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Comparing Performance and Organization of Product Development across Firms, Regions and Industries: The Applicability of the Automobile Case

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Comparing Performance and Organization of Product Development across Firms, Regions and Industries: The Applicability of the Automobile Case

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Abstract

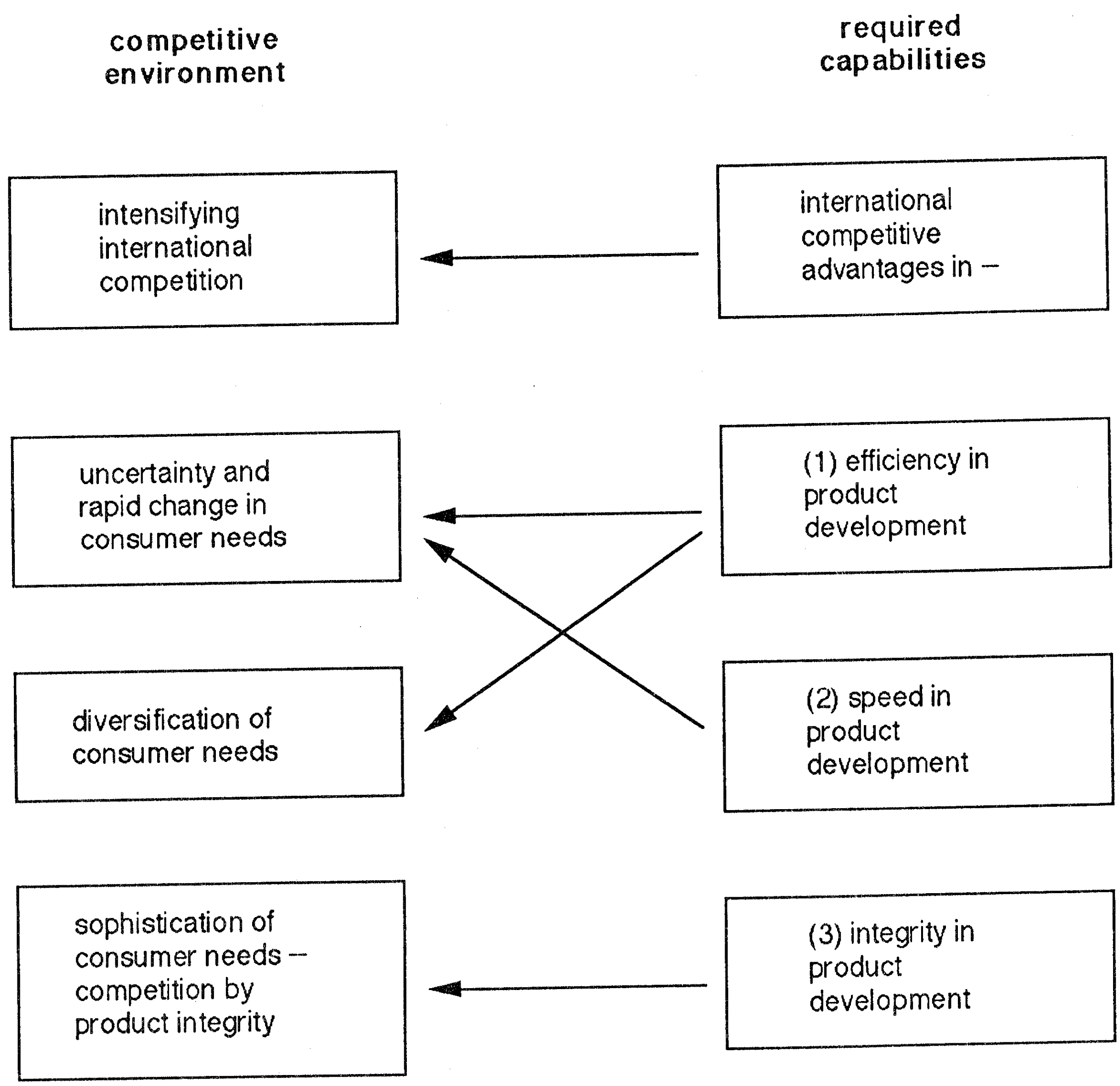
This paper examines how patterns of process and organization in product development, the downstream area of the firms' R&D operations, affect competitive performance of manufacturing firms. The U.S., European and Japanese automobile industry is selected as a case. After a description of the nature of the competitive environments in this industry, the paper first presents data from 29 projects at 20 automobile companies worldwide in order to identify significant inter-firm and inter-regional differences in product development performance such as lead time, development productivity and total product quality. It then argues that a certain consistent pattern of organizations and processes, including supplier involvement in product design, effective use of manufacturing capability in development, inter-stage integration between product and process engineering, and the heavy-weight product managers system, tends to lead to high performance in all of the three criteria. The paper finally examines the generalizability of the findings. It is proposed that applicability of the findings on effective product development to other industries may be examined along at least three dimensions: product-user complexity, product-process linkage, and product-component change.

1. THE NATURE OF THE NEW PRODUCT COMPETITION

In the 1980s, a new pattern of competition has emerged in many industries worldwide, including the automobile, computer, consumer electronics, and other consumer durables and machinery. This trend, which is quite likely to continue in a growing number of industries in the 1990s, may be characterized by the following four points (Figure 1).

First, international competition has intensified. This is not just a matter of expansion of imports (e.g. Japanese cars in Europe and North America, or

Figure 1 Emerging Competitive Environment and Required Capabilities in Product Development



European cars in Japan). It also means direct international product rivalry in the same market segment. For instance, today's U.S. consumers are more likely to consider Ford Taurus, Nissan Maxima, Mazda 626 and Peugeot 405 when they buy a family sedan. A Japanese buyer may also compare Opel Vectra, VW Passat, Toyota Camry and Honda Accord. For consumers, international product rivalry means wider variety in their brand choices.

Second, the market has become more uncertain and volatile as customer tastes have grown complicated and unpredictable, the number of rival products has risen, and changes in consumers' lifestyle have accelerated. This is particularly apparent in the Japanese and American auto markets, but Europe does not seem to be totally unaffected by this trend. This implies that the producers must make greater efforts to respond quickly to the changes in market needs and rivals products, as well as to forecast future market changes accurately.

Third, the market has also become more diversified as customer tastes have become more fragmented into niches. In the U.S. auto market, for example, the most popular model in the 1970s would sell about 1.5 million units (including derivatives); the number is more likely to be less than a half million now. In Japan, also, the average number of cars sold per model has decreased during the past decades. Although superficial proliferation of product variations does not seem to bring about market success, the manufacturers may have to create greater variety at a more fundamental level of product concepts and basic designs.

Fourth, what we may call "product integrity" has become the focus of competition in many industries including automobiles (Clark and Fujimoto, 1990). As consumers have already accumulated experience with the product and have become sensitive to subtle differences of many product dimensions, they now demand consistency in all the product characteristics. In such a market, neither high technology in its crude form nor low price alone guarantees product success. Partial product excellence such as high performance in a few criteria or novelty in one component technology no longer impresses today's users. What they appreciate most is the consistency of total product-user interface in functions and semantics. We call the totality of the product that attracts and satisfies customers "product integrity".

2. SPEED, EFFICIENCY AND INTEGRITY

When the market and competition are characterized by the above conditions, effective organizations and processes for new product development must also have the following three capabilities simultaneously (Figure 1).

(1) *Speed in product development* (i.e. short lead time): Fast development facilitates accurate market forecasting and quick response to competitors' threat, which is advantageous in an unpredictable and rapidly

changing markets. The optimal length of the lead time depends upon the industry, region and timing, but many companies have found their lead time too long to compete effectively.

(2) *Efficiency in product development* (i.e. fewer resources needed for a standard product development project): Given the level of available engineering resources, efficient product development brings about more new products launched per period. More new products, in turn, can be used for more frequent renewal of existing models or faster expansion of product varieties, which is advantageous when the market is volatile and/or diversified.

(3) *Integrity in product development* : As product development is essentially a simulation of future consumption patterns, effective development processes and organization have to reflect these patterns of product-user interaction. When consumers become sensitive to subtle nuances in products, development organizations have to cope with subtle information. When product integrity is emphasized in the market, integrity in the development process and organization becomes critical for competition . Just as the key to high product integrity is the harmony of many detailed aspects of the product, the key to a high process-organization integrity is consistency in the many detailed activities of product development.

Thus, in order to achieve consistent product success in the new industrial competition mentioned above, a company simultaneously needs speed, efficiency and integrity of product development. In the world auto industry of the 1980s, there were a few companies which managed to attain top performance in all three dimensions.

3. INTERNAL AND EXTERNAL INTEGRATION

But what kind of organizations and processes are necessary to achieve all the three capabilities? Individual techniques and technologies such as computer-aided design and manufacturing (CAD-CAM), simultaneous engineering (i.e. the overlapping of upstream and downstream steps in development), value engineering (VE) and quality function deployment (QFD) may partially contribute to better performance, but total product success seems to require the overall improvement in organizations as well. Specifically, organizational integration seems to be the key when product integrity is called for in a dynamic and diversified environment.

If product integrity is called for in a stable and homogeneous environment, a simple organization with a powerful design genius, or a functional organization with a strong engineering tradition, would be sufficient for organizational integrity and product success. However, if product integrity is emphasized in a dynamic and diversified environment, a strong product integrator may be needed for each product or project. These integrators may (1) internally integrate the organization by coordinating functional divisions, and (2) externally integrate the producer-customer interface by creating product concepts and making sure that the concept is realized in every small aspect of the product. In other words, what may be needed for product success in the competitive environment mentioned above is a group of powerful internal/external integrators, each of whom becomes a strong project coordinator and a strong concept champion combined for each product. At the same time, members of the product development teams at the working level have to support the integrators by sharing concepts and goals with them.

To sum up, my prediction is that powerful internal/external integration is the key to fast, efficient and coherent product development and thus to consistent product success especially when the market becomes dynamic, diversified and sophisticated.

4. PRODUCT DEVELOPMENT PERFORMANCE

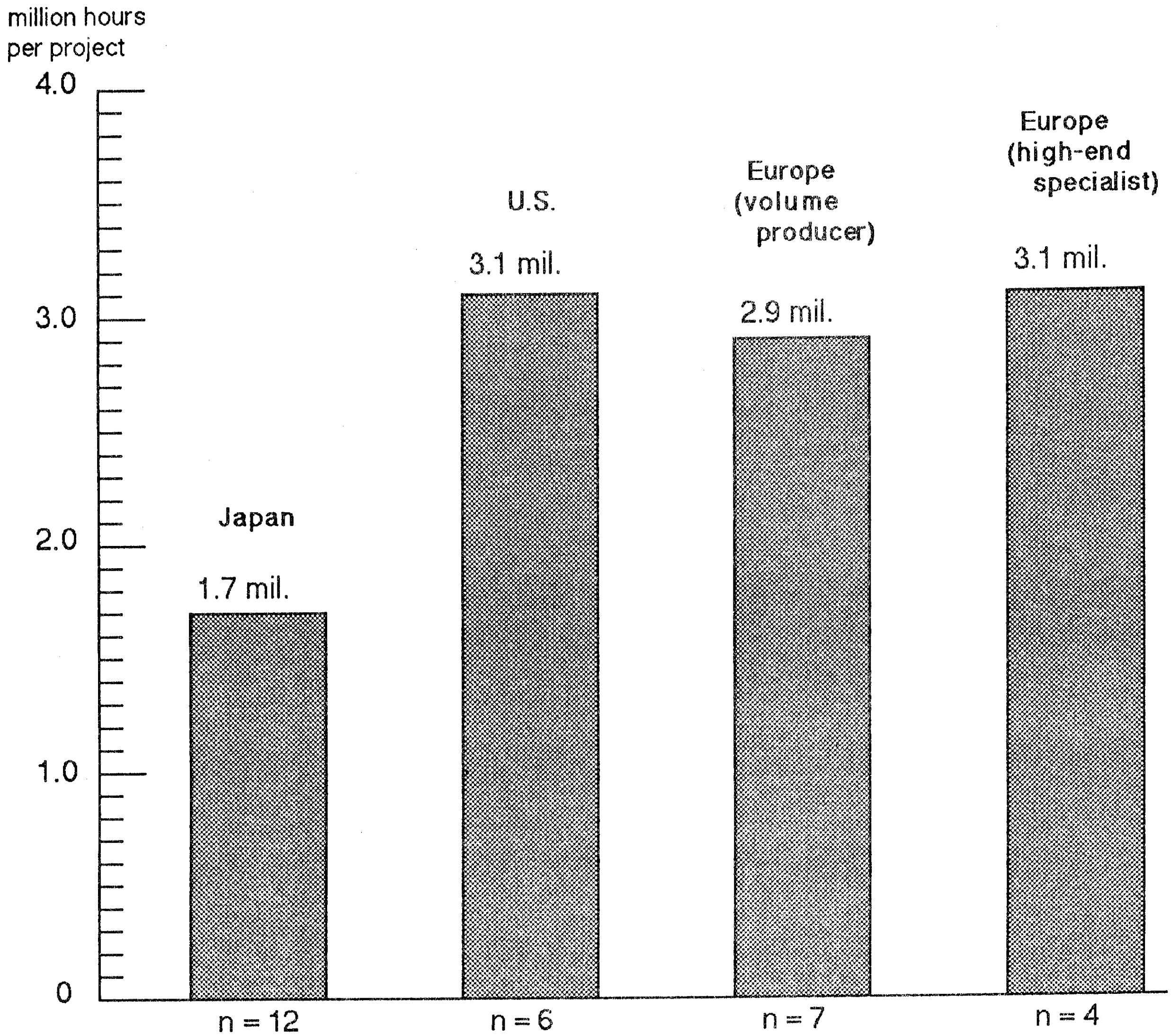
Let us now examine the above prediction in the case of the world auto industry. The following study was conducted mainly by Professor Kim Clark of Harvard Business School and myself from 1985 to 1990 (Clark and Fujimoto, 1989, 1990, 1991, Fujimoto, 1989, 1991). Twenty-nine product development projects from 20 auto manufacturers (9 European, 3 U.S. and 8 Japanese) were analyzed and compared in terms of performance, strategy, organization and process. Most of the sample auto makers were "volume producers", which sell the products to the mass market, however there were also some "high-end specialists", all of which were Europeans. While consumer tastes in the mass market have become diversified, unpredictable, and oriented toward product integrity in recent years, those in the high-end segment have remained relatively stable and homogeneous in the 1980s. Thus, our prediction was that, in the volume producer group, companies with powerful internal/external integrators may outperform their competitors, however this was not expected to be the case in the high-end specialist group in the 1980s.

As for the three dimensions of product development performance, the major findings were as follows (Figures 2 and 3, and Table 1):

1. In *development productivity* (measured by hours worked per project, adjusted for project content), the Japanese projects were on average nearly double as efficient as the U.S. and the European projects.

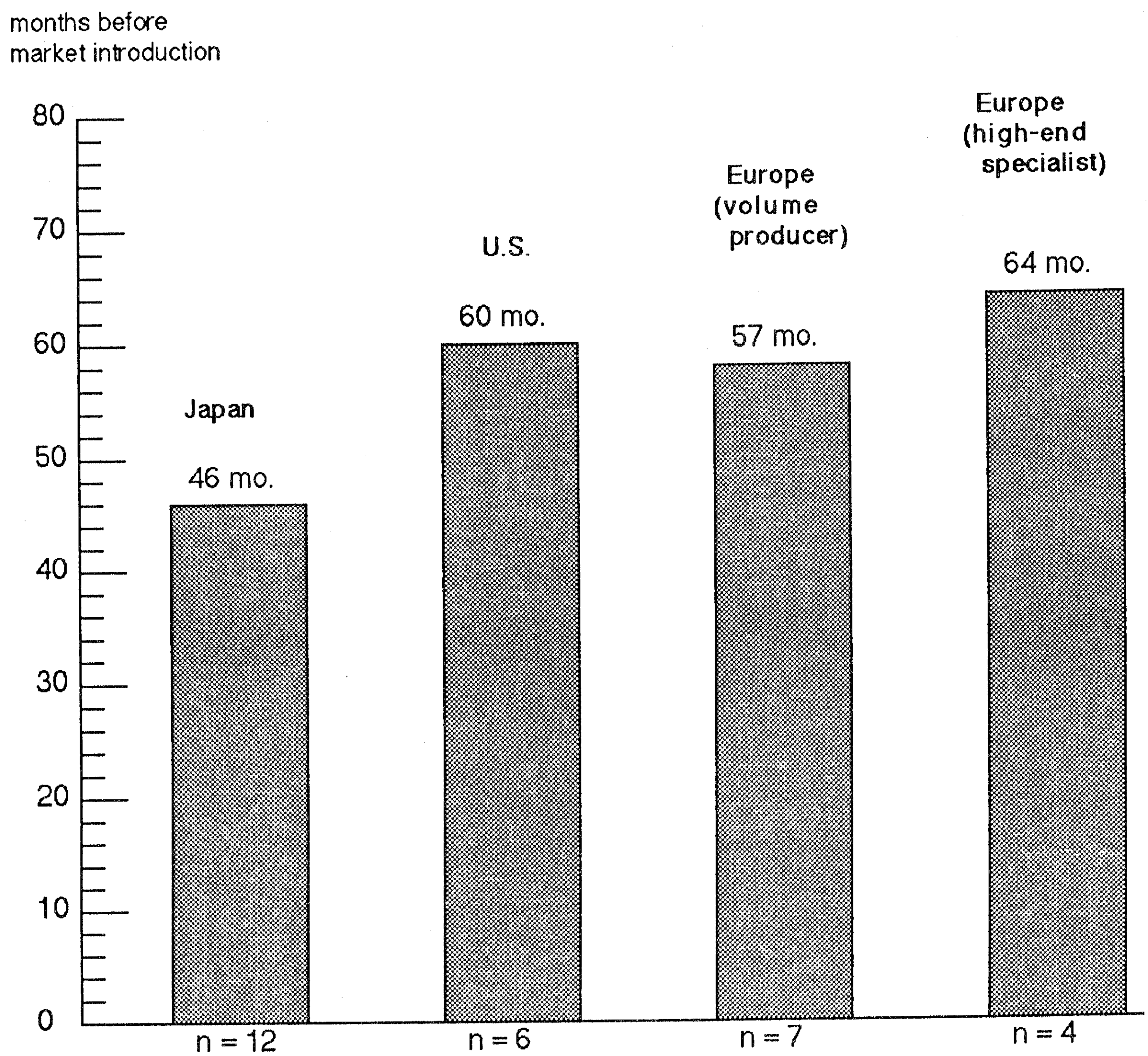
2. In *development lead time* (measured by time elapsed from concept study to start of sales, adjusted for project content), the Japanese projects were also completed on average about a year faster than the Western cases (4 years versus 5 years).

Figure 2 Engineering Hours Per Project
(adjusted for project content)



Source: Clark and Fujimoto (1991)

Figure 3 Lead Time from Concept to Market (adjusted for project content)



Source: Clark and Fujimoto (1991)

Table 1 Ranking of Organizations in TPQ Index

ranking	regional origin	score
1	Europe (high-end)	100
1	Japan	100
1	Japan	100
4	Europe (high-end)	93
5	Japan	80
6	U.S.	75
6	U.S.	75
8	Europe (high-end)	73
9	Europe (high-end)	70
10	Japan	58
11	Europe (volume)	55
12	Europe (volume)	47
13	Japan	40
14	Europe (volume)	39
15	Europe (volume)	35
15	Japan	35
17	Europe (volume)	30
18	Japan	25
19	U.S.	24
20	Japan	23
21	U.S.	15
22	U.S.	14

Source: Clark and Fujimoto (1991)

3. In *product integrity* (measured by total product quality index, or TPQ, which is a composite of such indicators as total quality, manufacturing quality, design quality and long-term market share), unlike productivity and lead time, no regional pattern was detected. The Japanese companies included both top-rank and bottom-rank players, as did the European and American groups. The top-rank Europeans turned out to be high-end specialists (Table 1).

The above findings illustrate the following implications. First, the more efficient projects (mainly Japanese) also tend to be faster (Figure 4). In other words, there is apparently no trade-off relationship between development speed and development efficiency -- you could have both.

Second, there are a few Japanese companies whose product development achieves speed, efficiency and integrity at the same time -- the all-round high performers. Third, there are also some Japanese companies which have short lead times, high development productivity, but are ineffective in product integrity. Thus, to be fast and efficient, or to be a Japanese, does not guarantee product integrity and market success. Fourth, there are a few European high-end specialists which achieve high product integrity without being fast and efficient in product development. This indicates that, at least during the 1980s, the high-end specialists were playing a quite different competitive game in a segment well isolated from the volatile mass-market.

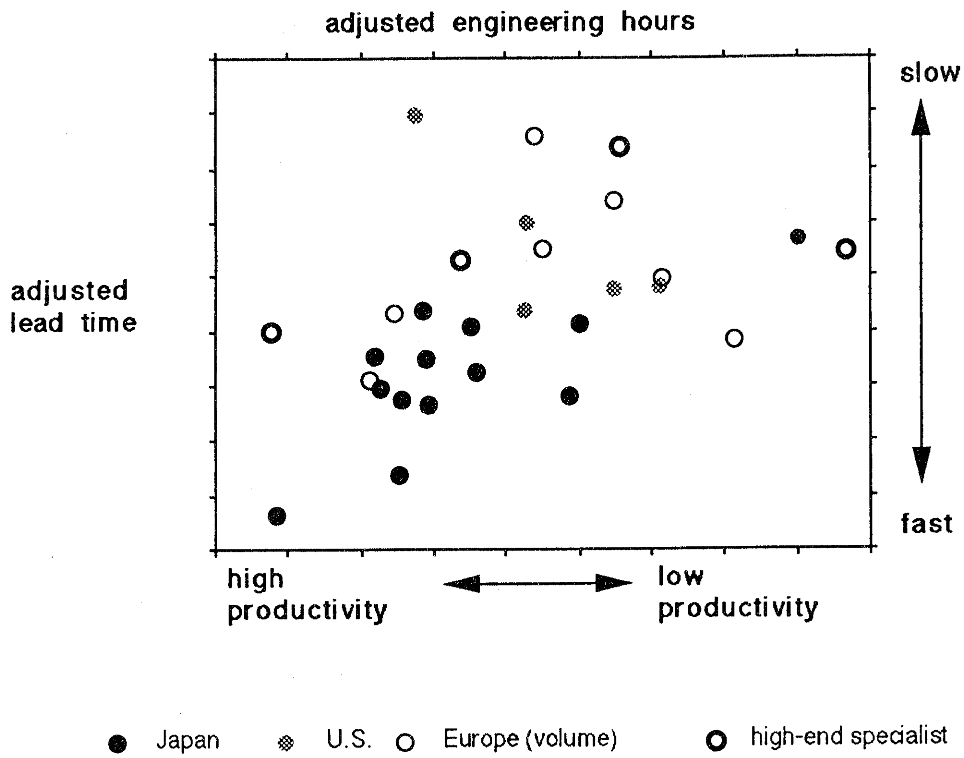
5. TYPICAL JAPANESE PRACTICES

Let us now turn to the organization and management side. What are the characteristics of these development organizations that achieve speed, efficiency and integrity at the same time? We investigated this question in two stages. First, we explored patterns for fast and efficient (but not necessarily successful in the market) product development by focusing on certain Japanese practices that apparently contributed to shorter lead time and higher development productivity. (Note again that the Japanese development projects in general tended to be both fast and efficient.) Second, by focusing only on the all-round high performers mentioned above, we tried to identify certain organizational patterns that seem to achieve speed, efficiency <u>and</u> product integrity simultaneously.

In the first case, we identified the three main characteristics of Japanese development organizations that were likely to contribute to shorter lead time and/or higher development productivity:

1. *The Role of Supplier Engineering:* The Japanese companies tended to keep the size of their own development projects compact by allowing

Figure 4 Lead Time and Engineering Hours
- Adjusted for Project Content -



Source: Clark and Fujimoto (1991)

parts suppliers do a significant part of the engineering jobs (Figure 5). The compactness of the projects, in turn, contributed to shorter lead time and higher development efficiency by simplifying the task of project coordination to a manageable level. The U.S. auto makers, by contrast, apparently tried to keep the project compact by using existing component designs developed in other projects, however their excessive use of common parts caused a deterioration of product integrity and distinctiveness. Thus, the engineering capability of the Japanese parts supplier systems seems to have benefited the Japanese auto makers.

2. *The Power of Manufacturing Capability:* The Japanese auto makers tended to apply their capabilities in manufacturing to critical activities in product development, such as prototype fabrication, die development, pilot runs, production start-up, etc., which, in turn, contributed to an improvement in the overall performance of product development. For example, application of the just-in-time philosophy to body die shops seems to explain in part why the average Japanese project's die development lead time is much shorter than that of the Western projects examined (Figure 6).

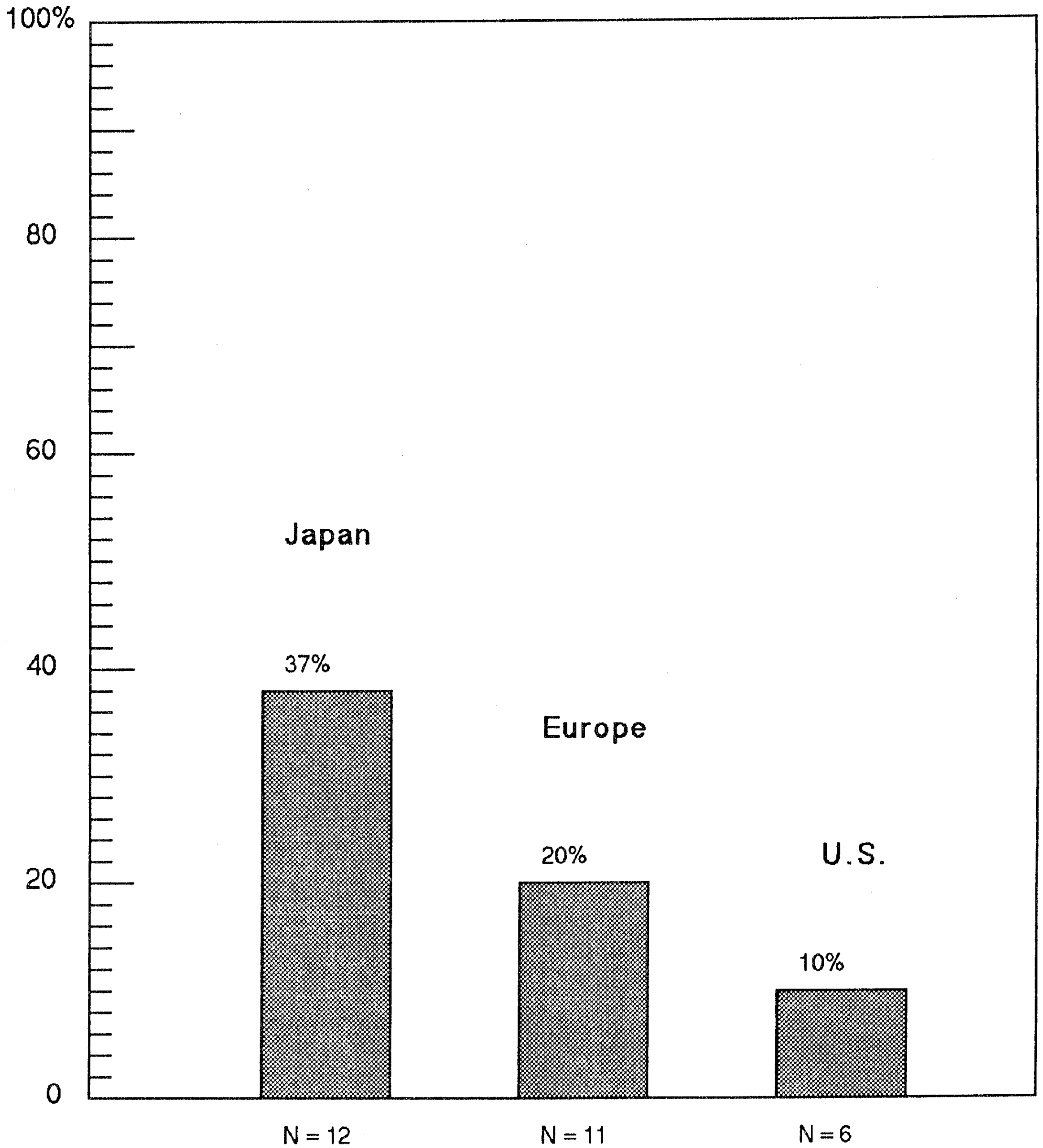
3. *The Combination of Stage Overlapping and Intensive Communication (Figure 7):* In order to shorten overall lead time, the Japanese project also tended to overlap upstream stages (e.g. product engineering) and downstream stages (e.g. process engineering) more boldly than the American and European projects. The Japanese overlapping approach can effectively shorten lead time only when it is combined with intensive communication between the upstream and the downstream. Effective overlapping also requires the capabilities of both upstream and downstream people to cope with incomplete information, as well as flexibility, mutual trust, and goal sharing between the two stages. Without such conditions, stage overlapping is likely to result in confusion, conflict, and deterioration in product development performance (Compare the two cases in the figure).

Both statistical results and field observations were generally consistent with the above three themes.

6. HEAVYWEIGHT PRODUCT MANAGER

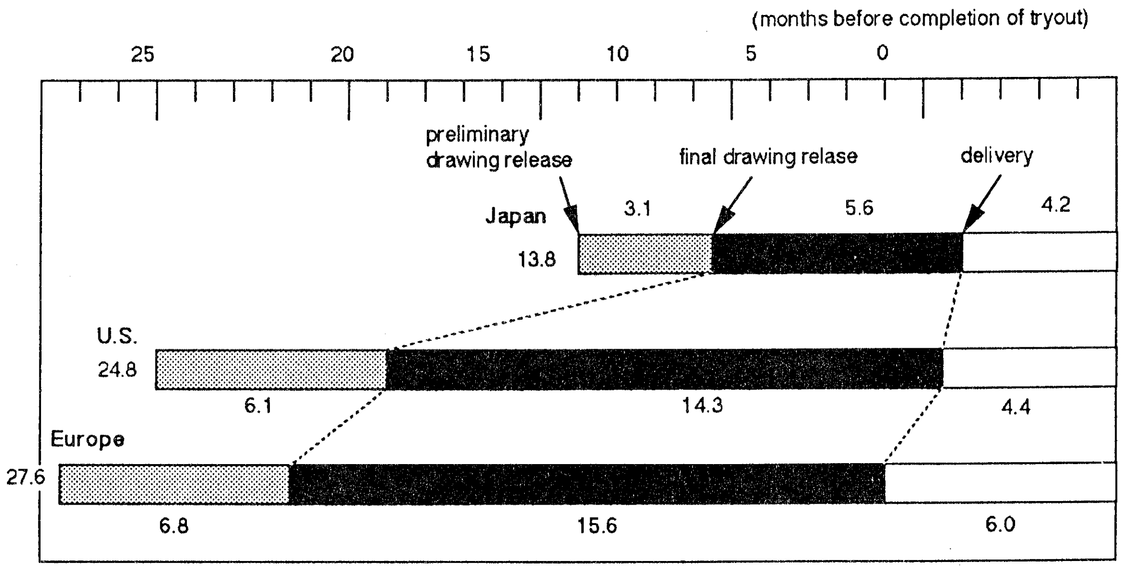
Let us now move to the second step: What are the patterns of development organizations that achieve high performance in efficiency, speed and integrity all at the same time? Looking at the Japanese practices in general no longer gives us the answer, since there are only a few Japanese auto

Figure 5 Estimated Ratio of Suppliers' Contribution to Product Development



Source: Clark and Fujimoto (1991)

Figure 6 Lead Time for a Set of Dies for a Major Body Panel



Note: Regional averages of 25 sample projects (11 Japanese, 6 U.S., and 8 European)

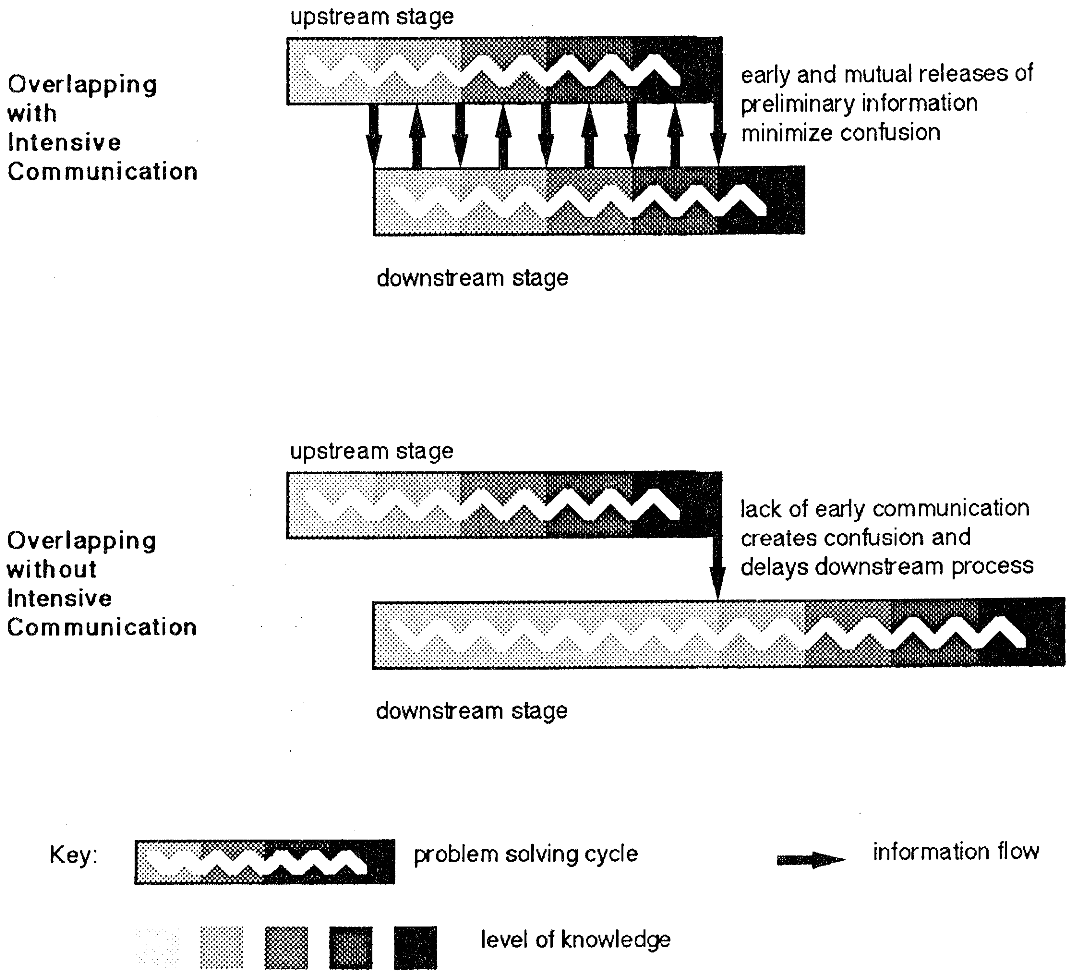
First to final drawing release for tooling order

Final drawing release to delivery of die – this approximately corresponds with die manufacturing lead time.

Delivery to completion of tryout

Source: Clark and Fujimoto (1991)

Figure 7 Overlapping with and without Intensive Communication



Source: Clark and Fujimoto (1991)

makers today that achieve all three. To investigate this question, we now focus on the integration of the development organization explained earlier, namely the existence of powerful internal/external integrators.

First, we developed indicators for three dimensions of organizations: the specialization of engineers and the strength of both internal integrators (i.e. project coordinators) and external coordinators (i.e. concept champions). We then examined the relationship between the three organizational dimensions and the three performance dimensions. The 3 X 3 results are shown in figure 8 (For the issue of definition and measurement, see Fujimoto, 1989, and Clark and Fujimoto, 1991). Note that each of the shaded boxes indicates that a particular organizational dimension was statistically significantly correlated with a particular element of development performance. The results indicate the following relationships:

1. The lower degree of specialization (i.e. the broader the task assignment of each engineer), the faster and more efficient the projects tend to be. Many development organizations (mostly Western) seem to be suffering from the *overspecialization* syndrome, while some others (mainly Japanese) appear to benefit from lower levels of specialization without losing technological expertise. However, specialization does not seem to be related to product integrity (measured by TPQ).

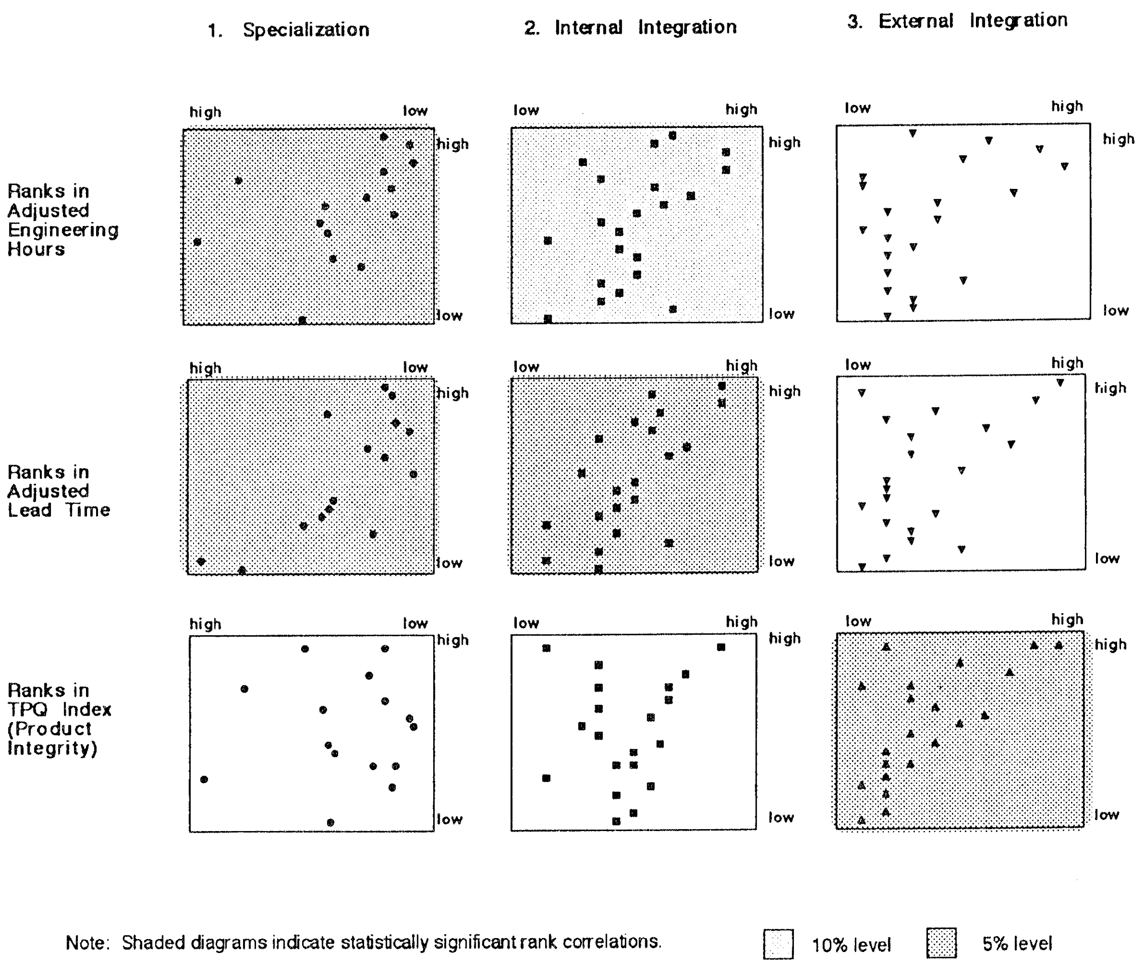
2. The stronger the internal integrator (project coordinator), the faster (and somewhat more efficient) the project tends to be. This result seems reasonable, since the reduction of lead time would call for stage overlapping with intensive communication between each one; this, in turn, would be facilitated by powerful project coordinators. Again, however, internal integration was not correlated with product integrity.

3. The stronger the external integrator, the higher the TPQ scores and the product integrity appear. This correlation seems to indicate that powerful champions who create and realize distinctive product concepts might be a key to product integrity and market success.

Combining the above three findings, we now predict that, in the auto industry of the 1980s, the development organizations which achieved high performance in lead time, productivity and product integrity simultaneously were those which combined the tasks of powerful internal and external integration into a single job. We call this type of internal-external integrator the *heavyweight product manager* -- a combination of a strong project coordinator and a strong concept leader (Fujimoto, 1989, Clark and Fujimoto, 1991).

To examine whether the heavyweight product manager system could actually achieve high performance in all three dimensions, we developed an

Figure 8 Specialization, Integration, and Development Performance



Note: Shaded diagrams indicate statistically significant rank correlations.

Source: Clark and Fujimoto (1991)

indicator to measure how close a given organization comes to the ideal profile of the heavyweight system. The results (Figure 9) indicate that, as far as volume producers of the 1980s were concerned, the heavyweight product manager system tended to yield high scores in all three dimensions of product development performance. This, however, did not apply to the high-end specialists, for which high product integrity was achieved with rather insignificant internal/external integrators.

Based on the clinical field surveys, we characterize heavy-weight product managers (PMs) as follows (see, also, Figure 10) :

- PMs have coordination responsibility in wide areas including not only engineering but also production and sales.

- PMs have coordination responsibility for the entire project period from concept to market.

- PMs take responsibility for not only cross-functional coordination but also for concept creation and concept championing

- PMs' offices maintain responsibility for specification, cost target, layout and major component choice, to make sure that product concept is accurately translated into the technical details of the vehicle.

- PMs maintain direct and frequent contacts with designers and engineers at the working level, in addition to indirect ties through liaisons.

- Direct contact with customers. The product manager's office conducts its own market research in addition to the regular market surveys done by marketing groups.

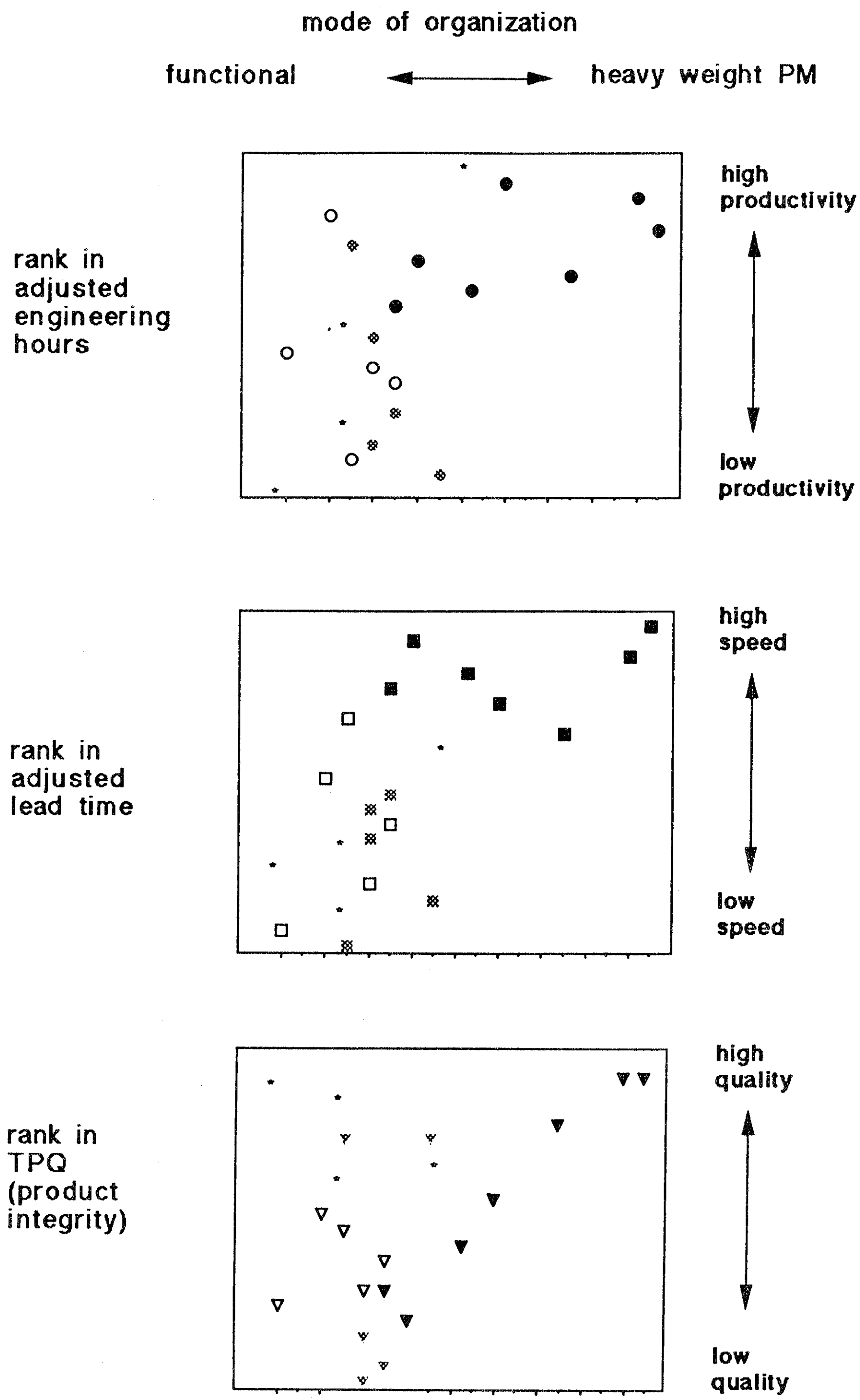
- PMs are multilingual and multi-disciplined in order to effectively communicate with designers, engineers, testers, plant managers, controllers and so on.

- PMs are not just neutral referees or passive conflict managers. They may initiate conflicts in order to prevent product designs/plans from deviating from the original product concept.

- PMs need market imagination, or the ability to forecast future customer expectations based on ambiguous and equivocal clues in the present market.

- PMs walk round and advocate the product concept, rather than doing paper work and attending formal meetings.

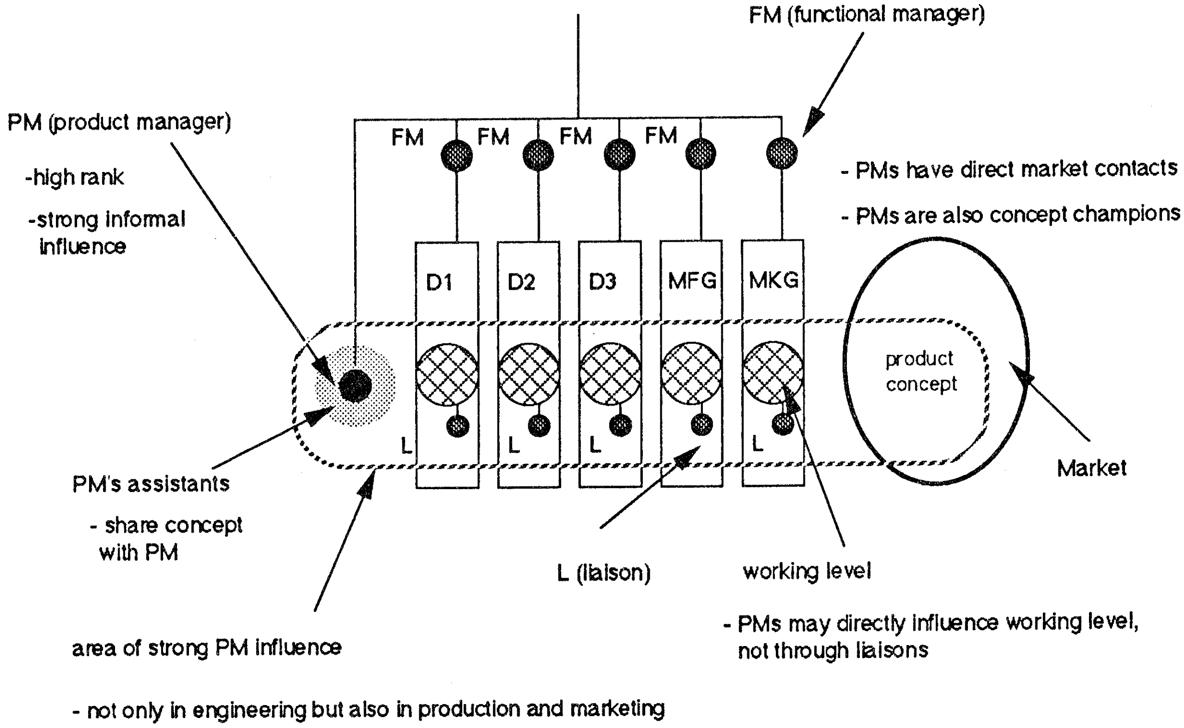
Figure 9 Mode of Organization and Development Performance



Note: ■ = Japan ※ = U.S. □ = Europe * = high-end specialist

Source: Clark and Fujimoto (1991)

Figure 10 Characteristics of Heavy-weight Product Manager



Note: D1, D2 and D3: functional units in development. MFG: manufacturing MKG: marketing

Source: Fujimoto (1989) and Clark and Fujimoto (1991)

- PMs are mostly engineers by training. They have broad, if not deep, knowledge of total vehicle as well as process engineering.

7. DISCUSSION: APPLICABILITY TO OTHER INDUSTRIES

We have examined the case of a single industry to illustrate patterns of effective product development in a dynamic, diversified and sophisticated market. Internal and external integration (i.e. heavyweight product manager) has been identified as one of the factors that might affect the performance of product development.

Nonetheless, there is one remaining question -- How generalizable are the above findings over time and across industries? Can the lessons from the automobile industry in the 1980s be applied directly to the same industry in the 1990s, or to other industries such as consumer electronics, engineering plastics, semiconductors and software? The remainder of this paper will explore a framework that may help us partially answer these questions. After briefly discussing the issue of cross-temporal generalizability, we will focus on a conceptual framework for the cross-industrial analysis of effective product development.

Cross-Temporal Difference: As for generalizability over time, it should be noted that the main source of inter-firm differences in competitive performance, or "focus of competition", may shift over time as the companies realize the performance differences between them and their world class competitors and try to narrow them. As a result, existing inter-firm gaps may diminish, but the new focus of competition may emerge elsewhere. For example, many of the Western auto makers, as well as some of the Japanese, started to change their project organization to heavy-weight structures, to involve suppliers in component engineering (so-called "design in"), to overhaul the prototyping and die-making processes, and to implement simultaneous engineering during the 1980s. Recent data also suggest that the lead time difference between the average Japanese and Western auto makers have narrowed by the early 1990s. Accordingly, the focus of competition in this industry may have somewhat shifted, by the early 1990s, from performance of each individual development project to other areas (e.g., skills in multiple project management). Product development performance on the individual project level nevertheless seems to remain important in many industries including that of the automobile.

Cross-Industrial Difference: As for cross-industrial generalizability, today's world automobile industry is so unique in size and complexity that the findings of the above research, as a package, do not seem to be directly applicable to other industries. At the same time, however, this industry is so multifaceted and multi-disciplinary that managers and engineers in almost any other would be able to yield certain important lessons from at least part of the automobile case. Overall, the research results in the automobile product development studies seem to be transferable, at least partially, to the cases of many other industrial sectors.

Many factors, including market size, types of customers, product characteristics, core technologies, patterns of competition, company size, and stages of industrial evolution, may influence the effective patterns of product development. Among these factors, basic characteristics of the product itself seem to partially explain why the effective patterns differ across the industries. That is, the successful pattern for developing a non-automobile product may resemble the case of the automobiles to the extent that the product shares certain characteristics with the autos, all other things being equal. Conversely, the most effective pattern may be different from that of the automobile when the product does not possess such characteristics. Thus, a proper inter-industrial framework for analyzing basic product characteristics may help researchers and practitioner know what they can learn from the experiences in other products.

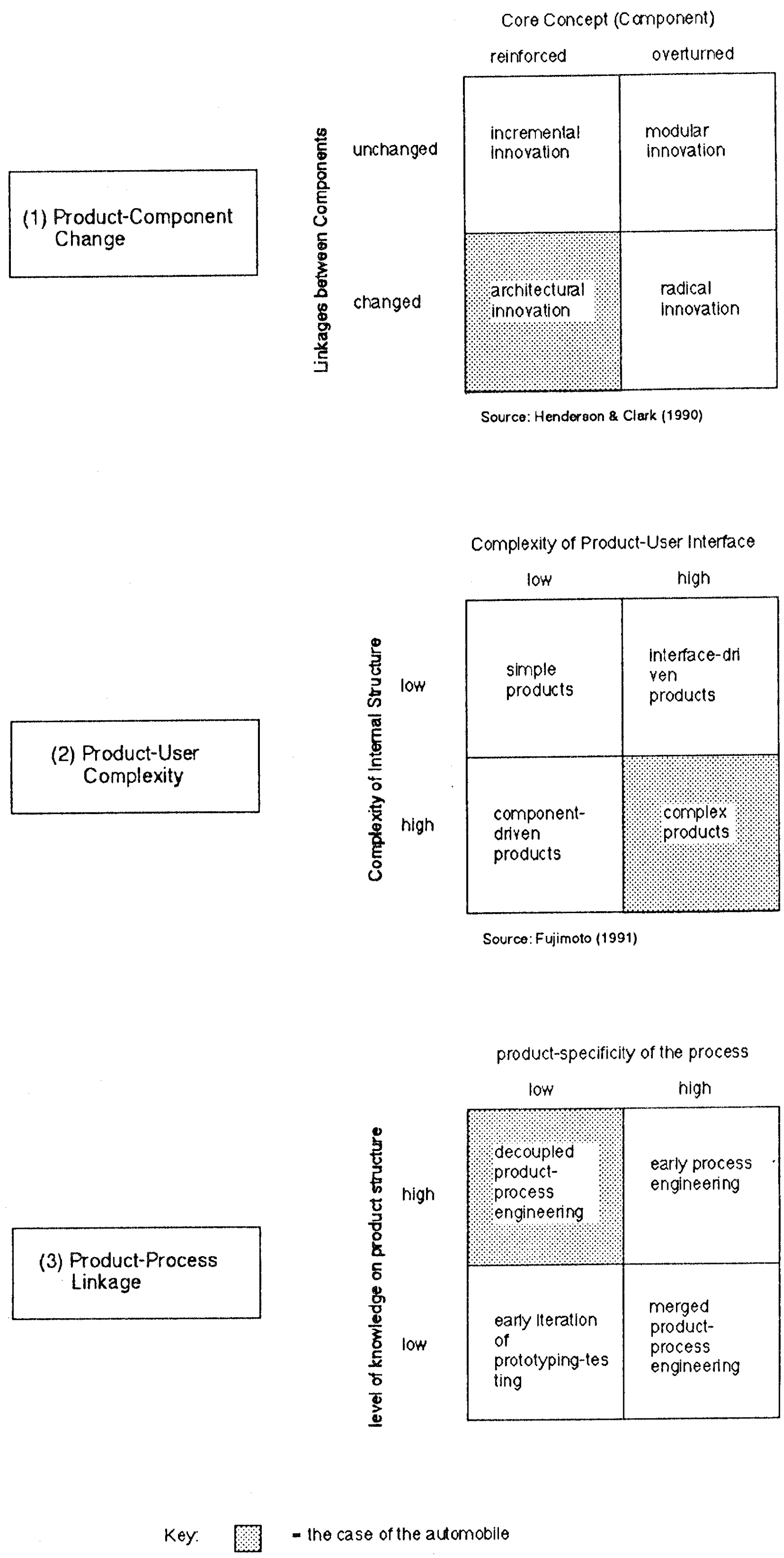
Although there seem to be many alternative ways to analyze and compare characteristics of products and their development projects across industries, the following section of this paper will present a preliminary framework with three dimensions: *product-component change, product-user complexity*, and *product-process linkage* (Figure 11). With regard to this schema, some basic characteristics of today's automobiles can be summarized as follows:

- The automobile is a complex consumer durable that is assembled from many discrete/fabricated parts. The size of a product development project, which typically consists of hundreds of specialized engineers, is much larger than that of most other products. That is, the product is *structurally* complex.

- Today's consumers tend to evaluate automobiles in terms of their balance and consistency with many product functions, rather than superior performance in a small number of criteria. They emphasize "product integrity." Thus, the product is *functionally* complex.

- Recent technological progress in this industry has been driven not by radical innovation of a core element but by rapid incremental innovations on the total system level. The innovations in this case have essentially been, in the terminology of Henderson and Clark (1990), "architectural."

Figure 11 Framework for Inter-Industrial Comparisons of Effective Product Development



- Product engineering and process engineering are two separate groups in the automobile manufacturers. Integration of the two groups is often regarded as a key to successful product development.

On the basis of the above assumptions, our hypothesis is that the effective pattern of product development in other industries tends to differ from that of the automobile to the extent that the product characteristics of those products deviate from the automobile case in terms of product-component change, product-user complexity, or product-process linkage, other things being equal. Although further research would be necessary to make accurate inter-industrial comparisons, the present framework should provide some insight for future studies.

8. FRAMEWORK FOR INTER-INDUSTRIAL COMPARISON

Let us now examine basic concepts, preliminary evidences and some predictions with regard to the three dimensional framework for inter-industrial analysis (Figure 11, Table 2).

(1) Product-Component Change: The first dimension is the relationship between changes in component designs and that in the overall product (i.e., system) designs (Abernathy, et al., 1983, and Clark, 1985). The framework proposed by Henderson and Clark (1990) provides useful insight on this dimension. Focusing on system products in which discrete components are interrelated, they classified types of technological changes along the following two dimensions: changes in component knowledge (i.e., knowledge of a core concept that a particular component embodies), and changes in architectural knowledge (i.e., knowledge about linkages between the components embodying core concepts).

By classifying innovations along these two dimensions, Henderson and Clark identified four types of technological changes: incremental, modular, architectural, and radical (Figure 11). *Incremental innovation* refines and reinforces existing technological knowledge both in component and architecture; *Radical innovation*, by contrast, changes and overturns both component and architectural knowledge. *Modular innovation* fundamentally changes a certain core concept embodied in a component with minor modification at the system (architectural) level. *Architectural innovation*, on the other hand, changes the way the components are linked while simultaneously maintaining the core concept of each component.

Although, in practice, it may be difficult to classify actual product development projects into the four cells, the framework does help us compare certain characteristics of product development processes between different types of products. It is particularly important, in this context, to distinguish

Table 2 Predicted Pattern of Effective Product Development

Dimension	Characteristics of the Product or Product Development	Predicted Patterns of Effective Product Development	Examples
Product-Component Change	incremental innovation	Fewer technological inputs; many small projects.	apparel
	radical innovation	Greater technological inputs are necessary.	first generation television set
	modular innovation	Integration of advanced and current engineering is key.	main frame computer packaging
	architectural innovation	Inter-component integration in current engineering is key.	automobiles
Product-User Complexity	simple product	A small team with intensive mutual adjustment is key.	packaged goods
	complex product	A large team with a powerful integrator is key. The effective integrator tends to be a designer-engineer hybrid.	automobiles
	interface-driven product	The effective integrator tends to be an industrial designer by training	small consumer electronics fashion apparel
	component-driven product	The effective integrator tends to be an engineer by training	machine tools
Product-Process Linkage	decoupled product-process engineering	Product-process integration is key.	automobiles
	merged product-process engineering	Product-process integration is natural.	beer process industry

modular from architectural types of product development. The framework may, however, be somewhat difficult to apply to a monolithic product (i.e., plastics, ceramics and other new materials), which cannot be decomposed into distinctive parts.

Prediction: One obvious prediction is that radical innovation would be riskier and take more technological resources than incremental innovation, other things being equal. However, a more interesting hypothesis may be made between architectural and modular innovation or product development.

Suppose, for example, that product development consists of *advanced engineering* of core concepts embodied in components and *current engineering* of the total system. In a typical case of architectural product development, advanced engineering of each component would be limited to the modification of existing component technologies to fit the new product. The component technologies are pooled into a "refrigerator", from which engineers can take parts out for current product development. In this case, integration between advanced engineering and current engineering would be less challenging than integration among different components in the current engineering.

In the case of modular product development, by contrast, intensive advanced engineering would be needed for fundamental changes of at least one component that with a core technology. Because the new component (i.e. new technological concept) has to be adapted to the existing product architecture, it would be reasonable to predict that the challenge here is inter-stage integration between advanced engineering and current engineering rather than inter-component integration within the current product development.

A comparison of Harvard studies on product development in the automobile (Clark and Fujimoto, 1989, 1991) and main frame computer (Iansiti, 1992) industries provide some insight in this regard, as the former is closer to the architectural type and the latter to the modular type. In the former case, while the core concepts of major components have not changed much for over the last seventy years, functions and configurations at the total vehicle level are still changing fairly rapidly (particularly in the U.S. between the 1970s and 80s). In mainframe packaging, technological elements are rapidly changing in pursuit of higher density and speed, while the basic product architecture of mainframe computers has not changed much for decades.

The empirical results of the two cases seem to be generally consistent with the above predictions. In the automobile product development case, analyzed earlier in this paper, the empirical studies identified a correlation between performance of product development (i.e., lead time and productivity) and internal integration at the current engineering phase; whereas the degree of integration between advanced engineering and current product engineering did not show any significant impact on the performance. In the case of multi-chip modules used for packaging of mainframe processor, the degree of integration between advanced engineering of the elements ("exploration" in Iansiti's term) and current engineering of the system had a significant correlation with performance variables, while internal integration did not. Thus, integrated problem solving at the upstream phase (between advanced engineering and current engineering) turned out to be an important factor for effective product development in mainframe packaging, but not in automobiles.

(2) Product-User Complexity: The second dimension deals with complexity of the product. When a product becomes complicated in terms of its internal structures and/or its user interface, project organizations for the product also tend to become complex, and the role of project coordinator (i.e., integrator), becomes important. The automobile is a typical example of a complex product (Figure 11): Internally, it consists of tens of thousands of parts, whose coordination is very difficult technically and organizationally. Trade-offs are intense among the components; layout design of many interconnected parts in a limited space without interference is a challenging task. Externally, its user interface is also complex in that today's customers expect many functions from the cars, some of their criteria are subtle and equivocal (e.g., drive feel, excitement, expressiveness), and they tend to emphasize holistic product experiences rather than narrow and numerical criteria. Thus, the automobile is classified as a "complex product" in Figure 11 (See, also, Clark and Fujimoto, 1991, and Fujimoto, 1991).

Another category in the same diagram is "interface-driven" products, in which interface coordination is more difficult than internal coordination. Typical examples include relatively simple audio-visual equipment (i.e., headphone stereos), in which LSI technologies drastically reduce the number of internal parts, while they proliferate product functions in the user interface. An opposite category is a "component-driven" product, such as conventional machine tools, where internal mechanical structures are complex, but their functions in the user interface are simple and straightforward. Finally, there are certain products (e.g., conventional packaged goods) that are simple both in user interface and in internal structure.

Predictions: An obvious prediction which may be drawn from the above framework is that development of more complex products tends to require a larger number of engineers, other things being equal. For example, the development of a large civil aircraft (a few million parts) involves at least a few thousand engineers and technicians; the automobile's (20,000 to 30,000 parts) are normally developed by 100 to 1000 people; development of a camera (200 to 500 parts) is implemented normally by 10 to 100 engineers and technicians. As the number of project participants increases, the role of project leaders tends to become more important and challenging. An analogy of chamber music versus orchestra music may be appropriate here: Integrity of the music (i.e., product) of a string quartet may be achieved by mutual real-time adjustment among the players without a conductor (i.e. full time project leader), while orchestra music needs a strong conductor as a full-time integrator. Thus, it would naturally follow that, as the complexity of the product increases, so does the role of project integrators, other things being equal.

Another, and more interesting, prediction may be made on who becomes project integrator in a case where the role of project integrator is important. It would be reasonable here to assume that those who can handle the most difficult area of coordination tend to become integrators or leaders of the project. In this regard, product engineers are usually recognized as specialists in internal structures and technical functions, whereas industrial designers are known as specialists in product-user interface (e.g., aesthetics, ergonomics). In other words, engineers tend to design the product from the inside out, while designers from the outside in (Gorb, ed., 1988, Lorenz, 1990).

What follows from the above logic is a prediction that a person with industrial design background would be more likely to become the integrator in interface-driven products, while a person with engineering background would lead component-driven products. As for a simple product such as packaged food, other people (e.g. marketing people) would more likely become product managers.

What about the automobile, then? The present framework indicates that a certain hybrid of an engineer and an industrial designer would tend to become the project leader. In fact, our finding that a "heavy weight product manager" is an effective means of integration for automobile mass producers is quite consistent with this prediction. As described above, heavyweight product managers can be characterized as persons with an engineer's skills and a designer's mind (Fujimoto, 1991). They have broad knowledge about the engineering content of the product, but they also think and behave somewhat like industrial engineers, in that they are responsible for concept creation. Although further empirical research is necessary, a tentative prediction is that the most effective pattern of project leadership would be similar to the case of the automobile industry when the product in question is classified as a complex product.

(3) Product-Process Linkage: The third dimension of these product characteristics is the product-process linkage. The basic question here is whether product engineering and process engineering can be de-coupled. To analyze this, let us first consider the generic process of design in a product development project. Starting from concept creation and advanced technology development, a product development project usually goes through a chain of design activities from *functional design* (e.g., determination of technical parameters or specifications) to *structural design* (e.g., layout, exterior/interior design, and detailed engineering drawings for components),

and to *process design* (e.g., process flow, equipment, tools, recipe). The first two are generally regarded as product design (Figure 12).

At least two factors seem to affect the connectedness of product and process engineering (Figure 11). First, the *level of knowledge of the product structure* seems to affect the degree of interdependence between product design and process design. When there is a clear "blueprint" that represents structures of the product, and sufficient knowledge of the relationship between product structures and product functions, the chain of design may be de-coupled into two stages: translation from product concept to structural design through functional design, and translation from structural design to process design. When the development process can be de-coupled, development organization can be also de-coupled into two specialist groups: product engineers focusing on the former translation (i.e., designing a structure that achieves the target function and thus realizes the concept) , and process engineers in charge of the second translation (i.e., designing optimal process to make the structure physically). This kind of separation between product engineers and process engineers is quite common in fabricated-assembled products (including the automobile) , where engineering drawings or blueprints exist as pivotal information in the development process.

When the level of the structural knowledge is low, however, functional design and process design tend to become interdependent and inseparable. When there is no guarantee of a manufacturable structure that also achieves given functional objectives, the only way to check the feasibility of the functional design is to design a process, make things according to the process, check their properties, and reach the functional targets through iteration of the trials. Thus, functional design and process design become intertwined. Accordingly, product and process engineering become difficult to separate.

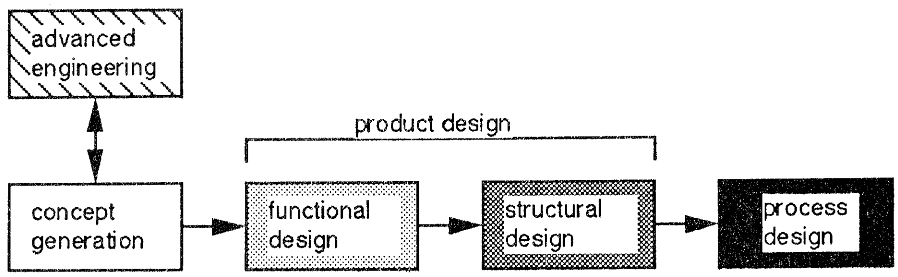
For example, to the extent that the micro structure of beer is a black box to engineers, recipe (process design) and property of the new beer (functional design) have to be developed more or less simultaneously (Figure 12). Beer engineers have to repeat test-brewing at a miniature pilot plant until they get the "right taste." The moment they find it, the engineers can complete functional design and process design at the same time (ignoring minor changes of recipe due to scale up). Thus, in the beer industry, it is hard to decouple product engineers and process engineers, as there is no information that corresponds to blueprints in mechanical design.

Second, product engineering and process engineering tend to become inseparable when *product-specificity of the process* is high. When there is only one way of making a given product structure, it would be natural that the designs of the structure and the process necessary to make it be inseparable.

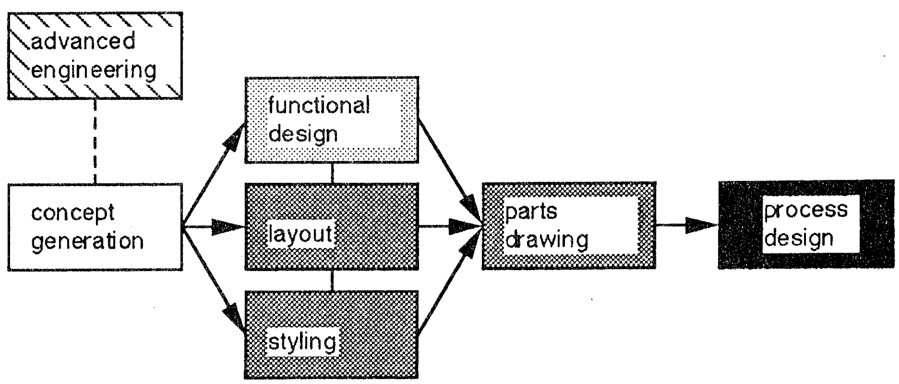
In the case of the automobile and other mechanical products, components of identical shape and materials can normally be fabricated by many alternative processes. For example, a body panel of the same structure may be made by hand, "soft" dies (plastics or zinc alloy), or steel dies. In other

Figure 12 The Design Chain

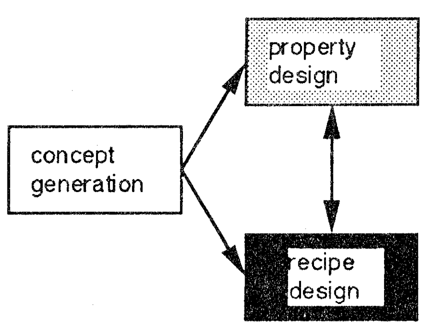
A Generic Design Chain



An Example of the Automobile's Design Chain



An Example of Beer's Design Chain



words, many process designs correspond to a single structural design. To the extent that different process designs can be applied to the same structural design, it would be more reasonable to decouple product engineering and process engineering as two separate jobs. In theory, product engineers can design and build functionally optimal structures without much consideration of their manufacturability, while process engineers choose the best solution to produce a given structure.

In the case of beer, again, engineers assume that there is generally a one-to-one correspondence between a given product design and process design. Once the engineers at the pilot brewery find that a certain recipe can create a new beer of a certain property, they *scale up* the operations carefully so that both the recipe and the product property are conserved and reproduced at the commercial scale plant. In fact, some beer companies design their pilot plants as the smallest possible brewery at which a given recipe will reproduce the same product at the commercial scale.

Predictions: Overall, product engineering and process engineering seems to be relatively separable in the case of the automobile, in which the relationship between product structures and product functions is well known, blueprints play a pivotal role in product development, and there is a certain degree of freedom in process design for a given product structure. By contrast, it would be difficult to conceive of product engineers and process engineers as two totally separate groups in the case of beer. Generally speaking, inseparability of product and process engineering appears to be fairly common in the so-called "process industries" such as chemicals, plastics and ceramics (Barnett, 1991).

Where product engineering and process engineering are de-coupled as two specialist groups, it seems reasonable to predict that the integration of product and process engineering is a more challenging job to the integrators. Thus, while simultaneous engineering between the product and process engineering stages has been recognized as a key to effective product development in the automobile and many other fabricated-assembled products, this may be less important in typical process industries, where product engineering and process engineering are technically inseparable in the first place.

What is key to effective product development in such industries seems to be accumulated knowledge of the causal relationships between process designs and product functions, which would help firms reduce the number of prototype production necessary to achieve the functional goals and/or help them preserve the desired property of the product during the scale-up process. It is therefore important for breweries or plastic makers, for example, to develop a data base of their past trial productions and scale-ups.

9. SUMMARY AND FUTURE RESEARCH

The first half of this paper analyzed the empirical results of the study on product development in the automobile industry. Three dimensions of product development performance (i.e. lead time, productivity and integrity of product development) were identified as key contributors to a firm's competitiveness when international competition intensifies in volatile, diversified and sophisticated markets. A comparative study of twenty-nine projects in the Japanese, U.S. and European automobile manufacturers revealed significant inter-firm as well as international differences in such performance criteria. A pattern of development processes and organizations that correlates with high performance was also identified.

The second half of the paper explored a framework by which researchers may examine the generalizability of the empirical results in a particular industry. Three dimensions: product-component change, product-user complexity, and product process linkage, were discussed. Using the framework, we may be able to rephrase the findings in the automobile industry in more general terms. In the framework illustrated in Figure 11, product development in the automobile during the 1980s may be characterized by the *architectural innovation of a complex product through de-coupled product and process engineering*.

The predictions based on the above framework seem to be consistent with the empirical findings in the automobile industry that was illustrated in the earlier part of the paper. That is:

(1) Because most automobile product development is *architectural:*

- Integration of advanced engineering and current engineering does not correlate with project performance.
- Internal integration of current engineering does correlate with performance.

(2) Because the automobile is a *complex product:*

- Each development project is large and complex, and the role of the integrator is important.
- Supplier involvement in engineering reduces the complexity of inter-component coordination and thereby contributes to project performance.
- The heavyweight product manager, an integrator who blends engineer's skills and designer's minds, contributes to project performance.

(3) Because automobile development *decouples product engineering and process engineering:*

- Integration of product and process engineering becomes a key to high project performance.

The present framework might thus partly explain why effective patterns of product development in other industries and products are sometimes different from the automobile case. For example, it might partially explain: why the integration of advanced and current engineering was important while internal integration at the downstream stage was not in the development of mainframe packaging (i.e. modular innovation), why industrial designers often become project leaders in effective product development in the small consumer electronics industry (i.e. interface-driven products), or why simultaneous engineering is not a big issue in product development of certain process industries (i.e. merged product-process engineering).

The framework for inter-industrial comparison presented in this paper is by no means complete. Greater effort through both empirical research and theory building is needed before we are able to reach a framework that can analyze effective product development across a wide range of industries. It would be particularly challenging to find a simple one that can explain a wide variety of actual cases.

In this regard, we have to conduct further empirical studies, both clinical and statistical, in many different industries and countries by using more or less compatible research formats. At the same time, we have to refine and enrich the existing conceptual framework. We probably know by now, from our past research and literature, that there is no one best way for effective product development that can be applied to any industry at any time. It is nevertheless still important to develop a framework that can explain, at least partially, why patterns of effective product development differ across industries in some cases, and why they are shared by in other cases.

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Biography

Takahiro Fujimoto has been an Associate Professor at the University of Tokyo, Department of Economics since 1990. After receiving a B.A. in economics from the University of Tokyo in 1979, he joined Mitsubishi Research Institute as a researcher and participated in various research and consulting projects mainly in the automobile and machinery industries. He entered the Doctoral program at Harvard Business School in 1984, and received his D.B.A. in 1989 with his thesis, "Organizations for Effective Product Development -The Case of the Global Automobile Industry-". At Harvard, he was a major participant in an international comparative study of automobile product development led by Professor Kim B. Clark. After completing the doctoral program, he became a Research Associate at Harvard Business School, where he completed a book, Product Development Performance (35-th Nikkei Award of Excellent Books) with Professor Clark. Other publications in English include: "Lead Time in Automobile Product Development: Explaining the Japanese Advantage" (Journal of Technology and Engineering Management, 1989), "Product Integrity and the Role of Designer-as Integrator" (The Design Management Journal, 1991, First Annual Jay Doblin Award), and "Product Development and Competitiveness" (Journal of Japanese and International Economy, 1992).