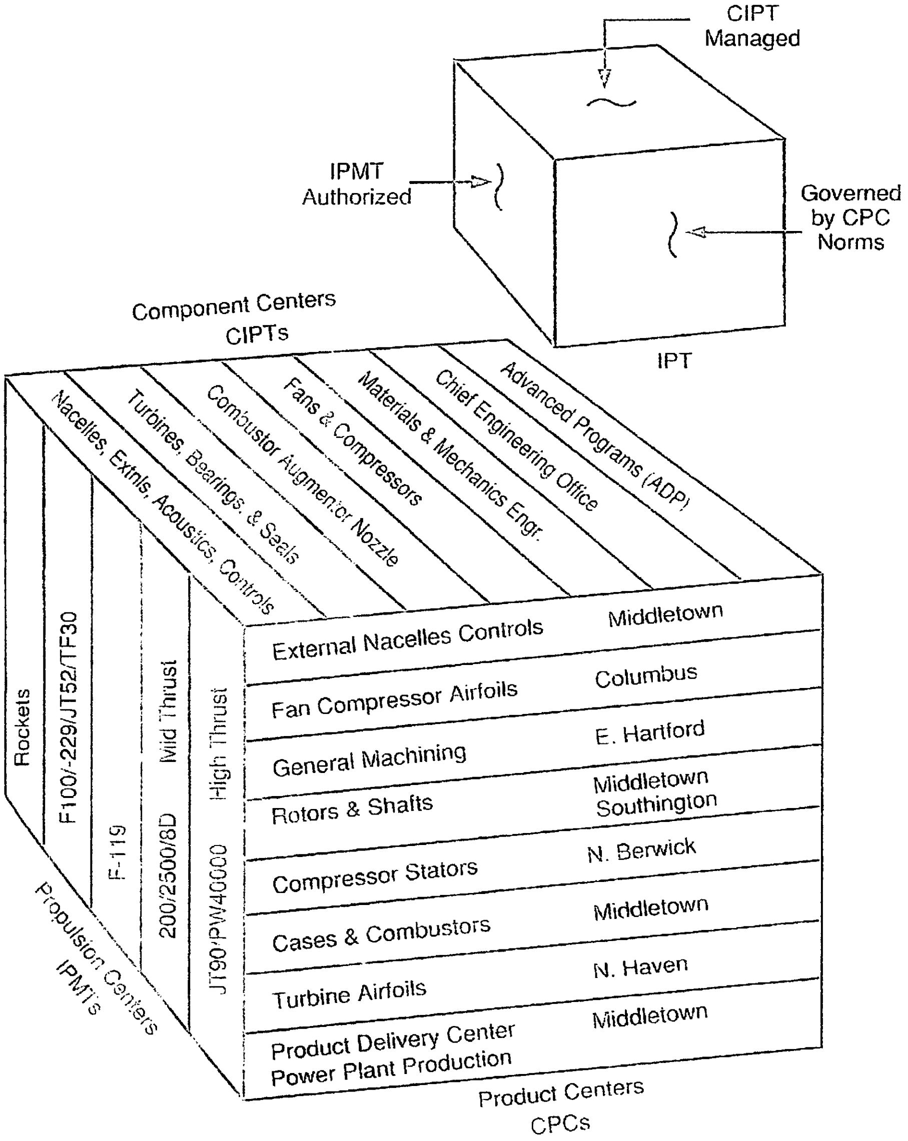
In the mid-1980s, Pratt & Whitney faced competition in all its major products and its market share began to decrease. In addition, total engine deliveries in the industry began to decrease as a result of the shift from four to two engine aircraft designs. Pratt's management, in what seemed a bold move at the time, responded with the introduction of three initiatives: one in manufacturing and two to bridge the gap between product development and manufacturing. In manufacturing, the "focused factory", with flow lines and business units organized by parts, was introduced in 1984; and on the interface with product development, cross-functional teams were created to evaluate each part and process used and to agree on norms for part design, material selection, and processing techniques, and a new system of Integrated Product Development (IPD) was formed to resolve major cross-functional conflicts during engine development.

The results of these three initiatives were significant and provided the foundation for the more drastic changes to come in the early 1990s. "Time-to-market for the new PW4084, entering airline service in June 1995, shrank from five years under the old project engineer system without IPD to about four years with IPD, and the number of engineering hours declined by a similar fraction.... lead times for physical production of engines from initial order and raw materials to shipped unit shrank from the traditional twenty-four months to eighteen by the end of the 1980's, but then stagnated..."[1].

The end of the cold war and a crisis in the commercial airline industry caused drastic reductions in orders in the 1990s and increased the competitive nature of the aircraft engine manufacturing business. Manufacturers began to offer competing engines for each new airframe, with aggressive pricing and financing terms, resulting in much lower profits on the initial sale. "A new engine design could cost as much as $ 1.5 billion. Worldwide market shares in 1993 for the three players – Pratt, General Electric (GE), and Rolls Royce – were 45%, 43% and 13%, respectively.... GE represented Pratt's most significant threat.... GE reputedly had over twice Pratt's return on sales.... Pratt had developed a reputation for being too slow, too meticulous, and much too expensive to be competitive"[2]. United Technologies Corporation senior management realized that fundamental changes were needed to revitalize Pratt & Whitney, and in December 1992, appointed a new president that was "given the task of transforming the company into a lean and flexible organization able to deliver better, more timely products with a more efficient use of resources"[3].

Under the new president, Pratt & Whitney went through drastic changes over the four-year period from 1993 to 1996. The old organization structure based on plants was replaced by a new system of Product Centers, one for each category of parts plus an eight center for final assembly (see Figure 4.1, Womack and Jones 2003). This meant the relocation of manufacturing activities from one plant to another and to the closing of a large fraction of Pratt's plant space (from 12.5 million square feet in 1992 to just over 10 million in 1997). After a series of negotiations with the union and state government, total headcount was reduced from 40,000 in 1992 to 29,000 by the end of 1994, and flexible working (multi-skilling, job rotation, multi-machine operation, continuous movement of jobs and work between plants) became the norm. The number of senior managers was reduced from 72 to 36. By mid-1995 Pratt had a completely new production system; the batch-and-queue had been replaced by a flow organization that stressed first-time quality. One example of the magnitude of the results achieved with the new production system could be seen on the North Haven facility (then designated the Turbine Airfoils Product Center), where, between August 1993 and December 1994, productivity increased by 47%, lead times decreased 50%, quality improved by 89%, and inventory was reduced by 30%.

In contrast, the product development and engineering organizations had changed very little, and was perceived as slow moving and inward looking. "The organization chart at this point, with the new Product Centers fully in place, looked unsettlingly like a Rubik's Cube"[4] (see Figure 4.1, Womack and Jones 2003). Any new product program involved an elaborate matrix of divided responsibilities and two hand offs between three massive organizations, generating confusion and high costs. "In simplest terms, developing a new product meant defining the whole (thrust, weight, fuel consumption, product cost) in a Propulsion Center, engineering and producing each major component in Component Centers, and then engineering the individual parts making up each component in the Product Centers"[5].



Key

IPT = Integrated Product Team
CIPT = Component Integrated Product Team
IPMT = Integrated Product Management Team
CPC = Charter Part Council
GESP = Government Engines & Space Propulsion
LCE = Large Commercial Engines

Figure 4.1 – Pratt & Whitney organization 1994

The solution was implemented in 1996 with the creation of much stronger Propulsion Center product teams, with dedicated component design engineers. The design engineers remaining in the Component Centers were relocated either to the small engineering function charged with developing new design methods, technologies, as well as maintaining design standards and engineering systems, or to one of the new Module Centers created out of the old Product Centers (see Figure 4.2, Womack and Jones 2003). The Module Centers were stand-alone businesses responsible for current production and support to new product development, being able to completely engineer and manufacture one of the seven modules making up a jet engine. These modules were then delivered to the Assembly Center, which would assembly, test and deliver the complete engine to the final customer.

Relocation of manufacturing activities and closure of plant space continued and Pratt's manufacturing footprint stood at just less than 8 million square feet by 2003.

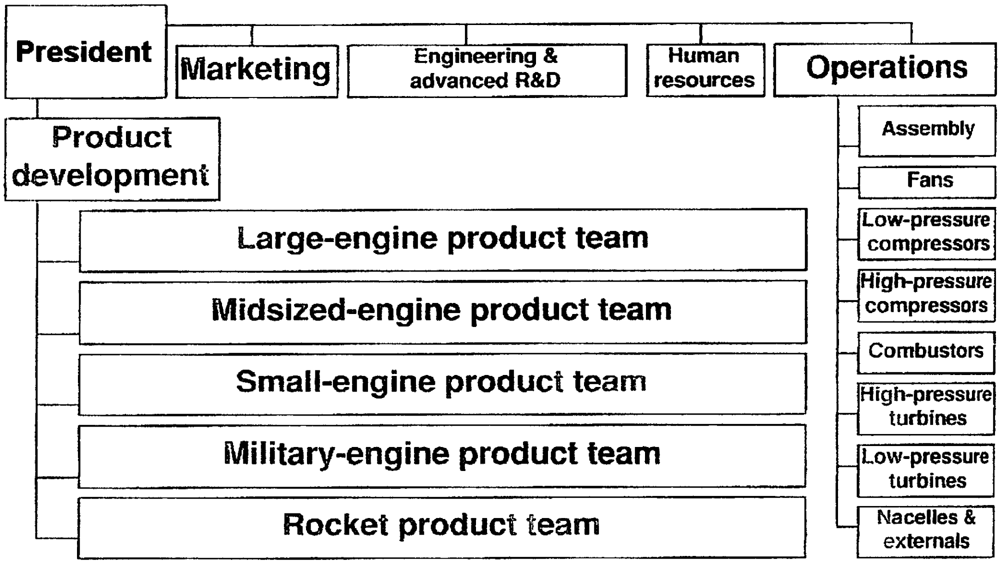


Figure 4.2 – <u>Pratt & Whitney organization 1996</u>

4.3 Analysis

The Pratt & Whitney organization of 1996 provided the basis for a significant turn around in product delivery (with contributions from both development and manufacturing) and customer satisfaction. The collocation of the development teams and the improvement of the cross-functional approach to product development were viewed as essential to achieve a focused, efficient, and "leaner" organization. The implementation of the new organization took more than the one-year forecasted, but by 1999 a truly integrated product development, with a balanced approach to meet all business objectives, was in place. By then, objectives such as product quality, product cost, and delivery dates, started to be consistently achieved; engines were certified in shorter development times, with fewer test hours, fewer resources, and about half the development cost of previous similar products.

Responsible for the delivery of complete engines to the customer, the Middletown facility was a good place to visualize the impact of improvements in product and process-manufacturing development on the final product delivered to customers. By 2003, Pratt & Whitney's Middletown-Connecticut facility housed the Engine Center (Assembly module in Figure 4.2) and the Compression Systems Module Center (Low-pressure and High-pressure modules in Figure 4.2). Approximately 2,500 people worked in the facility that had 250,000 square feet of space for production assembly and another 300,000 square feet devoted to engine development. The assembly area supported five distinct production lines (two military and three commercial).

With the consolidation of engine assembly in Middletown, the entire production process was streamlined using lean production methods. The number of workstations and the tasks assigned to each station were set by the required production and delivery rate. The implementation of this flow line assembly, which started in 1999, was responsible for moving from a position where Pratt was struggling to deliver six military engines per month to delivering between twelve and fourteen per month on schedule and within cost. By 2003, the flow line practice was also used on the assembly lines of commercial engines.

Pratt & Whitney applied its flow line approach very early in the F119 program (the engine for the Lockheed Martin F/A-22 aircraft) and started building, for the first time, the flight test engines on an active production assembly line. Pratt was working F119s into the flow line for the F100s, achieving three engines per month in 2003; but the increase in volume, due to a target of six engines per month by 2008, would not allow the mix any longer. Also, by using the same mechanics that would eventually build the production F119, experience and expertise were developed and applied on improving the manufacturing process, leading to improved performance on the F119 production line; and in 2003, the F119 engine was completely assembled in just 13 days.

The F119 had been designed with a strong focus on assembly and maintenance. "All controls and externals are located on the bottom half of the engine, allowing maintenance crews ground-level access when the F/A-22 engine bay doors are open. Only six tools are needed to remove the controls and externals…"[6]. Many of the design features that made the F119 easy to assemble made it easier to maintain. The F119 was designed also with 40% less parts than previous generation engines, contributing to its lower cost, maintainability, and reliability.

4.4 Conclusion

Throughout the 1990s, the numbers of engines per aircraft and the number of spare parts needed per hour of engine operation have continued to fall, largely offsetting the increase of the number of aircraft in operation and leading to a stagnant total sales volume in the jet engine industry.

By 2003, airline profitability, the primary driver of new aircraft (and jet engines) demand, appeared likely to remain weak for years to come. Looking at the other half of industry revenues that came from military customers, the situation was not much more optimistic. With the end of the Cold War and confusion about the military's needs for the "war on terrorism", there was no growth expected here either. Continuing orders for spare parts for the large number of military engines currently in use was offset by the continual downward revisions of major new aircraft programs (e.g. the original projection of 750 twin-engine F/A-22 aircrafts for the U.S. Air Force had been steadily scaled back to 276 aircraft by mid-2003).

To complete the picture, fierce competition for a shrinking volume of large jet engines continued between the three manufacturers (Pratt & Whitney, GE and Rolls Royce), with no signs that one of them would exit the industry.

Given this scenario, it was easy to understand why Pratt & Whitney had not been able to grow its revenues since 1997 (see Figure 4.3). But operating profits and returns showed a remarkable growth, mainly coming from a continued application of "lean principles", in manufacturing first, and then in product development (see Figures 4.4 and 4.5). This performance was a remarkable contrast to the crisis of the early 1990s, when Pratt's business fell immediately into deep loss.

Nevertheless, given the long-term realities of the market and a continued erosion of its market share, Pratt & Whitney faced huge challenges in 2004.

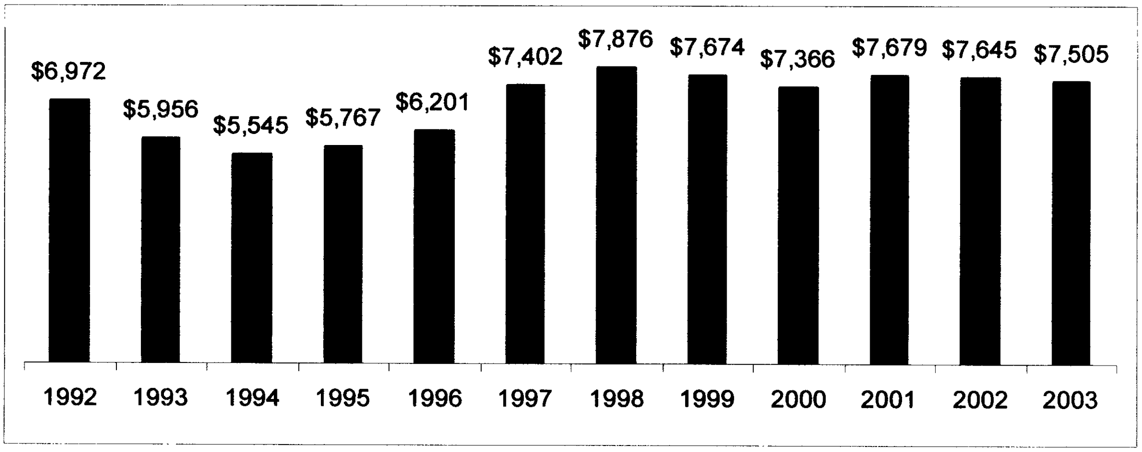


Figure 4.3 – Pratt & Whitney historical revenues ($ millions)

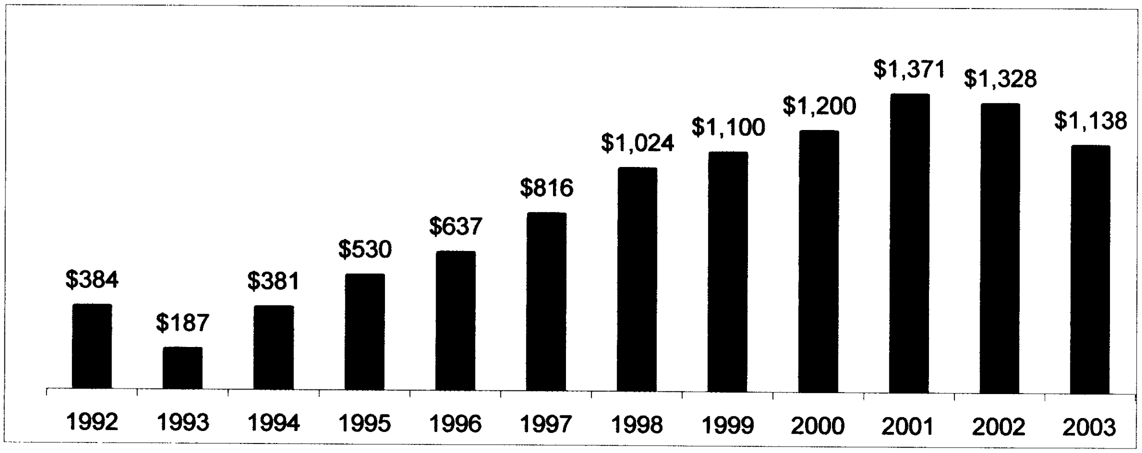


Figure 4.4 – Pratt & Whitney historical operating profits ($ millions)

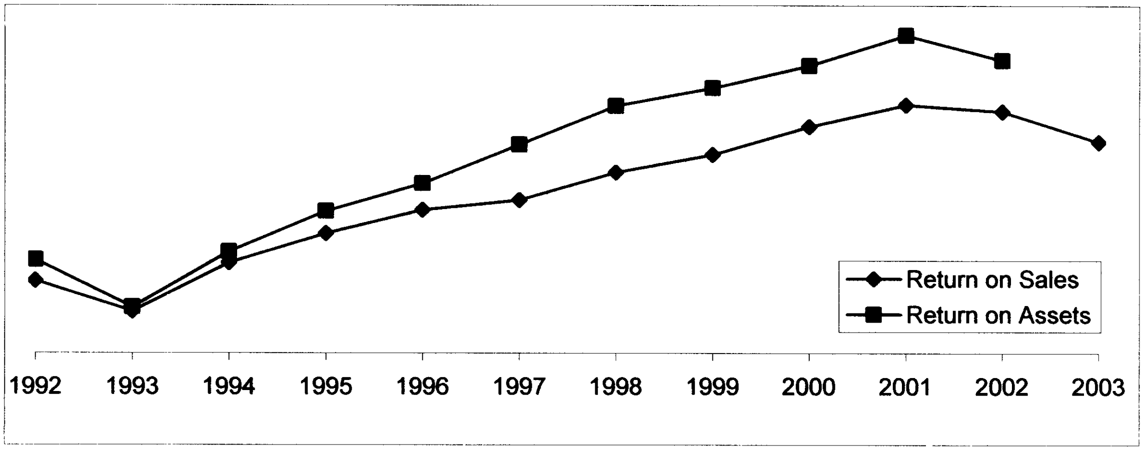


Figure 4.5 – Pratt & Whitney historical return on sales and assets

Chapter 5: Case Study Analog Devices

5.1 Background

Analog Devices, Inc. (ADI), headquartered in Norwood, Massachusetts, designed, manufactured and sold high-performance analog, mixed-signal and digital signal processing integrated circuits used in signal processing for industrial, communication, computer and consumer applications. ADI's products played a fundamental role in converting real-world phenomena such as temperature, motion, pressure, light and sound into electrical signals to be used in a wide array of electronic equipment. Such equipment ranged from industrial process control, factory automation equipment, security systems, defense electronics, base stations, central office equipment, wireless telephones, computers, automobiles, CAT scanners, digital cameras and DVD players. ADI had a company brand recognized throughout the electronics industry for innovative, high-performance technology and world-class engineering support. ADI's portfolio of more than 10,000 products served the needs of more than 60,000 customers worldwide. ADI's brand, portfolio of products, breadth of customers and core competency in signal processing technology combined to form one of the strongest franchises in the entire semiconductor industry.

The cornerstone of ADI's business strategy was its fragmented product portfolio (the top ten analog products accounted for only 12% of revenues and the top 25 only 21% of revenues) and broad customer base (12% of revenues were derived from the ten largest customers, and the top 1,000 customers accounted for 41% of revenues).

ADI, with 8,400 employees (including 3,100 engineers) and eight manufacturing sites worldwide (being three outside the U.S.), had 2003 sales of $ 2.047 billion (net income of $ 298 million) divided among industrial (between 35% and 40%), communications (between 35% and 40%), computers and computer peripherals (15%), and consumer electronics (10%). ADI sold its products worldwide through a direct sales force, third-party distributors and independent sales representatives. ADI had direct sales offices in 19 Countries. ADI had 2003 sales (based upon point of sales) divided among North America (26%), Europe (19%), and Asia (55%). ADI commanded a 45% of the analog data converter and 40% of the analog high-performance amplifier markets.

By 2003, Micro-Electro Mechanical Systems (MEMS) technology had just become a core technology for ADI, after several years of investment. Since ADI tested a MEMS accelerometer for the auto industry in 1987, and invested half-a-million dollars to define a new market in the area of sensors in 1988, multiple innovative applications for its MEMS sensors had emerged and several of these ideas were commercialized. ADI was the world's largest supplier of inertial sensors to the automotive, consumer, and industrial markets and the only high-volume producer of MEMS devices.

5.2 Business Context

Until the late 1980s, ADI had played a niche strategy, focusing its attention on being the first to market with new products whose unique performance enabled it to earn substantial margins. These applications usually required only modest production volumes. But since then, several of the newer applications for ADI's products had developed substantial high-volume potential. For high-volume applications, customers were demanding lower prices and better delivery performance. ADI decided to concentrate on penetrating the higher-volume markets developing in computers, communications networks, and consumer products and to use the lower-cost structure from serving these markets to maintain and increase penetration in its traditional lower volume industrial and military markets. In order to support this strategy, in the early 1990s, ADI increased its focus on product quality, on-time delivery, lead-time, yields, and new-product time to market.

During the early 1980s, two engineers from ADI worked on the initial development of a MEMS accelerometer design and looked into the feasibility of its manufacturing. By 1986, after sharing their findings with others in ADI, it was decided to focus on an application in the automotive market; and in 1987, the first test of a MEMS accelerometer for the auto market was performed. In 1988, ADI top management allocated the first budget to develop MEMS designs.

By 1990, the MEMS project budget was doubled to $ 1 million. The chip design was defined but the manufacturing process was not reliable. Unlike the other ADI products, the automotive market required the manufacturing of chips in large volume. The project faced tremendous difficulties in supplying orders as the manufacturing process continuously failed on every attempt to ramp-up production. "As one manager explained, there was innovation in the manufacturing process that we had no idea why it worked… in the middle of ramping up and major product delivery, everything failed"[1]. It took more than 2 years for ADI to make accelerometers in volume due to the lack of capacity and process that could produce thousands of devices cost-effectively. Production was done in small batches and devices were hand tested. "By 1994, they had only shipped about total 60,000 accelerometers"[2]. Between 1994 and 1996, the accelerometer design was refined and improved, and a lot of research and development was done on the manufacturing process, tool sets specific for the MEMS devices, and on materials and chemicals. The manufacturing process was stabilized but without a full understanding how it really worked. "They could not successfully change it or modify it without the process becoming unstable again"[3]. By 1996, ADI was shipping 6 million accelerometers per year, and the project was moved to the newly created Micromachining Division.

"While the internal focus was on improving the process to increase yields and quality, the new micromachining division was also trying to enter other new markets and develop new devices based on their emerging competence in MEMS technology. As the division began to understand the MEMS technology, other MEMS products and applications were beginning to be simultaneously developed"[4].

5.3 Analysis

The MEMS project started facing the uncertainties of an untried technology concept, an undiscovered application, and an unknown product and process technologies. The development of this emerging technology, and its subsequent commercialization, enhanced significantly ADI's process and production capabilities.

The MEMS project required ADI to both build and expand its knowledge base, as there was no available basic information on MEMS other than some experimental work in university laboratories. In several critical technical areas, despite lacking any real prior knowledge, ADI acquired, through a process of experimentation, a minimum level of understanding required to interweave these technical fields and develop solutions (see Figure 5.1, Coates and McDermott 2002).

Field of knowledge	Pre-existed or created
Electrical engineering	Pre-existed
Mechanical engineering	Created
Silicon material engineering	Pre-existed
Micromachining expertise	Created
Controlled environment processes	Pre-existed
Wafering processes	Created
Packaging technology	Created
Batch processing	Created
Product assembly	Created
Market understanding	Created

Figure 5.1 – Knowledge required for MEMS product and process development

The use of this knowledge base, combined with a relentless experimentation campaign via product and process development projects, gave ADI the ability to design and manufacture MEMS based products (see Figure 5.2, Coates and McDermott 2002).

The MEMS project adopted an integrated multi-functional approach. The designs had inputs and were periodically reviewed by engineers from all different domains. The incorporation in the design of both electrical and mechanical properties, and potential needs of materials and fabrication, resulted on structures much more stable and, thus, more manufacturable. The project also made heavy use of simulation focused on the incorporation of electrical and mechanical functionality on the design, via the development of proprietary design tools and software ("learning before doing").

The MEMS project developed production facilities and equipment outside the ADI's centralized manufacturing organization. Building initially on tool sets derived from those in ADI's central manufacturing, the project gradually modified these to specifically make MEMS devices rather than ICs; the project also had machines specifically fabricated by suppliers (using special contracts that prevented their use by potential competitors). Over time, ADI became a leading expert in applied micromachining.

Packaging and testing were two other key areas that required several process projects.

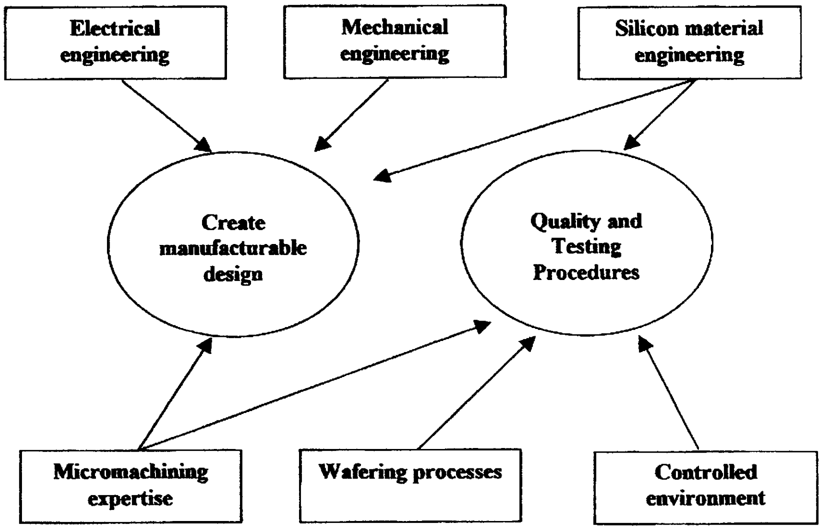


Figure 5.2 – MEMS product, process, and production capabilities

5.4 Conclusion

The reliability of the products and manufacturing process has given Analog Devices a significant competitive advantage over other MEMS developers. The manufacturing-process capabilities were fundamental for ADI to produce MEMS accelerometers at low-cost and high-volume and to provide the flexibility to experiment and produce the gyroscope and other MEMS devices.

Chapter 6: Notes on General Motors and Toyota

6.1 Background

In April 2002, on a document titled "Global Vision 2010", Toyota publicly outlined the direction it needed to take in the 21st century and its determination to step up the pace of reforms targeting growth. In this document, Toyota aimed to achieve a 15% global market share by 2010, up from the 11% in 2002. By contrast, General Motors, the then current market leader with 15% market share in 2002, had been experiencing steady erosion from the 20% market share position it held back in 1985.

"Toyota's vision is given credibility by the success of its Global 10 initiative launched in the mid-1990s to gain 10 percent of the global motor vehicle market by 2000. In 2000, Toyota's global share was 10.01 percent"[1].

By 2003, Toyota was the third-largest auto manufacturer in the word, behind General Motors and Ford, with global vehicle sales of over six million per year in 140 countries. "Auto industry analysts estimate that Toyota will pass Ford in global vehicles sold in 2005"[2]. It is important to note that Toyota's steady gains in market share had not been "bought" at the cost of low margins. Toyota was far more profitable than any other auto manufacturer, and its 2003 profit were larger than the combined earnings of General Motors and Ford ("its net profit margin is 8.3 times higher than the industry average"[3]).

In 2003, Toyota's Corolla was the top-selling small car in the world. Toyota's Camry was the top-selling passenger car in the U.S. (for the fifth time in six years), and Toyota's Lexus was the top-ranked luxury vehicle, outselling BMW, General Motors' Cadillac, and Mercedes-Benz in the U.S., for the fourth consecutive year. "According to a 2003 study in Consumer Reports, one of the most widely read magazines for auto-buying customers, 15 of the top 38 most reliable models from any manufacturer over the last seven years were made by Toyota. No other manufacturer comes close. GM, Mercedes, and BMW have no cars on this list"[4].

It was also important to understand that Toyota continued to grow without needing to be a dramatic innovator in the vehicle market. With few exceptions, Toyota had been a follower in the new market segments with highest growths (pickups, minivans and SUVs). Toyota was able to follow this strategy because its product development process delivered new products on time, with very few defects, and cheaper than similar offerings from competitors. And its manufacturing and supply chain processes delivered higher quality at lower cost and allowed Toyota to practice higher selling prices within each segment of the market.

"The brilliance of Toyota's processes mean that Toyota does not need to gamble on daring product designs within an established segment of the market or to pioneer new segments. Its situation is remarkably similar to that of General Motors in its golden period from the early 1920s into the 1960s, when Alfred Sloan decreed that gambles on product technology were unnecessary as long as the company could quickly match any successful innovation by more daring competitors"[5].

6.2 Toyota And The 21st Century Car

"Toyota executives considered the early 1990s to be a very dangerous business climate for Toyota. The problem was that Toyota was too successful"[5]. At the peak of the Japanese bubble economy, with Toyota's business booming, the Toyota leaders feared complacency. At that time Toyota had a very strong and capable product development system, but it had remained largely unchanged for decades. In 1993, Toyota thus launched an initiative called Global 21 (G21) tasked with developing new methods for development and manufacturing of cars for the 21st century. The final outcome of the G21 project was the launch in October 1997 of hybrid car Prius, but the most important result from the project was the creation of the "obeya" system of product development (for a detailed description of the old and new systems, see Cusumano and Nobeoka 1998).

In 1996 the auto industry standard for developing vehicles was five to six years. But as early as 1982, Japanese auto companies were developing car just under 4 years. By 1996, Toyota was already able to develop variations of an existing model in 18 months. With the "obeya" system, the breakthrough Prius made it in only 15 months. By 2003, Toyota had the fastest product development process in the world. New cars and trucks took 12 months or less to design, while competitors typically required two to three years. And interestingly enough, Toyota did not use many of the practices often considered critical to successful concurrent engineering. In Toyota, the multidisciplinary teams were not collocated or dedicated to one vehicle program, there was heavy use of prototypes, specifications were frozen very late in the process, and the process was very unstructured.

6.3 Toyota Product Development System

The traditional design approach, whether concurrent or not, tends to quickly converge on a solution and then modify that solution until the design objectives are met. It seems an effective approach unless the starting solution is the wrong one; the subsequent iterations to refine the wrong solution can be time consuming and lead to suboptimal design. Another problem with this approach arise when concurrent work takes place between members of the development team; as the design passes from group to group for feedback from different functional perspectives, every change causes further changes and analysis, resulting in rework and additional communication demands. There is no guarantee that the process will converge (see Figure 6.1, Sobek, Ward and Liker 1999).

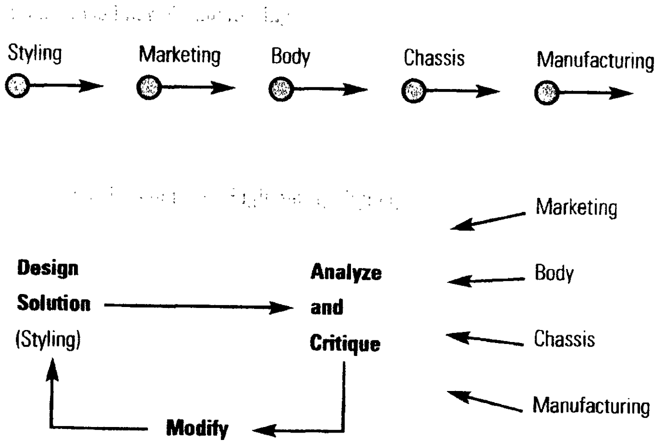


Figure 6.1 – The point-based product development

The "obeya" system is based on a set-based concurrent engineering approach. It begins with a broad consideration of different sets of possible solutions and gradually narrowing down the set of possibilities to converge on a final solution. Here, development team members develop and communicate sets of solutions in parallel and independently. As the design progresses, team members gradually narrow their respective sets of solutions based on the additional information from development, testing, customer and other member's sets. As the design converges, team members commit to staying within the sets so that others can rely on their communication (see Figure 6.2, Sobek, Ward and Liker 1999). The gradual convergence to a final design helps the development team to make sound decisions at each stage and to work concurrently with low risk of rework. The set-based approach works in the context of multiple functions defining and communicating sets, while converging to mutually acceptable solutions that optimize the system performance, not the sub-system performance. As an example, “In developing a vehicle’s styling, Toyota makes more one-fifth scale clay models than most competitors do. Toyota maintains at least two full-scale models in parallel (typically from two studios), while most competitors pick one styling design, create one full-scale clay model, and go immediately to detailed design. Simultaneous with the development of the two to three full-scale models, Toyota engineers develop structural plans for multiple styling design ideas and analyze them for manufacturability”[6].

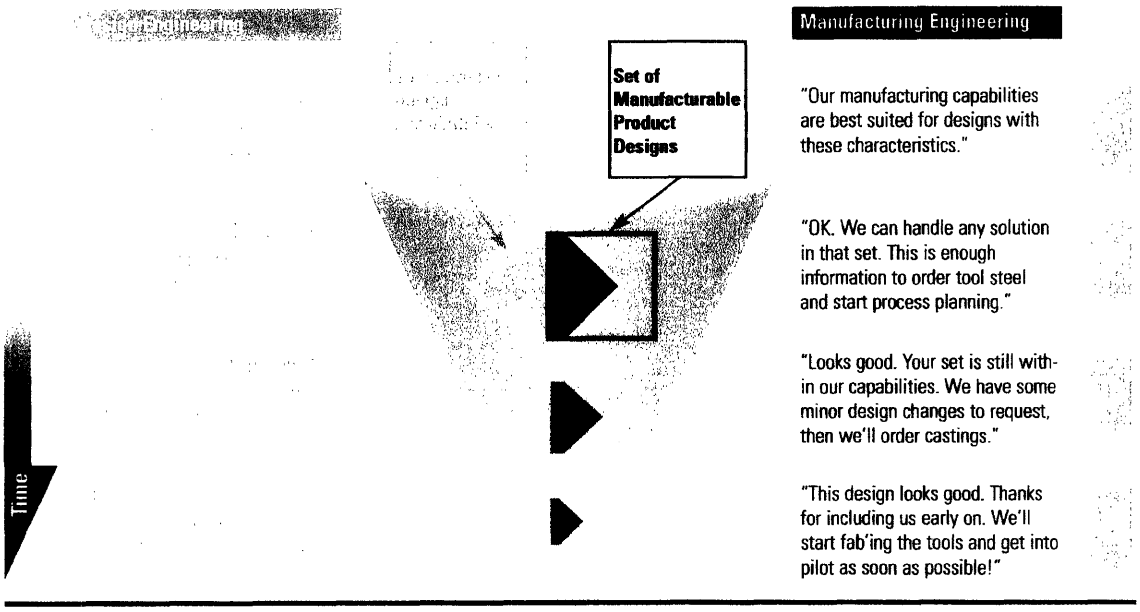


Figure 6.2 – The set-based product development with example of design and manufacturing interaction

Toyota's approach recognizes that early in the design process, the "right answer" cannot be known. Rather, it must be unveiled through several iterations. "The precise functionality that customers want must be discovered, how to map that functionality onto component parts and sub-systems must be discovered, how to construct those component parts and sub-systems must be discovered, and how to join components and sub-systems must be discovered too"[7].

There are many factors that contribute to the efficacy of the Toyota Development System, and the set-based concurrent engineering approach is only one of them. The Toyota's engineering culture, with deep technical expertise in both its engineering and management ranks, is a fertile ground for the set-based approach to work. Another key factor is the Toyota's Vehicle Development Centers matrix organization, with general managers heading functional organizations and chief engineers leading vehicle programs (see Figure 6.3, Cusumano and Nobeoka 1998).

In the Toyota organization, the chief engineer specifies a range of solutions within which engineers must explore and the engineers responsible for the sub-systems specify ranges of solutions as boundaries within which more junior engineers must explore. The chief engineer and his subordinates give functional specialists the opportunity to explore design opportunities and to find feasible component, sub-system, and interface solutions. The convergence from a feasible set to a single specified interface design occurs not only cross-sectional among the sub-system designers, but also longitudinal across the different stages of the product development. Taking the example where Toyota has two full-sized clay models when the design is handed from the stylists to the manufacturing people, "the Toyota approach acknowledges that the stylists can accept a final product somewhere within a range of physical dimensions, and manufacturing can produce a physical product within another range of dimensions. The key is to allow the stylist and the manufacturing engineers to explore the feasible space that is common to both functional specialties before committing to a single final design"[8].

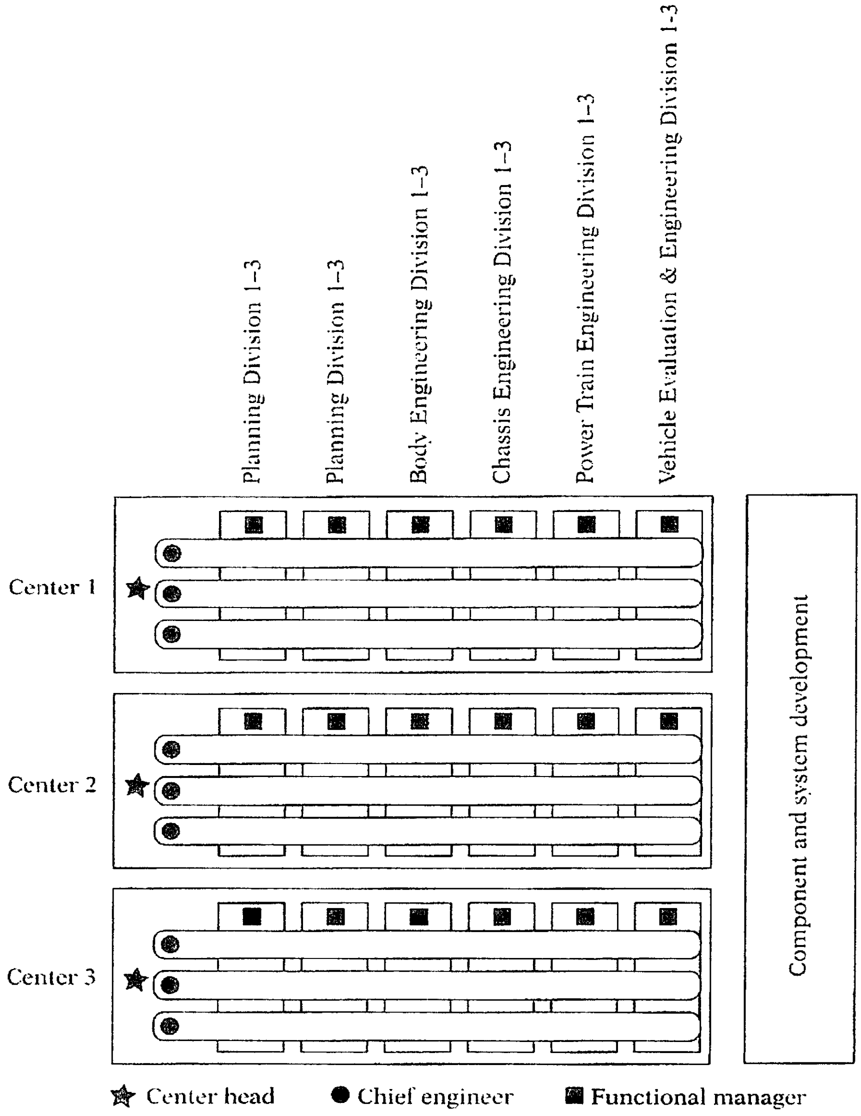


Figure 6.3 – Toyota's product development organization after 1994

6.4 General Motors And Leaner Product Development

Like most other auto manufacturers in the 1990s, General Motors also launched a number of major initiatives to change how it did product development. Though the world's largest auto manufacturer, General Motors suffered from low profitability partly due to manufacturing inefficiencies but also to slow and costly product development and components organization. A typical example of GM's problems in 1993 was on the huge variety of similar components (e.g. "its 1993 models had more than 200 different steering columns, 89 steering gears, and 44 power-steering pumps"[9]).

General Motors started by emphasizing process improvement in project management, moving towards the use of faster lean techniques with overlapping phases and heavyweight project managers. General Motors continued by bringing together its various design, marketing, components, and manufacturing groups. In particular, control over all design, engineering, and technical staff was centralized with the creation of the GM Technical Center organization. The next step, and starting in 1994, was the creation of the Car and Truck Centers, operating as semi-independent centers (doing design and some component engineering work for multiple products), although most engineers work through the Technical Center (see Figure 6.4, Cusumano and Nobeoka 1998). In addition, General Motors appointed "Vehicle Line Executives" (VLE) that were responsible for product development based on common platforms, functioning somewhat like the Toyota's center managers. Another key practice at General Motors was the coordination of components development, selection, and procurement, very similar to the component sharing at Toyota.

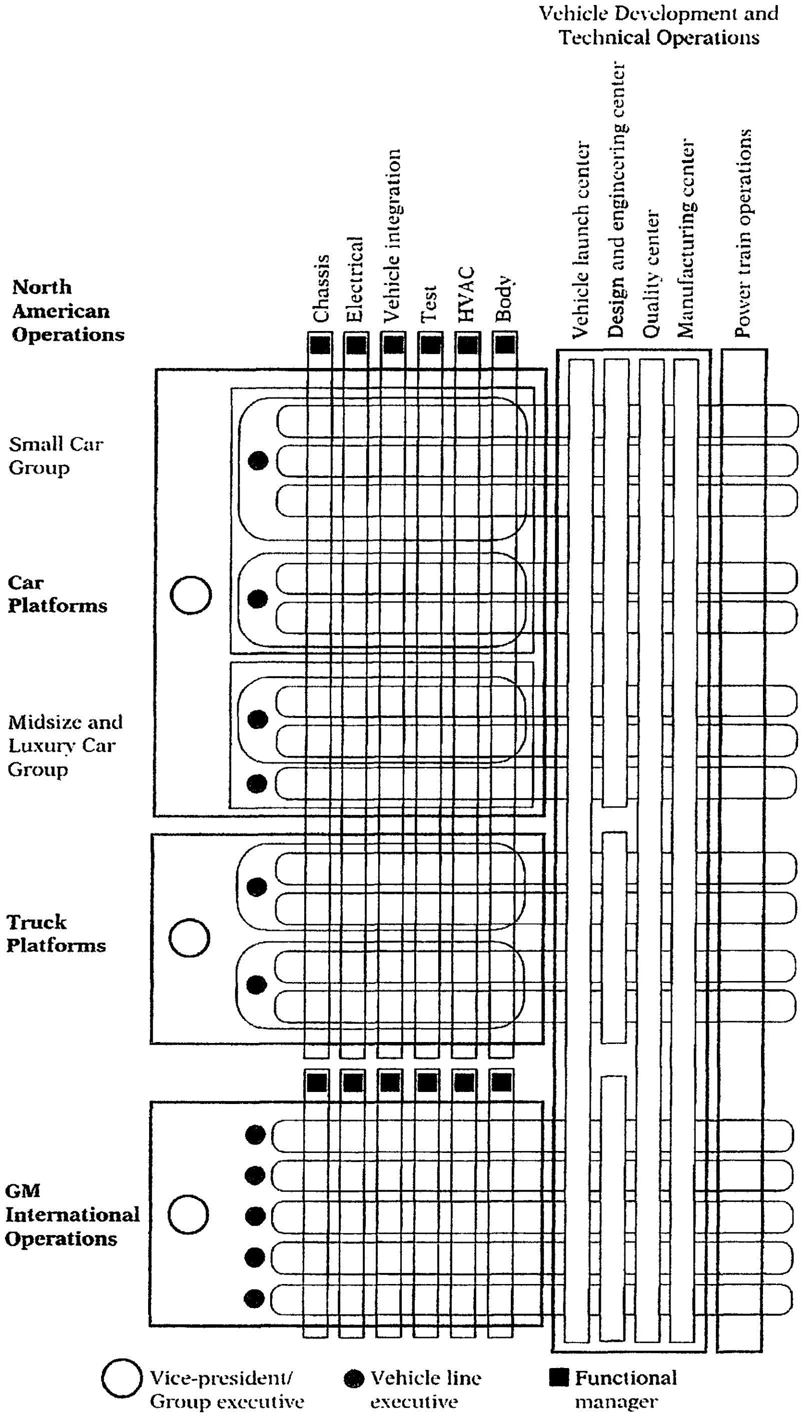


Figure 6.3 – General Motors' product development organization after 1997

By 2003, the General Motor's product development organization was not too much different from the one back in 1997; one of the visible differences was the consolidation of the two Small Car and Midsize and Luxury Car Groups into one Car Center. Despite the similarities between General Motors and Toyota's product development organizations (as depicted on figures 6.3 and 6.4), General Motors' product development system was based on a point-based concurrent engineering approach. Heavy weight project management focused on a particular platform or model, with multifunctional collocated design teams, following highly structured design processes, worked a point by point iterative search for solutions.

6.5 Different Approaches

Both General Motors and Toyota's product development approaches, point-based and set-based concurrent engineering, provide multiple opportunities for the integration of product and manufacturing-process development; both use extensively integrated development teams, design for manufacturing techniques, and prototyping as practices to support the integration. But, the underlying basic assumptions of each product development approach lead to very different implementation modes of these practices, and consequently to different results in the final product development performance.

In general, the set-based approach creates more opportunities for experimentation than the point-based one and Toyota takes full advantage of it.

At Toyota, the process of communicating the sets of solutions definitely increases the quality of the communication within the integrated development team, while decreasing the length and frequency of meetings (Ward, Liker, Cristiano, and Sobek

1995). Toyota's body designers waste little time on detailed designs that cannot be manufactured because the manufacturing personnel can precisely define the set of bodies that are manufacturable and structural decisions are made concurrently through the process before the detailed design begins. Toyota's engineers from different functions can work relatively independent because each meeting communicates information about an entire set of designs.

At Toyota, for every major part of the vehicle, the engineers responsible develop, maintain and update an engineering checklist, which represents the current capabilities, and consequently the set of feasible designs. The same is true for product and manufacturing engineers. When a product engineer start a design, the manufacturing engineer sends the latest checklist, so the product engineer knows the current constraints on the possible solutions; as long as the product engineer's design stay within those constraints, the design should be acceptable to manufacturing. By taking time upfront to explore and document feasible solutions from design and manufacturing perspectives, the development team achieves tremendous gains in efficiency and product integration later in the process, and also for subsequent development projects.

Toyota develops an extraordinary number of different designs (from 2 up to 10 times more than competitors) and "continues to refine the intermediate and final clay models until 27 months before production"[10](versus 37 for competitors). For the intermediate clay models, when they are completed, a meeting takes place with participants from different functional areas. Each functional area audits the model against its engineering checklist ("lessons-learned book"). "For example, a Toyota die designer showed us a lessons-learned book for a fender design. The book, ten to twelve pages long, contained approximately sixty to seventy different ranges of specifications that would ensure the fender design's manufacturability (e.g. intervals of acceptable curvature radii for angles). Developed during the past fifteen years, these books of every body part give a very detailed definition of what can be done from each functional area's viewpoint"[11]. Deviations are noted on an audit sheet describing the problem and possible solution. These audit sheets become the primary communication mechanism between the affected groups. The suggestions often address the problem to the satisfaction of all parties involved. However, if they are not able to reach a solution acceptable to all, a functional group will develop a new technology or process advance to make the design feasible (and then revise the "lessons-learned book").

6.6 Final Comments

Set-based concurrent engineering, combined with Toyota's capabilities for manufacturing, integrating systems and nurturing organizational knowledge, appear to be the basis for Toyota's product development excellence.

General Motors has been changing and trying to become leaner not only in manufacturing but also in product development. If the product development performance gap in relation to Toyota is to decrease, an integrated lean product development system, equivalent of GMS (the General Motors version of the Toyota production system), has to be adopted and implemented. But there are significant barriers. Ranging from the existing legacy systems, relationship with employees and suppliers, and perhaps the most important, engineering expertise, as truly concurrent engineering seems to require more skill and judgment than the traditional point-to-point approach ("Toyota engineers serve a minimum of fifteen years before reaching management positions, have extensive hands-on experience, undergo frequent training, and are vigorously encouraged to think about their jobs and technologies by managers who are themselves technical experts"[12].

Chapter 7: Conclusions And Recommendations

Effective manufacturing-process innovation can play a very important role in industries characterized by rapid product innovation and intense competition in new product development. In high-technology industries, behind many new products, there are extremely complex process technologies that are as important to the overall commercial success as the design of the products themselves. "In such context, the value of process development lies in how it contributes to the overall effectiveness and performance of the product development cycle"[1].

Despite the recent years progress observed on achieving compatibility between process development and product design (e.g. design for manufacturing, concurrent engineering), process development capabilities go well beyond and can contribute significantly to the speed, efficiency, and quality of new product launches.

Companies that develop sophisticated manufacturing-process technologies, more rapidly and with fewer resources, have strategic options that less capable competitors lack. Shorter process development cycles enables more aggressive product development lead times by staying out of the critical path and allows the organization to take on more projects (e.g. Toyota's manufacturing excellence is an enabler to the design of cars and trucks using 50% of the time and 50% of the resources that competitors typically require). In situations where there is a high degree of technical uncertainty on new product introductions, a faster and efficient process development organization offers the possibility of delaying key technical decisions and resources deployments (e.g. allowing the process design to wait on better information about the product while still meeting scheduled milestones). Where product and process technologies are tightly intertwined, manufacturing-process innovation can push the frontiers of technology and give product designers a higher degree of freedom by allowing fewer design compromises in the name of manufacturability (e.g. Analog Devices pushed the integration of electrical, mechanical, materials, and fabrication technologies in order to achieve a stable manufacturable MEMS product).

The wide range of manufacturing-process development activities, from computer-aided simulations to pilot runs in a commercial production facility, prompts different organizational structures and development strategies. There is no single best approach. Process development projects invariably require a range of experimental approaches to be used (e.g. Pratt & Whitney uses extensive computer-aided simulations in designing new engines but it also requires feedback on designs for certain parts through engine runs in test cells and in-flight tests). Choosing the appropriate mix of "learning before doing" and "learning by doing" is a continuous and dynamic task for management, as companies operate in an environment where technology, markets, and competition keep changing. Also, as a company gains experience with certain manufacturing-process technologies, its own capabilities and knowledge base evolve (e.g. Analog Devices continuously built and expanded its knowledge base in order to be able to produce MEMS products at low-cost and high-volume). Resource allocation across different phases of the product development cycle is one powerful way managers can induce the execution of a particular approach.

The capability of capturing the knowledge learned on each process development project and applying on the next one is largely influenced by management decisions in relation to process development structure and resources allocation (e.g. Toyota's "lessons-learned books" contain detailed information, collected over years and updated per project, on design's manufacturability of every part). Learning in process development requires a two-way concurrent communication, and feedback from manufacturing to R&D is as important as the transfer of knowledge from R&D to manufacturing. Creating such a capability is a significant contribution to manufacturing-process development excellence. Organizational or geographical barriers between R&D and manufacturing in general have a significant negative consequence.

Many companies fail to exploit the full value of manufacturing-process innovation and development by adopting a model based on mature industry settings where low cost is the primary driver of competitive advantage. In technologically dynamic industries, the value of process development has to be more broadly framed in terms of its support for faster, more efficient, and higher-quality product development (see Figure 7.1, Pisano 1997).

	Conventional Model	New Model
Primary Goals	Reduce manufacturing costs of existing products	Proactive support of timely, efficient, and high-quality launches of new products
Technical Focus	◦ Incremental process improvement • New capacity/ equipment/automation ◦ Troubleshooting ◦ Product modifications for enhanced manufacturability	◦ Exploration/development of new process architectures needed for new product designs
Product Development Role/Influence	Peripheral	◦ Central ◦ Process developers as core members of product development teams
Customer	Plant	◦ Plant ◦ R&D
Key Capabilities	◦ Process engineering ◦ In-depth knowledge of current manufacturing environment ◦ Minimize product disruptions	◦ Process science ◦ Ability to anticipate future manufacturing requirements ◦ Responsiveness to project level uncertainty
Learning	Maximize learning curve *within* product/process generations	Capture learning *across* product/process generations
Metrics of Performance	Improvements in yield, cost, quality, and capital over the life of a product	◦ Improvements in *initial* yield, cost, quality, and capital across products ◦ Lead time, efficiency, quality

Figure 7.1 – <u>The new model for process development</u>

Management must articulate a far different role for manufacturing-process development, in terms of its contribution to the company's product development capabilities, in order to unlock its hidden leverage. In high-performing organizations, process development is considered a critical element of the product development process and process developers are core members of the project teams, and are viewed as technical peers to those on the product development side of the organization. In high-performing organizations, management nurtures process development capabilities by applying a mix of learning and problem solving approaches that support the chosen business strategy and are built upon the company's specific knowledge base. In high-performing organizations, management adopts an evolutionary approach to process development through which each project incorporates incremental changes (in processes or practices) to reflect what has been learned from prior projects.

There is no one "right way" to manage manufacturing-process development. In technologically dynamic industries, matching a company's process development strategy to its unique operational context, and competitive and technological environments creates superior manufacturing-process development capabilities, which in turn contribute to achieving product development excellence.

Notes

Chapter 1

1. Wall Street Journal, 28 April 1992, p. A16.
2. Fortune, 3 October 1994, pp. 124-128.
3. Pisano (1997), p. 3.

Chapter 2

1. Abernathy (1978), p. 168.
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