97-F-12

Shortening Lead Time through Early Problem Solving —A New Round of Capability-Building Competition in the Auto Industry—

Takahiro Fujimoto
University of Tokyo

March 1997

Shortening Lead Time trough Early Problem Solving
- A New Round of Capability-Building Competition in the Auto Industry -

March 1997

Takahiro Fujimoto
Visiting Professor, Harvard Business School
Associate Professor, Faculty of Economics, University of Tokyo
(very preliminary -- not for citation)

presented at
International Conference on New Product Development and Production Networks -- Learning from Experiences in Different Industries and Countries
WZB, Berlin, March 20 - 22

University of Tokyo,
Research Institute for the Japanese Economy, Faculty of Economics,
Discussion Paper Series, 1997

Abstract

This paper presents both quantitative and clinical data from comparative studies of automobile product development, which I have participated in during the 1980s, early 1990s, and mid 1990s mainly at Harvard University. It focuses on the Japanese advantages in the 1980s, the western "reverse catch-up" in the 1990s (American in particular), as well as recent efforts by some Japanese auto-makers to further reduce lead times. The analysis generally indicates that the effective organizational routines (capabilities) that our previous studies identified (Clark and Fujimoto, 1991) have in fact been a primary focus of the capability-building efforts by the western auto-makers during the early 1990s. It also suggests that a framework that describes product development as a management of interconnected problem-solving cycles, which our past studies have adopted in analyzing effective product development (Clark and Fujimoto, 1989a, 1989b, 1991, Fujimoto, 1989, 1993), can also be applied to the analysis of more recent phenomena -- further reduction of engineering lead times from about 30 months to around 20 months (or less) by some Japanese auto makers in the mid 1990s. An analytical framework and some clinical evidence are presented in the second half of the paper. Early problem solving through what we call "front-loading" is emphasized as a key method for the lead time reduction at this phase of capability-building competition.

1. Introduction

This paper presents both quantitative and clinical data from the comparative studies of automobile product development, which I have participated in during the 1980s, early 1990s, and mid 1990s mainly at Harvard University (Clark, Chew and Fujimoto, 1987; Clark and Fujimoto, 1991; Ellison, et al., 1995, etc.) to analyze the dynamic process of capability-building competition in this industry. It focuses on the Japanese advantages in the 1980s, the western "reverse catch-up" in the 1990s (American in particular), as well as recent efforts by some Japanese auto-makers to further reduce lead times. Since systematic data collection on the last case has not started yet, I will present analytical framework and some preliminary anecdotal evidence at this point.

The analysis of this paper generally indicates that the effective organizational routines (capabilities) that our previous studies of the 1980s identified (Clark and Fujimoto, 1991) have in fact been a primary focus of the capability-building efforts by the western auto-makers during the early 1990s, although some other aspects, such as multi-project management and product simplification also became crucial issues (Nobeoka, 1993; Nobeoka and Cusumano, 1995; Fujimoto, 1994, 1996b, Fujimoto, Clark and Aoshima, 1992; Watkins and Clark, 1992). The present paper also suggests that the problem-solving framework that our past studies have adopted in analyzing effective product development (Clark and Fujimoto, 1989a, 1989b, 1991, Fujimoto, 1989) can be also applicable to the analysis of more recent phenomena. Thus, new technologies, practices, processes, and organizations have been introduced as the competition of capability-building in product development continued, but the principles for effective product development in this industry seem to have been robust, despite some changes in their applications.

2. Automobile Product Development in the 1980s

2.1 Product Development Performance

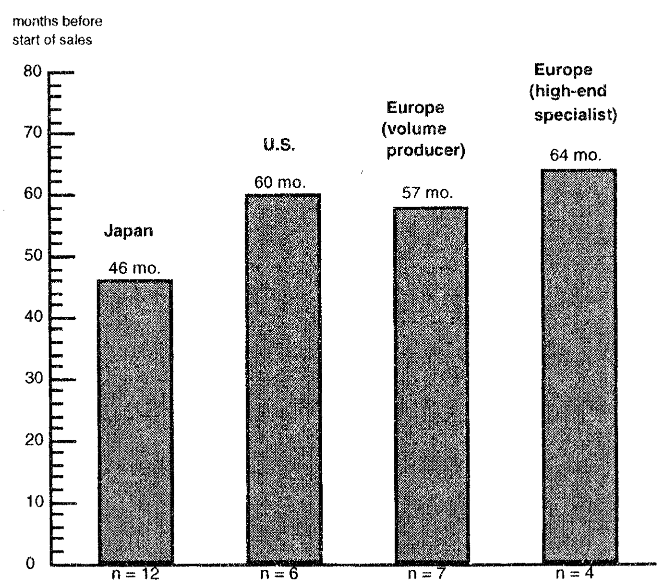
Let us first focus on the international comparison of product development performance in lead time, product development productivity and total product quality. The key findings in product development performance during the 1980s were as follows:

(1) Significant advantages of the Japanese in both lead time and productivity of product development were observed (**figures 1, 2**).

(2) Significant inter-firm differences in total product quality were found among the Japanese (**table 1**).

(3) Consequently, only a few Japanese auto makers achieved high performance in all three criteria.

Figure 1 Adjusyed Lead Time by Regional-Strategic Groups (1980s)



Note: Unadjusted lead time is time between start of concept study / product engineering and market introduction (start of selling) of the first version.
Adjusted lead time was calculated from the following ordinary least square regression model

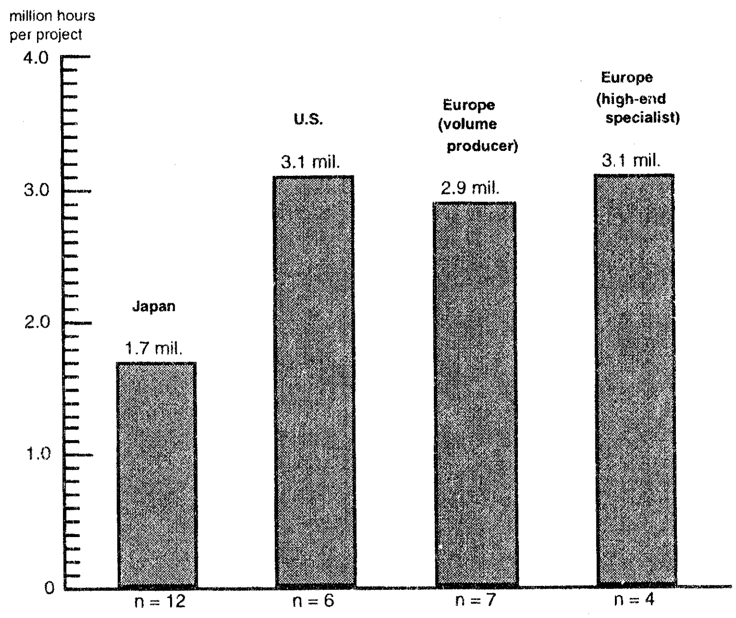
UNADJLT = 23.9+0.00048*PRICE+29.3*NH+1.23*BODY+14.2*USA+11.1*EUROVOL+18.2*HIGH
(9.1)(0.00030) (12.3) (1.88) (4.9) (4.7) (8.3)

R^2 = 0.69, Standard error = 8.9 ; Degree of Freedom = 22; Standard errors in parenthesis.

Average of PRICE is 14032. Average of NH is 0.44. Average of BODY is 2.14
Adjusted average was calculated by applying the average PRICE, BODY and NH to the above regression.

For definition of the variables, see Clark and Fujimoto (1991).

Figure 2 Adjusted Engineering Hours by Regional-Strategic Groups (1980s)



Note: Unadjusted engineering hours is hours spent on product planning and product engineering.
Adjusted engineering hours was calculated from the following ordinary least square regression model

UNADJEH= -3993+0.061* PRICE+7500*NH+729*BODY+1420*USA+1211*EUROVOL+1331*HIGH
(1008)(0.033) (1357) (208) (541) (518) (916)

R = 0.76, Standard error = 987; Degree of Freedom = 22 ; Standard errors in parenthesis.

Average of PRICE is 14032. Average of NH is 0.44. Average of BODY is 2.14.
Adjusted average was calculated by applying the average PRICE, BODY and NH to the above regression.

For definition of the variables, see Clark and Fujimoto (1991).

Table 1 Ranking of Product Development

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

Note: For further definitions of TPQ index, see Clark and Fujimoto (1991). Weights = 0.3 for total quality; 0.1 for conformance quality; 0.4 for design quality; 0.2 for customer share; Scores = 100 for top 1/3; 50 for middle 1/3; 0 for bottom 1/3; 100 for share gain; 50 for share loss; 75 for border case.
Source: Clark and Fujimoto (1991)

On the one hand, the Japanese makers as a group demonstrated significant competitive advantages in productivity and lead time. In development productivity (measured by hours worked per project, adjusted for project content by multiple regressions), the average of the Japanese projects (about 1.7 million person-hours) were on average nearly double as efficient as that of the U.S. and the European projects (about 3 million person-hours). In development lead time (measured by time elapsed from concept study to start of sales, adjusted for project content), also, the Japanese projects were on average about a year faster to complete a project than the Western cases (about 4 years in Japanese average versus 5 years in Europe and America). The regional differences were statistically significant even after the adjustment of project content factors such as product complexity and variety, innovativeness, ratio of carry-over parts, involvement of parts suppliers, etc.

On the other hand, performance differences within the regional group were also identified: 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), no clear regional pattern was detected, unlike productivity and lead time. A few Japanese companies appeared in the top-rank group in total product quality, but there were other Japanese found at the bottom. Similar patterns were observed in the European and American groups.

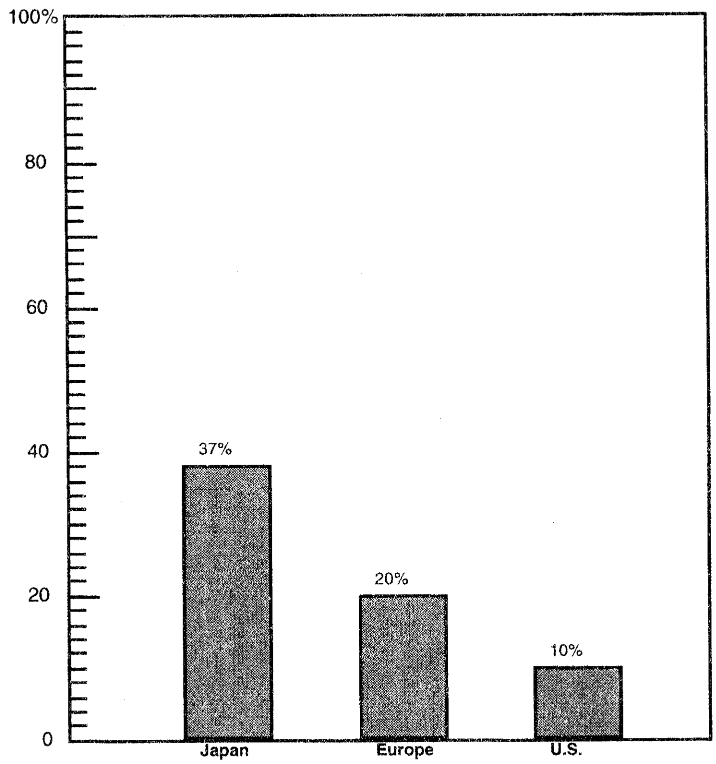
2.2 Product Development Capabilities

Clark and Fujimoto (1991) also found that, apparently corresponding to the presence of both region-specific and firm-specific effects in product development performance, both region-specific and firm-specific patterns also existed on the side of product development capabilities (i.e., organizational routines that creates competitive advantages of a firm). Through our data analyses, we identified the following capabilities at high-performing firms in product development (Note that capabilities (1) to (4) were found in the Japanese auto-makers in general, whereas the capability (5) tended to be found only in a few high-performing Japanese firms identified in the previous section):

(1) Suppliers' Engineering Capability: The Japanese companies tended to subcontract out a larger traction of product development tasks, particularly in detailed component design, prototyping and testing, to their first-tier parts suppliers, and thereby keep the in-house project compact (**figure 3**). 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. Clark and Fujimoto (1989, 1991) identified statistically significant positive effects between the degree of supplier's participation and

overall speed or efficiency of the projects. The Japanese makers also enjoyed lower component cost by letting the suppliers pursue design for manufacturing. Although some predicted that suppliers might take this opportunities to seek monopoly rents and raise component prices, the actual competitive results indicates that the effect of cost reduction by design-for-manufacturing outweighed the monopoly effects.

Figure 3 Supplier's Contribution to Product Development



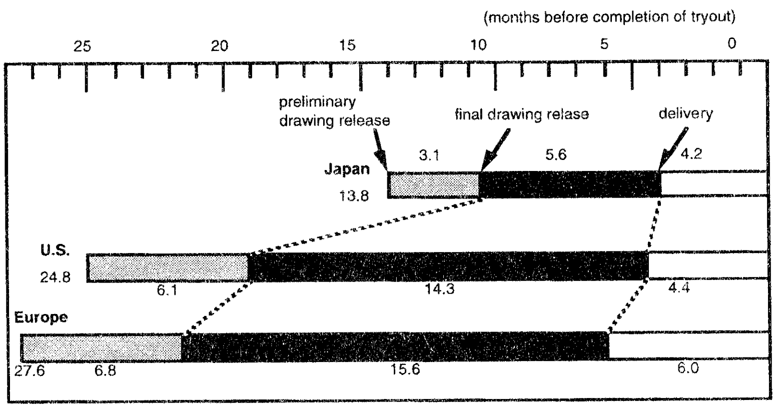
Note: Supplier's contribution ratio was calculated as estimated fraction of supplier engineering in purchased parts multiplied by parts procurement ratio (i.e. fraction of procurement cost in total production cost). Based on the data of 29 projects studied.

Source: Clark and Fujimoto (1991)

(2) <u>Manufacturing Capability in Product Development</u>: The Japanese auto makers tended to apply their capabilities in manufacturing to critical activities in product development, which, in turn, contributed to improvement in overall performance of product development. For example, application of

just-in-time philosophy to body die shops seem to explain part of the reason why die development lead time of the average Japanese projects was much shorter than that of the Western projects (**figure 4**). Their capabilities of managing prototype parts procurement, mixed model assembly, and quick shop-floor improvements also helped the Japanese makers carry out fast and effective prototyping, pilot run and production start-up.

Figure 4 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

The numbers do not add up exactly because some respondents reported total die lead time only

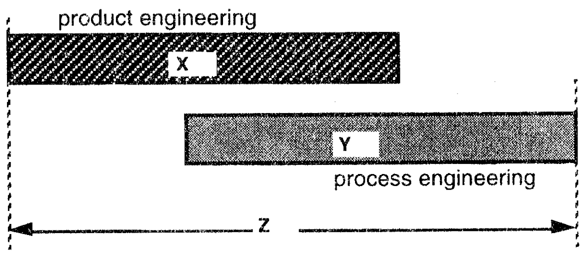
Source: Clark and Fujimoto (1991)

(3) <u>Capability of Inter-Stage Overlapping and Coordination</u>: The Japanese projects tend to overlap upstream stages (e.g. product engineering) and downstream stages (e.g. process engineering) more boldly than the American and European projects in order to shorten overall lead time (**figure 5**). The Japanese practices indicate that the overlapping approach can effectively shorten lead time only when it is combined with intensive communications between the upstream and the downstream. Effective overlapping also needs 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 (Clark and Fujimoto, 1989b; 1991). Without

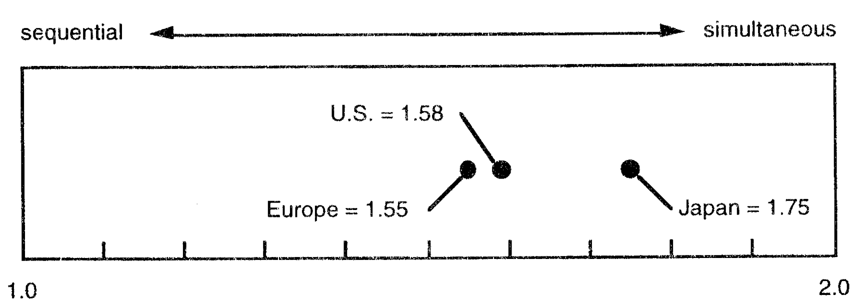
such conditions, stage overlapping is likely to result in confusion, conflict, and deterioration in product development performance .

Figure 5 Definition and Result of Simultaneity Ratio

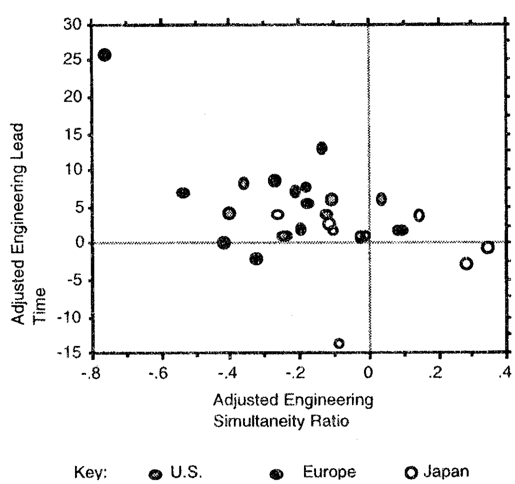
A. Definition **simultaneity ratio = (X + Y) / Z where,**



B. Regional Averages of Simultaneity Ratio

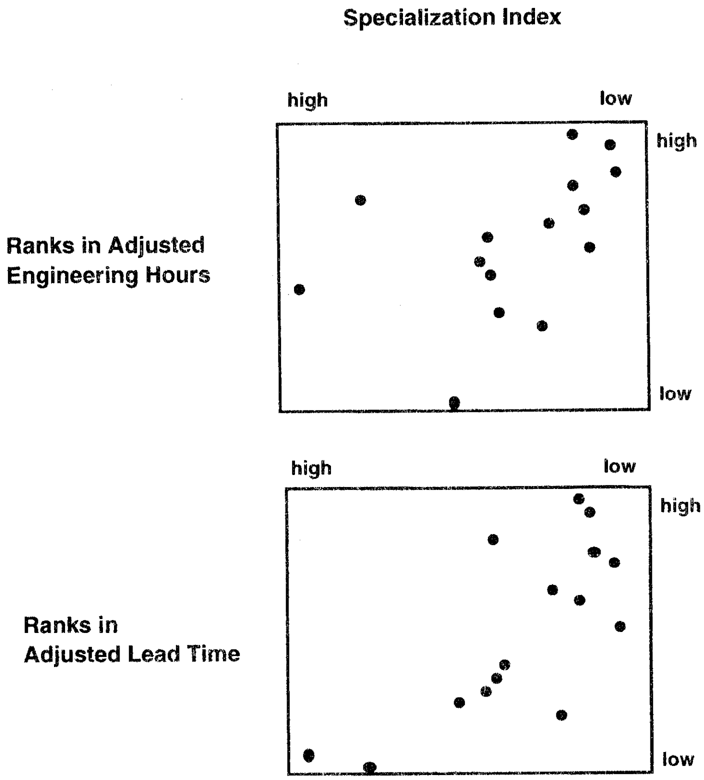


c. Simultaneity Ratio and Engineering Lead Time



(4) Wide Task Assignment: The empirical result of Clark and Fujimoto also indicates that the lower the specialization of individual product engineers (i.e. the broader the task assignment of each engineer), the faster and more efficient the projects tend to be (**figure 6**).

Figure 6 Specialization and Development Performance



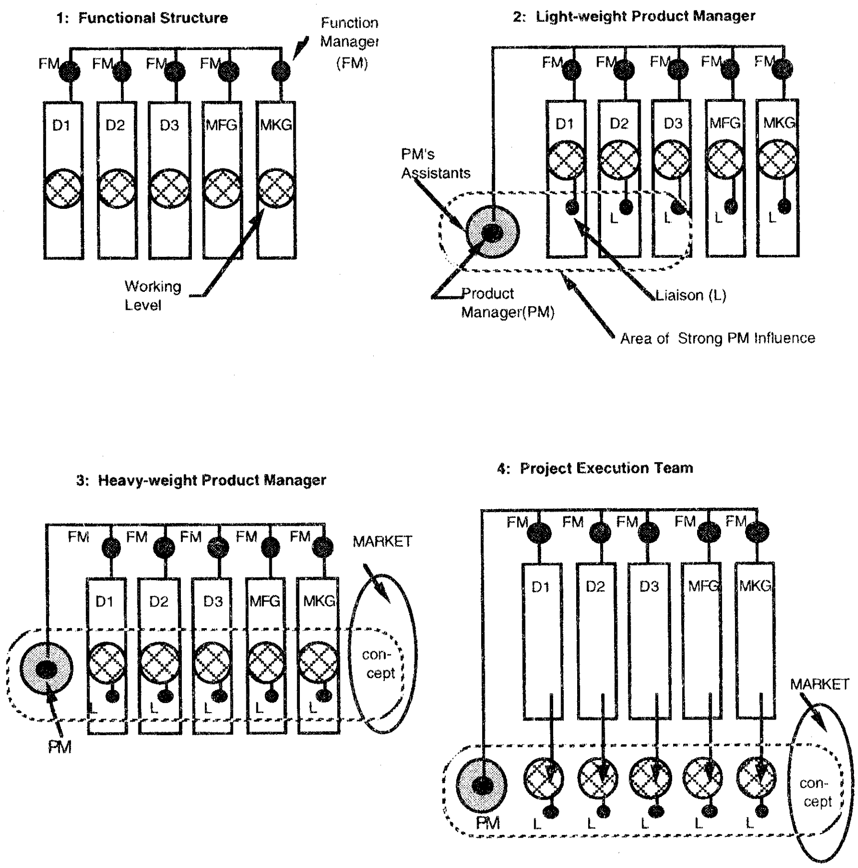
Note: Spearman rank order coefficient is significant at 5% level.

Source: Fujimoto (1994)

This result implies that many of the product development organizations in the auto industry of the 1980s were suffering from "overspecialization" syndrome. Although, generally speaking, specialization of engineers is necessary for efficient accumulation of technical expertise for a complex product like the automobile, this data indicates that the capability-building on this direction may result in *over-shooting*, or over-building of such capabilities that turns out to be dysfunctional.

(5) Heavy-Weight Product Manager: The development organizations which achieved high performance in lead time, productivity and product integrity simultaneously tended to be those which combined powerful project coordinator and concept creator in one role (types 3 and 4 in **figure 7**). We called this role "heavyweight product manager" (Clark and Fujimoto, 1990; 1991; Fujimoto, Iansiti and Clark, 1996). Our statistical result, using certain indices of organizational patterns, indicated that heavyweight product manager system tended to result in high scores in all three dimensions of product development performance, as far as volume producers of the 1980s were concerned (**figure 8**).

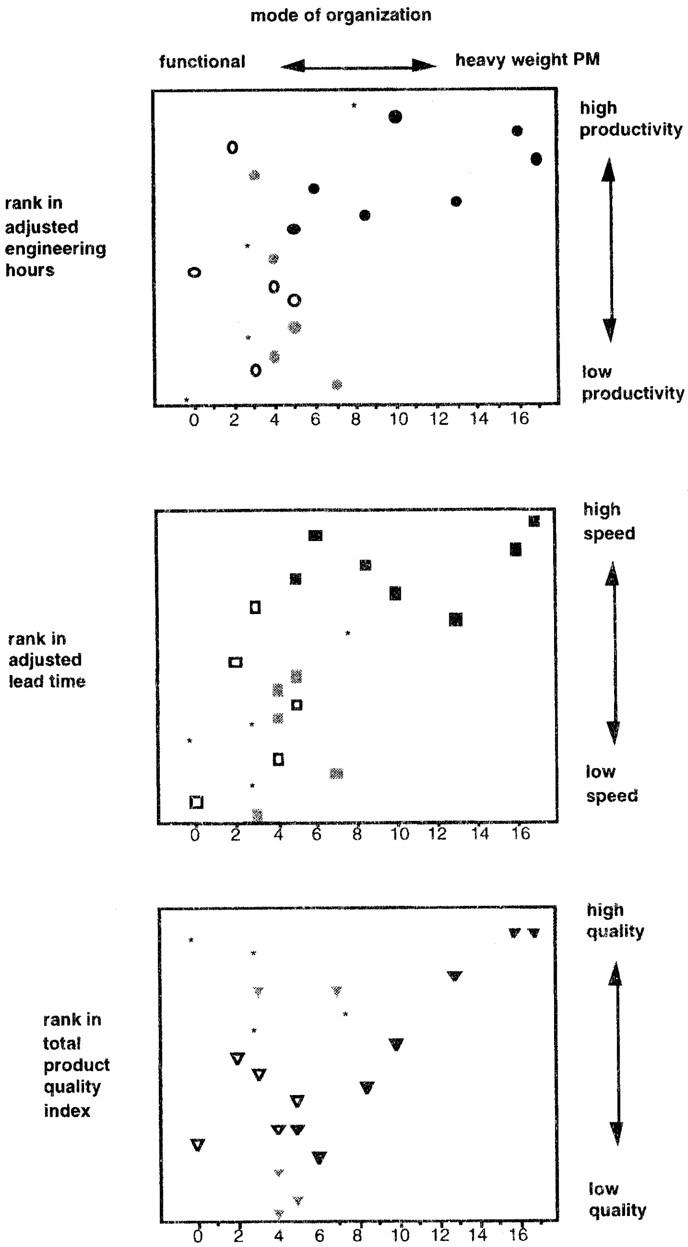
Figure 7 Four Modes of Development Organization



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

Source: Clark and Fujimoto (1991)

Figure 8 Mode of Organization and Development Performance



Note: ■ = Japan ▒ = U.S. ◘ = Europe * = high-end specialist

Source: Clark and Fujimoto (1991)

To sum up, our data analysis in the 1980s suggested that effective product development organizations that enjoy short lead times, high development productivity, and high total product quality at the same time needed to build a set of mutually complementary routines-capabilities. There was no magic techniques that could instantly make a company the world class product developer -- the key to success was a pattern constancy. The study also indicated that the common-denominator of the high-performing routines -- supplier involvement, manufacturing for design, integration of product-process engineering, small and coherent team, and heavyweight product manager -- is effective management of interconnected problem solving cycles which include: early, rapid, and accurate execution of each problem solving cycle; effective simulation (be it physical, virtual, or mental) of future production and consumption; frequent and high-band-width communications that integrates numerous problem solving cycles. Effective organizations for product development were the ones that facilitated effective management of the interconnected problem solving cycles.

3. The Early 1990s: The Western "Reverse Catch-up"

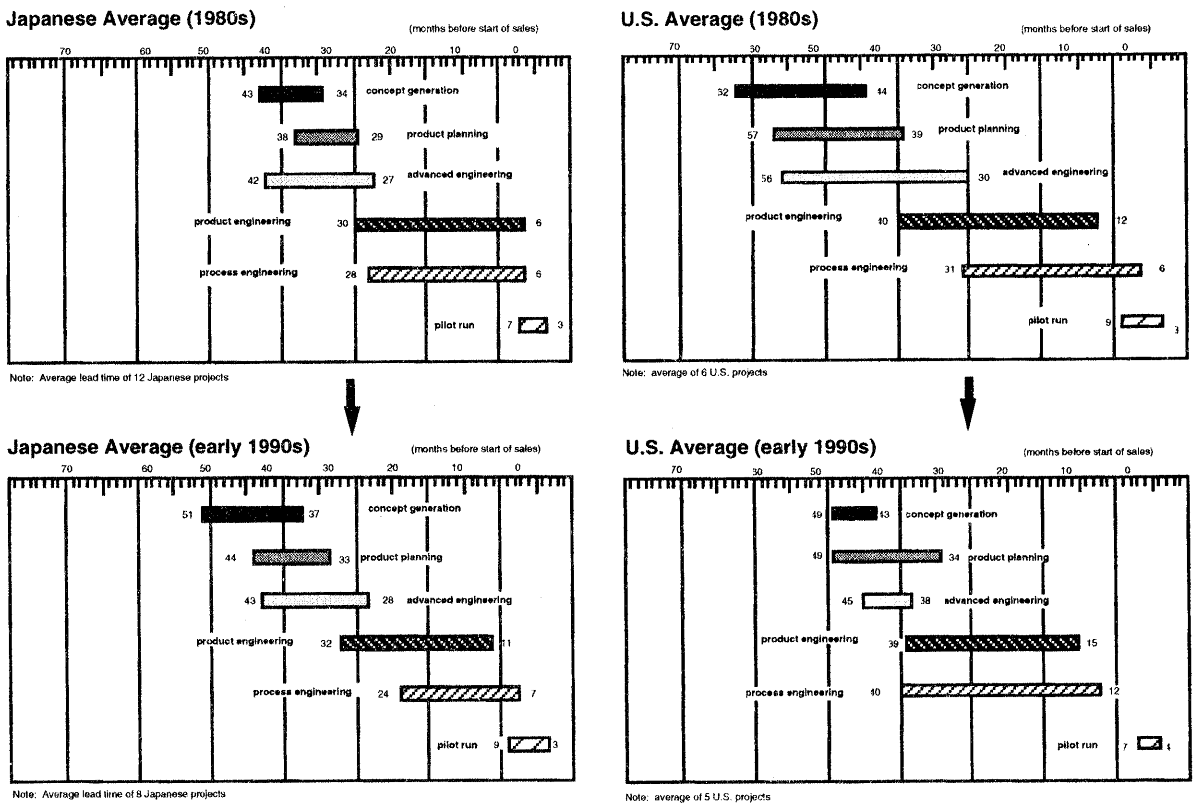
Partial but Significant Catch-up by the American Makers: In the late 1980s to the early 1990s, product development performance of the Japanese firms did not show any significant progress in terms of lead time and engineering hours, if not product integrity, according to the Harvard University's study (Ellison, et al., 1995). Average engineering lead time (virtually the same as the time between exterior model approval to start of sales in the Japanese case; about 30 months) and engineering work hours (i.e., productivity; around 2 million person-hours per project after adjustment) did not change much. Planing lead time (from the start of concept generation to project approval or exterior mode approval) became significantly longer, making the total development lead time also longer (See **figure 9** for the changes in lead times)

In addition to the stagnant improvements in product development performance, the Japanese auto-makers also suffered from "fat" product design problem that surfaced as the cost disadvantage of the Japanese automobiles after the further appreciation of yen in 1993 - 1994 (Clark and Fujimoto, 1994; Fujimoto, 1994a, 1996b).

The U.S. makers, on the other hand, caught up with the Japanese quickly in both engineering hours and total lead time. Main contributor of the lead time reduction at that time was planing lead time rather than engineering lead time, though (**Figure 9**).

Figure 9 Average Project Schedule (Unadjusted) - 1980s versus early 1990s -

(the numbers may be subject to slight changes)



Source: Fujimoto (1994). Based on Ellison, et al. (1995).

They also converged their pattern of organizational routines to that of the Japanese effective producers of the 1980s in many aspects (Clark and Fujimoto, 1991; 1994, Ellison et al., 1995, Fujimoto, 1994a). For example, the data that Clark, Ellison and Fujimoto collected in 1993 as an update of the former Harvard study (Ellison et al., 1995) clearly indicate that the U.S. auto makers changed their product development structures from mostly light-weight product manager types in the 1980s to mid to heavy weight ones in the 1990s (**table 2**). The study also shows that the ratio of black-box parts in total procurement cost at the sample U.S. projects jumped from 16% on average in the 1980s to 30% in the early 1990s (The equivalent number in Japan is about 50 to 60%). It also identified tendency of convergence in product development capabilities in such areas as die making lead times, prototype making lead times, product-process overlapping ratio, and so on. Thus, in most of the themes that Clark and Fujimoto (1991) identified in the 1980s, we had observed partial adoption by the Western auto makers by 1993.

Table 2 Regional Comparison of Product Development Performance and Routines - 1980s versus 1990s -

		Japan	U.S.	Europe	total
number of sample projects	1980s	12	6	11	29
	1990s	8	5	12	25
unadjusted total lead time (mo.)	1980s	43	62	61	53
	1990s	51	52	59	55
unadjusted engineering hours	1980s	1.2 mil.	3.5 mil.	3.4 mil.	2.5 mil.
	1990s	1.3 mil.	2.3 mil.	3.2 mil.	2.5 mil.
adjusted total lead time (mo.)	1980s	45	61	59	53
	1990s	55	52	56	55
adjusted engineering hours	1980s	1.7 mil.	3.4 mil.	2.9 mil.	2.5 mil.
	1990s	2.1 mil.	2.3 mil.	2.8 mil.	2.5 mil.
% of supplier's proprietary parts	1980s	8	3	6	6
	1990s	6	12	12	10
% of black box parts	1980s	62	16	29	40
	1990s	55	30	24	35
% of detail -control parts	1980s	30	81	65	54
	1990s	39	58	64	55
prototype lead time (mo.)	1980s	7	12	11	9
	1990s	6	12	9	9
die lead time (mo.)	1980s	14	25	28	22
	1990s	15	20	23	20
% of heavy weight PM projects	1980s	17	0	0	7
	1990s	25	20	0	12
% of mid to heavy PM projects	1980s	83	17	36	52
	1990s	100	100	83	92
% of common parts	1980s	19	38	30	27
	1990s	28	25	32	29
product complexity index	1980s	95	92	83	90
	1990s	68	76	100	85

Source Ellison, Clark, Fujimoto and Hyun (1995).
For the methods of adjustment for product complexity and definition of product complexity index, devised by Ellison, see appendix of the above paper.
For other definitions, see, also, Clark and Fujimoto (1991).

Why Did the Japanese Lead Time Get Longer? As the Harvard study indicated, the Japanese product development lead time got longer in the early 1990s mainly by prolonged planing lead time. The reason for this change is not necessarily clear, but certain circumstantial evidences and interviews indicates at least two possibilities. First, as the major Japanese auto makers expanded its overseas operations around this time, the number of derivative models mainly for overseas markets per basic model (platform) increased, making the coordination for planning more difficult and time-consuming. Second, as the

Japanese makers started to simplify their product designs partly by using more common parts, they found that more deliberate planning was needed to gain cost advantages from using common parts without causing negative effects on product integrity and distinctiveness (There many be some time lags between the period of data collection and that of the design simplification).

Although nothing conclusive can be said at this point due to the lack of further clinical information, the above stories seem to be consistent with our way of looking at product development as an interconnected problem solving cycles (Clark and Fujimoto, 1989a; 1989b; 1991). Clark and Fujimoto (1989a), for example, argued that (i) product development is essentially a bundle of problem solving cycles, (ii) that its planning stage can be characterized as a network of horizontal linkages of problem solving cycles between the components that are functionally and structurally interconnected, (iii) and that its engineering stage can be characterized as vertical linkages of problem solving cycles. Based on this logic, we predicted that using more common parts, where product integrity is emphasized in the market, tends to crate more coordination difficulty between component designs and thus prolonging planning lead time (This does not happen in engineering lead time as component engineering tasks are partitioned by components at this stage). Our data were consistent with this hypothesis. The hypothesis on the proliferation of overseas derivative models was also consistent with this view.

4. The Mid 1990s: The Japanese Cutting Lead Times Again?

4.1 Reduction of Engineering Lead Times by Some Japanese Makers

To understand the nature of the industrial marathon in product development, let us examine a relatively recent cases of a new challenge by the Japanese auto makers: further reduction on lead times. This example indicates that re-intensification of competition could happen at any area of product development performance, and that the renewed competition requires renewed efforts for capability re-building.

The source of the new competition in development lead times is again the Japanese. In the mid 1990s, some Japanese started to shorten lead times between the styling model approval and start of sales (close to what we *call engineering lead time*) from approximately 30 months to around 20 months or even less (Nobeoka and Fujimoto, 1996. In February 1997, for example, Nissan announced that it will develop all the new models after 1997 with 19 months lead time between exterior design fix and production). This was a challenge not only to their Western competitors but also to the Japanese themselves: As explained earlier in this book, the average Japanese engineering lead time was about 30 months in our 1980s survey, and it was basically unchanged in our early-1990s study. Other historical evidences tell us that the Japanese major projects (except some exceptional cases such as Mazda Miata) maintained this 30 month standards for nearly twenty years until the mid 1990s, when they suddenly started to cut engineering lead times not incrementally but rather drastically by nearly a year.

This was the time when the Western catch-up overall lead times was already obvious and that in engineering lead times also stated to realize. It is of course true that shorter lead times do not guarantee success of individual new products, but it would raise the "batting average" of the firm's new products, and it would also result in fewer engineering work-hours (i.e., higher development productivity), which brings about more opportunities of new product introductions, other things being equal. Thus, to the Western auto makers, which were in the middle of closing lead time gaps, this spurt of some Japanese firms means that the target is moving again. Thus, the capability-building competition is refueled, and the "industrial marathon" continues (Clark and Fujimoto, 1994).

4.2 Problem-Solving View for Analyzing Lead Time Cutting

In analyzing the data, the key concept was *early, short and overlapped problem solving*. Again, the basic principle does not seem to change much from Clark and Fujimoto (1991) in this particular industry. An underlying assumption is that it takes more cost and time to solve problems later in the development projects, while fidelity of the early simulation models tends to be low (Clark and Fujimoto, 1991; Fujimoto, 1993). The question is how to make the best balance between these conditions.

For analyzing lead time cutting, let's start from the following basic characterization of the automobile product development:

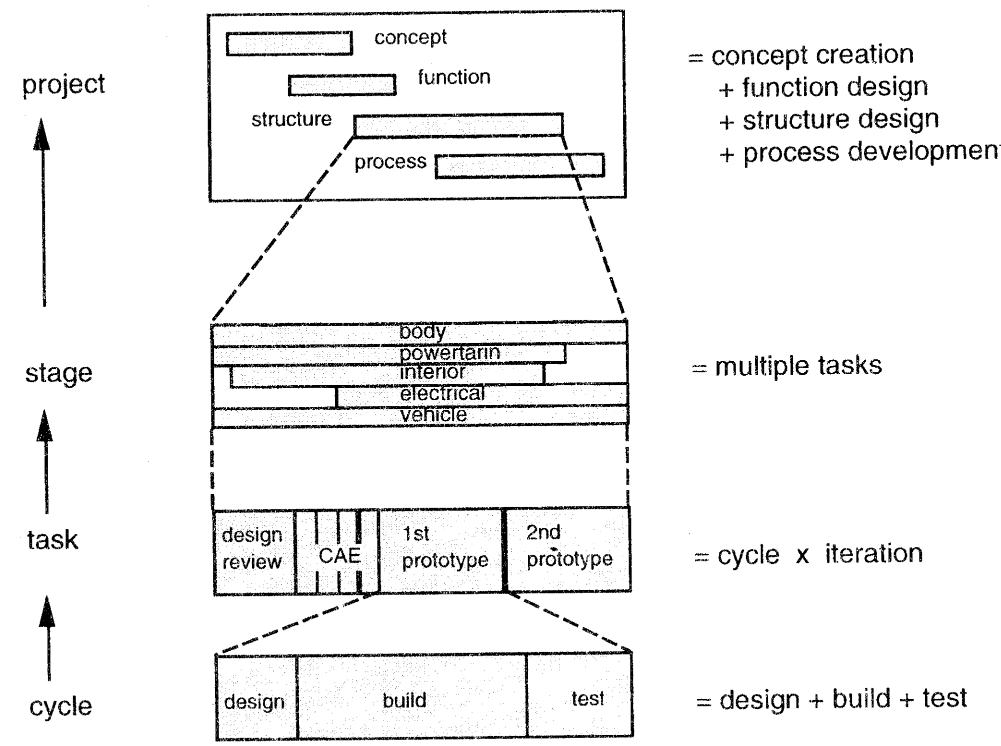
(i) Product development consists of a bundle of numerous *problem solving cycles*, each of which consists of design, build, and test activities. Each cycle includes *simulation* models (e.g., physical engineering prototypes, clay models, pilot vehicles, computer simulations, though experiments, etc.) for predicting effects of the design alternatives on future consumption and production processes. The problem solving cycles are structured as a hierarchical form: the cycles are iterated to complete a *task* that create a solution for each component; the tasks are integrated into major *stages* of development such as product engineering and process engineering (**figure 10**).

(ii) Automobiles continue to be a complex and integrated product (i.e., integral product architecture in the term of Ulrich and Eppinger, 1995) that are difficult to decompose into functionally independent components. The components are interdependent and/or interfering with each other in many cases. There are efforts to make this product more module-oriented, particularly in Europe, but there are some limits. Thus, *horizontal linkages* of tasks (component problem solving cycles) have to be managed for reduction of lead times.

(iii) Automobiles continue to be a complex products which needs at least some physical functional prototypes to check its functional and structural integrity and total system performance. They also continue to be mass-produced products made mainly by steel, and thus need stamping die development. To the extent that both prototype making and die making needs significant lead times, *vertical linkages* between product and process engineering stages need to be carefully managed.

(iv) To reduce lead times of product development as a bundle of problem solving cycles, managers and engineers have to shorten, simplify, or overlap the activities at <u>all</u> stages of the hierarchy shown in **figure 10** -- compress time needed for each activity; reduce iterations for solving a problem; overlap the cycles on a critical path, and so on. Of course, such measures for lead time cutting have to be conducted without sacrificing cost and quality of the product.

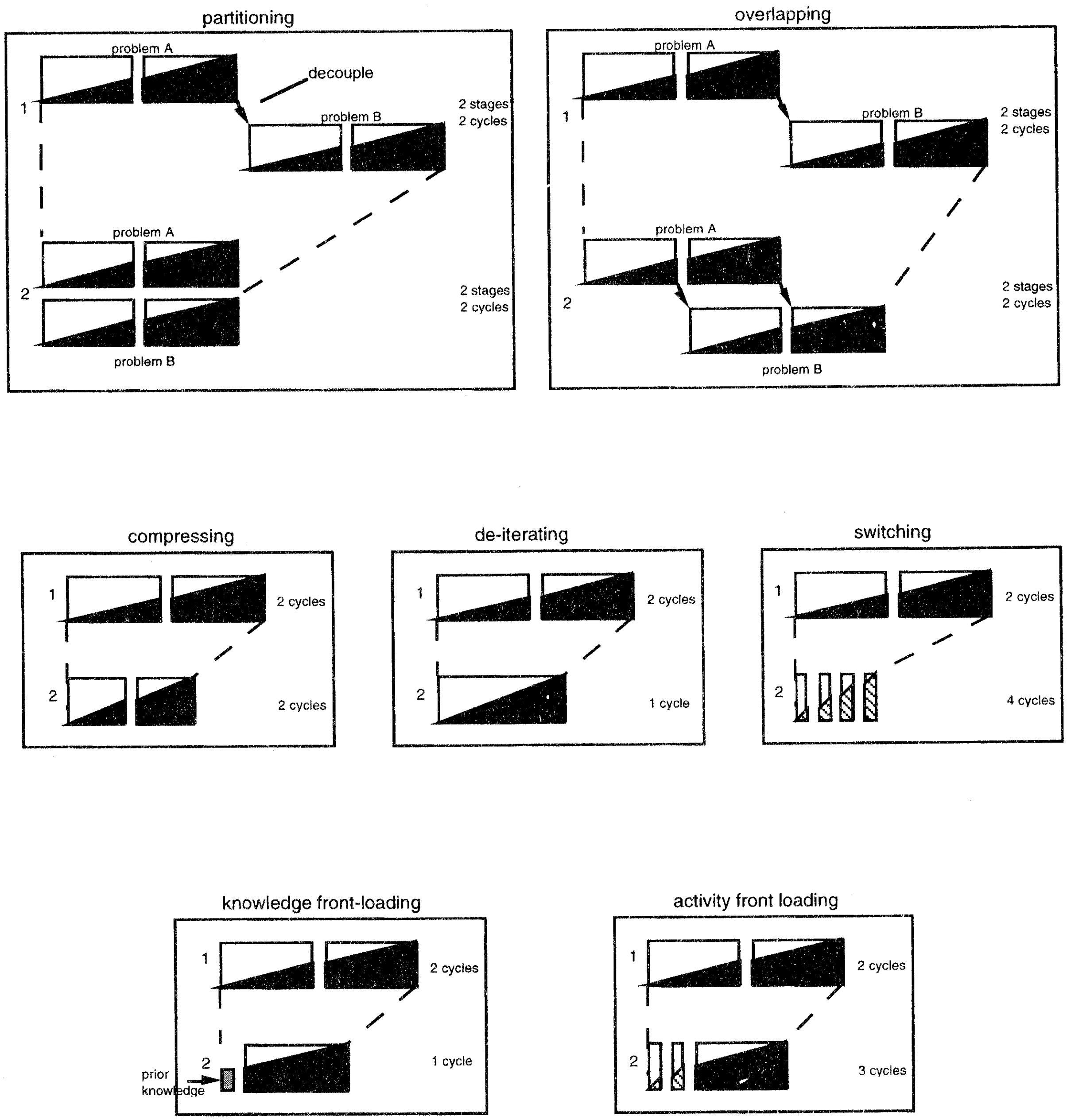
Figure 10 Product Development Project as Problem Solving Cycles and Stages



Note: Overlapping of design/build/test and overlapping of cycles are omitted for graphical simplicity

Based on the above assumptions and the problem solving perspective, let's now classify basic ways for lead time cutting. **Figure 11** shows alternative methods of cutting product development lead times through enhancement of a firm's problem solving capabilities.

Figure 11 Basic Ways for Shortening Problem Solving Time (from case 1 to case 2)



Note: A rectangular stands for 1 cycle of problem solving. Horizontal axis is time; Vertical axis is the fraction of the problem solved. For simplicity, it is assumed that all the cycles presented here are cost-effective and feasible. Also, only two modes of problem solving are assumed: physical (prototyping) and virtual (computer simulation) for simplicity.

physical simulation (high fidelity, long cycle) virtual simulation (short cycle)

Note that our main point here is that *shorter lead time means earlier completion of problem solving.* We can imagine a situation in which lead times are unilaterally cut by sacrificing the degree of problem solving (e.g., cutting the development lead time by three months and create many more manufacturing problems and design changes during the production start-up period), but we do not call it real lead time cutting. With this in mind, let's look at the figure, which classifies several ways of lead time cutting at the microscopic level: *partitioning, overlapping, compressing, de-iterating, switching,* and *front-loading.*

For simplicity, our base case (state 1 in each case) in **figure 11** is problem solving that needs two cycles to complete; A rectangular stands for one cycle of problem solving (i.e., one iteration of a design-build-test cycle), in which the horizontal axis stands for time, while the vertical axis represents the fraction of the problems solved at that point; The black or shaded triangles mean that problems are gradually solved as problem solving cycles progress and iterate; Only two modes of problem solving (simulation) are considered in the **figure** for simplicity of discussion -- physical prototype simulation (black) and virtual computer simulation (striped).

Based on these assumptions, and starting from the base case, we can identify at least several methods of lead time cutting, which we will explain next. Note that, for each column, state 2 enjoys shorter lead times than state 1, but for different reasons.

(i) Partitioning : The first two columns of **figure 11** assumes two stages or tasks of problem solving (A and B) linked in tandem so that the output of stage A becomes input of stage B. For example, body engineering of a fender panel and die development for that fender are a typical pair of stages. Floor panel design and electric wire harness design are another example of pair of tasks.

The first thing that the engineers may typically try is partitioning or de-coupling (von Hippel, 1990). When there are two interconnected problem solving tasks or stages, and if there is an opportunity to eliminate or weaken this informational link, then the manager may get extra freedom to shift the downstream problem solving upward and thereby cut the overall lead time. The partitioning strategy works particularly well at the level of the problem solving task -- by modularize the product architecture (i.e., simplifying the interface between parts), we may de-couple problem solving tasks on the critical path, make them parallel, and thereby reduce the overall lead time[1].

(ii) Overlapping : Starting from a similar situation of two stage problem solving, managers can try another frequently used strategy -- overlapping. This is the case in which the downstream stage/task (B) is moved to the parallel or semi-parallel position vis-à-vis the upstream (A) without de-coupling them. Preliminary information is delivered from the upstream to the downstream so that the later can flying-start its problem solving cycles. The case in the figure is the simplest abstract case, but more concrete examples, as well as conditions or success) were already discussed in our previous work (Clark and Fujimoto, 1989a, 1989b, 1991, etc.)[2].

So far we have explored how to shorten problem solving duration in the multiple cases, where the solutions (partitioning or overlapping) were basically to re-position the downstream stages/tasks up-front. The other way of shortening lead times is to shorten the stage/task itself, shown in the middle part of **figure 11**. Let's explore such possibilities next.

(iii) Compressing: This is the simple case of speeding up the same kind of activities inside each cycle, enhance the problem solving capability of design, build or test, and thereby shorten lead times without changing basic sequence or mode of problem solving. This is largely a result of day-to-day improvement efforts of speeding up detail designing, prototype making, functional testing, analysis, etc. The reduction of lead times tends to be incremental, accordingly.

(vi) De-iterating : Another simple idea is to reduce a the number of iterations before the final solution is acquired, using the same mode. For instance, the number of batches of physical prototype building may be reduced: The number of CAD-CAE iterations for convergence may be also reduced. In any case, simple de-iteration tends to be a power play that requires enhancement in sheer capacity of simulation models or efficiency of search strategies.

---

[1] At the level of *stages*, there is an inherently logical sequence from concept creation to functional product design (product planning) to structural product design (product engineering) to process engineering, simple de-coupling is not feasible. At the level of activities in each cycle, there is an also a logical sequence of design-build-test that cannot be ignored, simple partitioning is not possible.

[2] Note that the overlapping strategy can be applied to the level of stages, tasks, cycles and activities.

(v) *Switching* : This means reduction of lead times (usually a significant reduction) by changing the mode of the problem solving cycle from a slow one to the rapid one. A typical example is the switch from physical prototyping (a traditional long cycle mode) to virtual computer simulation (a non-traditional short cycle mode). Thomke (1996), for example, reports and analyzes the condition of such switching in the case of integrated circuits. The cases of complete replacement of physical prototypes by computer models is not common yet as of the mid 1990s, but we will see this in more industries in the near future.

The three cases mentioned above, compressing, de-iterating and switching, are, in a sense, basic building blocks, whereas the last two cases, shown at the bottom of **figure 11**, is somewhat more complex combination of these elements -- *front-loading*. Front-loading, as a means for shortening lead times, means to make early efforts to acquire information for completing the problem solving task faster (**Thomke and Fujimoto, 1997, forthcoming**). The information may include partial solutions to the problem or partial knowledge on causality. Such information may be acquired by simply fetching prior knowledge (knowledge front-loading), or by conducting preliminary problem solving up-front (activity front loading).

(vi) *Knowledge front loading*: means acquiring prior knowledge so that the problem is already partially solved when the problem solving starts. As the figure indicates, prior knowledge creates opportunity for reducing the iterations and thereby shorten overall lead times. . So it may be regarded as a variant of de-iteration. Typical cases of prior knowledge is information from the predecessor projects (Watkins and Clark, 1992; Aoshima, 1995). Knowledge front loading tends to be effective in the products which are evolving at a moderate speed, so that the prior knowledge is not obsolete.

(vii) *Activity front-loading*: This is the case where partial solutions are quickly created by certain rapid modes of problem solving (e.g., CAE simulation, rapid prototyping methods, design review meeting, etc.), which alleviate the work load for completing the problem solving later on. Note that this is, in a sense, a combination of early *switching* and later *de-iteration*. This pattern becomes effective in relatively complex and equivocal products, for which the fidelity of rapid simulation methods (e.g., CAE) is still limited (Otherwise the previous case of complete switching to the new simulation method will simply happen). Note that, in this particular case the number of problem solving cycles increased (from 2 to 3), but overall lead time was reduced. (We will return to details of activity front loading later on.)

These are the main methods of cutting lead times through enhancing problem solving capabilities. These methods can be applied to the case of the automobile and any other product development cases in which lead time cutting is a focus of competition. These methods may be used wherever feasible at the levels of stages, tasks, cycles and activities of problem solving.

5 Preliminary Evidence: Partitioning, Overlapping, and Front-loading

Having laid out the problem-solving framework for analyzing lead time cutting, let's take a look at some empirical evidence on the those Japanese firms that are reducing engineering lead times in the mid 1990s. Since this is a new phenomenon, systematic data collection has not started yet at this point (A new Harvard University Auto Study on product will carry out the new round of data collection in 1997), we have to rely mostly on anecdotal evidence. Thus, the following discussion is based on interviews at several Japanese auto-makers conducted between 1994 and 1996, although the names of the companies are neither disclosed nor hinted for confidentiality purpose.

It turned out that, through this field research, that the major ways for lead time cutting in the mid 1990s have been *partitioning, overlapping,* and *front loading* shown in **figure 11**. Simple *compression* of the same developmental activity may also be an important factor in analyzing, for example, drastic lead time cutting in major die-making activities is apparently happening at some companies, but this paper does not analyze it due to insufficient information. *De-iterating* is also observed in physical prototype construction, but this is not a simple de-iteration but rather a result of front-loading. *Switching* from physical prototypes to virtual simulations is also important, but what is happening in the auto industry is not a complete switch from the former to the latter (Thomke, 1995, discuss the case of the complete switch), but a partial switch as a part of front-loading. So, the rest of the paper focuses on partitioning, overlapping and front-loading (particularly the latter) and interpret the anecdotal evidence from the problem-solving's point of view.

5.1 Partitioning

Some lead time cutting firms studied so far pointed out that they were doing early task partitioning effectively for reducing lead times. The basic idea here is to de-couple previously intertwined activities and thereby start the bottle neck activities earlier.

Early and rapid parts decomposition (i.e., early development of bills of materials) is done by some firms by, for example, using 3-D CAD. This enables the auto-maker to shorten lead time by early task partitioning.

Earlier decomposition of functional targets for components is also done for some important and time-consuming total vehicle function (e.g., noise-vibration-harshness). Such decomposition may need collaboration of testing, CAE, and design sections. A flexible team or task force may be made that specializing in important total-vehicle functions.

Modularization of product architecture makes the total vehicle design easier to decompose structurally and functionally into parts in the first place and thereby facilitates **earlier component prototyping-testing** of key components. In this way, the first prototype can use fully tested component designs. There is apparently no agreement among the Japanese as to how far the companies want to modularize their future cars. Some are aggressive, but others are cautions. So far there is no evidence that those reluctant to modularize lag behind others in lead time reduction.

A related strategy is to **decompose upper body and under body** and do the detailed underbody engineering earlier -- prior to styling decision. In the case of today's unit body structure, upper and under bodies are two integral parts of the total vehicle. Upper body is subject to exterior design decisions, so detailed engineering of the upper body cannot be done before the exterior design fix (clay model approval). If upper and under bodies can be decomposed, detailed engineering of the latter can be now shifted prior to the design fix, and thereby disperse the body engineering work load and complete the total body engineering earlier. This is possible particularly when a new model is derived from an existing (but modified) platform. (see **figure X, case 3**).

5.2 Overlapping

Overlapping at Micro Levels: As indicated in our data analysis on the early 1990s (Ellison et al., 1995. See), stage-level overlapping between product and process engineering did not play an important role in improving product development of the Japanese throughout this period: The Japanese lead time performance did not improve much in the first place; The Japanese stage-overlapping was already very high in the 1980s, so there was not much room for further simultaneity; Our data in fact indicated less overlapping between product and process engineering compared with the case of the 1980s (see **figure 9**). This, however, does not mean overlapping as a principle became unimportant. In the 1990s, when many companies worldwide emphasized *stage* overlapping at a rather macro-organizational level (e.g., between product and process engineering), it is likely that some Japanese shifted their attention to more micro-level overlapping, such as *task* overlapping between the components within a stage, *cycle* overlapping problem within a task, or overlapping design, prototyping and testing *activities* within a cycle. That is, overlapping at micro levels seems to have increased its relative importance.

For example, some firms that was already doing product-process inter-stage overlapping effectively in such critical-path areas as body engineering and die engineering (Clark and Fujimoto, 1989b; 1991) often found that inter-task simultaneous engineering between body and other parts (e.g., wire harness) was not as good. The relatively poor coordination between body and wire harness engineers created unduly long wires and many connectors that added costs and sources of defects. So these firms emphasized simultaneous engineering (or integrated problem solving) between certain interlocked component development tasks **within the product engineering stage**. As a result, for example, wire harness engineers, who used to be politically weak vis-à-vis body engineers increased their voice. In the case of body and wire harness, the task-overlapping between the two product engineering groups resulted in simpler wire harness designs (shorter wires, fewer connectors), as well as fewer iterations of design changes (i.e., shorter lead times for this set of tasks).

Simultaneous engineering between components also called better coordination between different process engineering departments (e.g., press vs. welding vs. casting vs. machining vs. assembly). Some companies have tried to establish a process engineering coordinator for each product development project, working closely with product manager in the early 1990s (see, for example, Fujimoto, 1996a, for a case of Toyota).

Limits of Simultaneous Engineering : As mentioned, we have already discussed much about this strategy in our previous works (Clark and Fujimoto, 1989b; 1991). We will therefore skip the details of overlapping problem solving strategies in this book, but we have a few comments on the recent trends of so called *simultaneous engineering* or *concurrent engineering*--a similar concept with our overlapping problem solving.

We basically agree with many of the arguments on the benefits of simultaneous-concurrent engineering--shortening lead times, design for manufacturing, higher product coherence, and so on. However, we do not agree with the idea that this is a simple matter of making developmental activities as simultaneous-concurrent as possible, or front-loading and sharing information across the functions as much as possible. The key criterion is, again, whether the simultaneity or communication facilitates *early problem solving*. Concurrent activities and early information releases, when carelessly managed, may create confusions and thereby increase iterations of design changes that may make the overall development project lead times longer. As we have advocated in previous works (Clark and Fujimoto, 1989b; 1991), such integrated problem solving needs careful management and enhancement of communication, problem solving capabilities, skills, cultures and attitudes. Without such capability building for integrated problem solving, a rash introduction of simultaneous-concurrent engineering may result in no substantial improvements, or, worse, confusion and resentments in the organization.

5.3 Front Loading -- the key in the mid 1990s

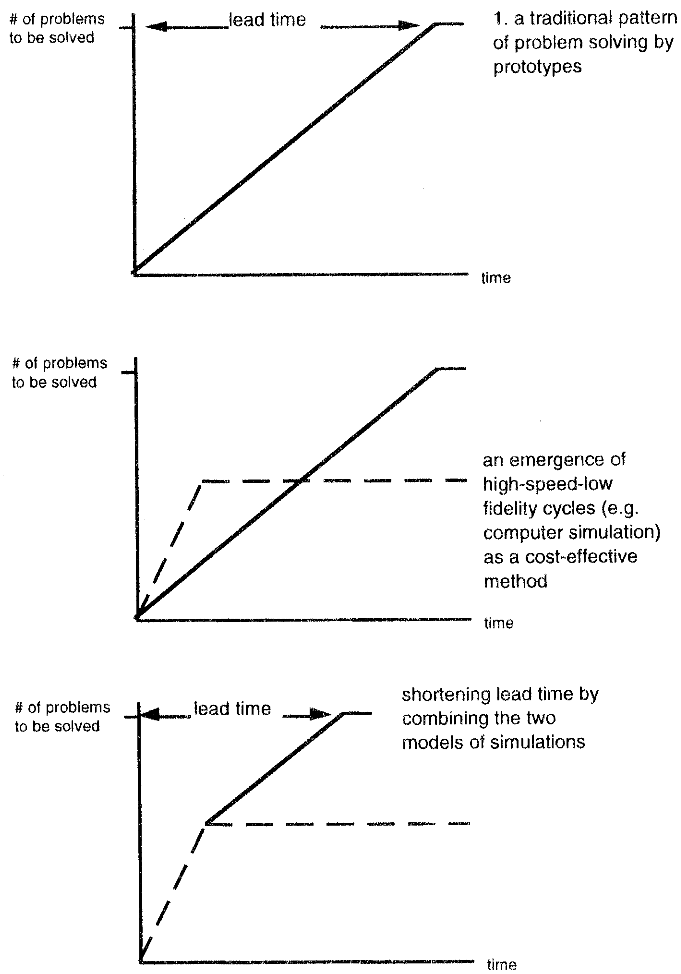
More than anything, front loading is the one that is the most important in explaining the lead time cut among the Japanese (Nobeoka and Fujimoto, 1996). Let's explore its logic and practice in further detail.

The Logic of Front Loading: To the extent that we characterize a product development project as a system of numerous problem solving cycles, we can define *front-loading* as *early acquisition of information for early completion of problem solving iterations* (Nobeoka and Fujimoto, 1996; Thomke and Fujimoto, 1997). Front-loading, in this sense, refer to a situation in which (i) increasing problem solving cycles at the early stage (*activity front loading*) or (ii) use the prior knowledge about past problem solving (*knowledge front loading*) reduce the necessary amount of problem solving cycles at the later stage so that the overall resource and/or time needed for the entire product development project (see the bottom two case of **figure 11** again).

For now, let's examine the case of activity front loading within a certain task or stage, in which early and rapid problem solving cycles (e.g., CAE) reduces iteration of long cycle problem solving (e.g., prototypes) later on. For simplicity, suppose that there are two types of simulation models (**figure 12**) : physical prototypes and virtual computer models. Traditionally, physical prototyping tended to need longer lead times and higher cost per cycle, but enjoyed higher fidelity (reliability of results of each run). By contrast, virtual simulations were relatively rapid, but its overall fidelity or representativeness was lower than the physical ones (this is shown as the lower saturation level in the **figure 12**.)

As fidelity of computer models increased, (or unit cost to get the same fidelity decreased), virtual iterations at early stage of iterations became economically and technically feasible. Firms started to make many iterations of virtual prototypes (low cost, shot cycle time methods), which enabled the first physical prototype to be built closer to the ultimate target range so that the number of the latter iterations could be dramatically reduced. As a result, as **figure 12** shows, total number of iterations (virtual + physical) may increase, but total lead time is reduced.

Figure Early Problem Solving (Activity Front-Loading)



<u>Solving Problems before Prototypes is Key</u>: The name of the lead time cutting game in the mid 1990s is *to make the first engineering prototype (and prototype drawings) as complete as possible and cut the prototype iteration*, or to solve as many problems as possible before the first prototype drawings are released. This is essentially what we call "early problem solving."

Physical prototype vehicle is essentially a *slow, expensive but high fidelity method* for simulating the product-customer experience. Since there is no other simulation methods that can substitute prototype vehicles in their ability to reproduce accurately total vehicle functions (if not partial representation -- crash testing may be effectively done by today's CAE, for example), the problem solving iterations for the product engineering stage needs to end with physical prototypes (you cannot eliminate physical prototype altogether, unlike some other electronic products (Thomke, 1995). In traditional cases, there were two or three iterations (or batches) or prototype building (each with 30 to 40 on average), so if you can successfully reduce the number of iterations, then its lead time cut effect is dramatic. This is what these companies were trying.

How can we reduce the number of problems remaining before the first prototype is built? There are two complementary approach -- (i) early use of rapid problem solving (activity front loading), (ii) prior knowledge (knowledge front loading), which increases the fidelity of the design information before the prototype. Effective prototyping itself is also the keys.

(i) Early Use of Rapid Cycle Problem Solving: There are some alternative methods for simulating the product and its function with higher speed, but with lower fidelity, than the prototypes themselves. Some are new technologies, and others are traditional organizational methods.

Computer-Aided Engineering (CAE) simulations, linked often with 3 dimensional Computer-Aided Design (3-D CAD), are increasingly used for early evaluation of product functionality and marketability. In some firms CAE simulation is required before releasing a design to the prototype shop. Effective firms so far tend to use them selectively and cleverly rather than depending on sheer computing power of super computers for all problems (Reduction of design lead time itself by CAD is not significant compared with its impact on other lead times such as CAE simulation, CAM for prototyping, , quick making of bills of materials, etc.). Some firms are using 3-D CAD-CAE also for early evaluation of design manufacturabillity and assemblability.

3-dimensional CAD-CAE enables the development projects to integrate parts for structural checking (e.g., parts interference, dimensional miscalculation) earlier than the first prototype, which is the first opportunity for such integration in the past. Evaluation of total vehicle functions is more difficult, but accuracy of CAE for this purpose is gradually increasing. Some firms also try to make the **CAE simulation results more visual** so that problems can be detected more easily and quickly by engineers other than CAE specialists.

Rapid prototypes (RP), or partial prototypes using certain 'soft" materials (papers, wood, plastic, clay, etc.) and often directly linked to 3-D CAD data through computer-aided manufacturing (CAM) or through stereo-lithography, are used more frequently at lead-time-cutting firms. Rapid prototyping may also be used for early evaluation of assembly or manufacturing feasibility.

Use of **pre-prototypes**, with more representative materials but less representative designs (e.g., using under bodies of previous models) than rapid prototypes are also used more often for early simulation of functionality of the vehicles and parts. When assemblability of parts designs can be evaluated reasonable accurately without accurate prototypes, **pre-prototypes** may be made and used for assembly simulation manually prior to first prototypes. Such evaluations were often done at the first prototypes previously.

Effective lead time cutters tend to link the physical pre-prototyping and CAE simulations so that the two methods can efficiently achieve early problem solving. This seems to be important, as we often observe political tensions between the physical prototyping unit and the CAE units within a product development organization. Without close collaboration between the physical and virtual simulations, often led by product managers, effective implementation of front-loading seems to be different.

Some of the effective lead time cutters use **Design Reviews** (DR) earlier, more frequently, and with wider participation, as well as other forms of early evaluation of designs, with or without early prototypes or CAE simulations. DR is essentially a **collective mental simulation** of design alternatives. DRs were mostly done after the first prototypes in the past, but some Japanese firms are doing more DRs earlier.

(ii) Prior Knowledge: Smart Use of CAE and RP: Effective firms tend to front-load **knowledge from previous projects**. Many problems are found and solved even before the project starts. This gives the project more focus on the areas where problems occurred more frequently than other areas (e.g., under body, engine compartment, door-lid openings, cockpits, pillars). Simulation models tend to be made earlier and more accurately in these areas than other areas (selective simulation).

Although recent technologies of electronics and materials are enabling relatively rapid and inexpensive ways of building and running simulation models, technology does not seem to be the sufficient condition of lead time reduction , though. For example, effective companies tend to use rapid prototyping and CAE **selectively** and wisely by deliberately matching the nature of the problem to be solved (functionality, aesthetics, fitting, manufacturability, etc.) and types of the prototypes to minimize cost and time and just-enough fidelity. This simplifies the simulation models, given the problems to be solved, and thus shorten lead times for simulation model building and running, while saving cost. Behind such selective and smart use of new technology is a combination of deep **prior knowledge** in both engineering problems themselves and new simulation tools. The latter alone is not enough.

Early involvement of downstream stages (e.g., production, suppliers) also facilitate use of prior knowledge, since they bring in experiences of pervious projects. The first physical prototype is naturally an opportunity for production people to check design for assembly and manufacturing: Prototypes are sent to assembly plants for checking manufacturability, or core assembly operators or leaders are dispatched to prototype shops (Clark and Fujimoto, 1991). Some companies are involving production engineers and plant staff into the engineering design process prior to the first prototype (e.g., production people joining the engineers pre-prototype design reviews).

There may be optimal timing and level of involvement, though. It may not be a simple case of "the earlier the better for everyone" Deliberately selective front-loading, rather than unconditional front-loading, seems to be important (The same logic applies to the case of suppliers). Again, front-loading is desirable when and only when it facilitates early and cost-effective problem solving.

Early involvement of testing and prototyping people in certain preliminary designs at the pre-engineering stage (e.g. layout drawings) is also important for subsequent lead time reduction through early problem finding.

<u>Early creation of more representative and detailed designs</u>: Using the results of early rapid problem solving, firms are increasing fidelity or representativeness of early design information. **Layout drawings** now include more detailed aspects of parts designs; First prototype designs are made in more details. Where **prototype drawings (shisaku-zu)**, tool-order drawings (tehai-zu), and final drawings (ryosan-zu) were made sequentially, they now tend to merge, as the former becomes more detailed and complete.

Fidelity of CAD itself improved in recent years. CAD changed from little more than sketches to full-fledged detail drawings. The connection between CAD and CAM and CAE got more accurate accordingly.

<u>More Effective Physical Prototyping</u>: What should be improved is not only problem solving and knowledge loading <u>prior to</u> the prototype building, but the prototyping itself [-- this is not front loading itself, though --]. Physical prototype making based on more representative production methods is

pursued by some effective firms. Prototype parts are more frequently made by **production dies** (typically plastic parts) or soft dies cut from the same CAD-CAM as the production dies. This improves accuracy of manufacturability evaluation based on the prototypes, as opposed to pilot vehicles later on.

Effective firms appears to have people who can translate the simulation results using prototypes into predicted results at the production stage more accurately. To the extent that the simulation models are not perfectly representative, human causal knowledge (i.e., **interpretation of the results**) that supplements physical and virtual simulation models is still important. That is, interpretation of the prototype simulation results may be as important as the accuracy of the simulation itself.

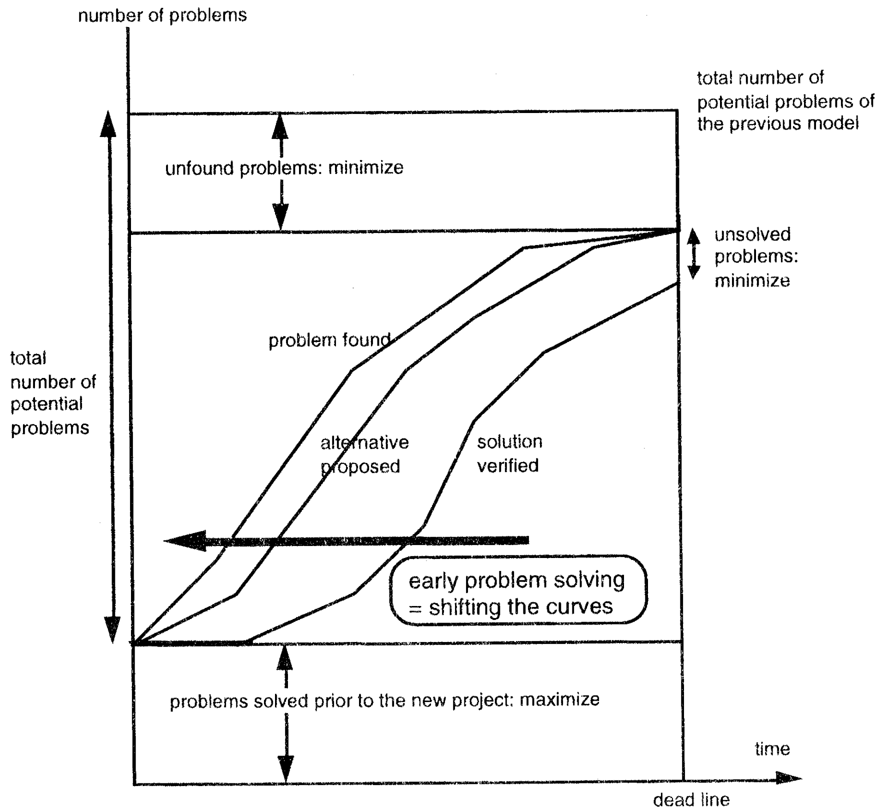
Once design problems are found at the prototype stage, some effective firms enforce short lead time between problem finding and alternative generation (proposals for design changes) by imposing a strict **deadlines** for each problems found. This simple measure shortened design change lead times effectively.

5.4 Overall Effect: Shift of Problem Solving Curves

I have so far explored various ways of shortening lead times separately, but the bottom line is to solve the overall customer problem by a new product as early as possible. Conceptually, this means shifting a *cumulative problem solving curve* shown in **figure 13**.

Let's assume a case of a full model change for now. The model is renewed because the auto-firm judges that the existing one does not solve target customers' problems any more. The gap between the existing model's functions and future customers' expectations is the overall problem to be solved, which can be decomposed into numerous sub-problems to be solved through the new product development. We can plot the number of such sub-problems on the vertical axis, time on the horizontal axis, and draw a cumulative problem-finding curves, an alternative generation curve, and a problem-solving curve for each product development (**figure 13**).

Figure 13 Shift of Cumulative Problem Solving Curve

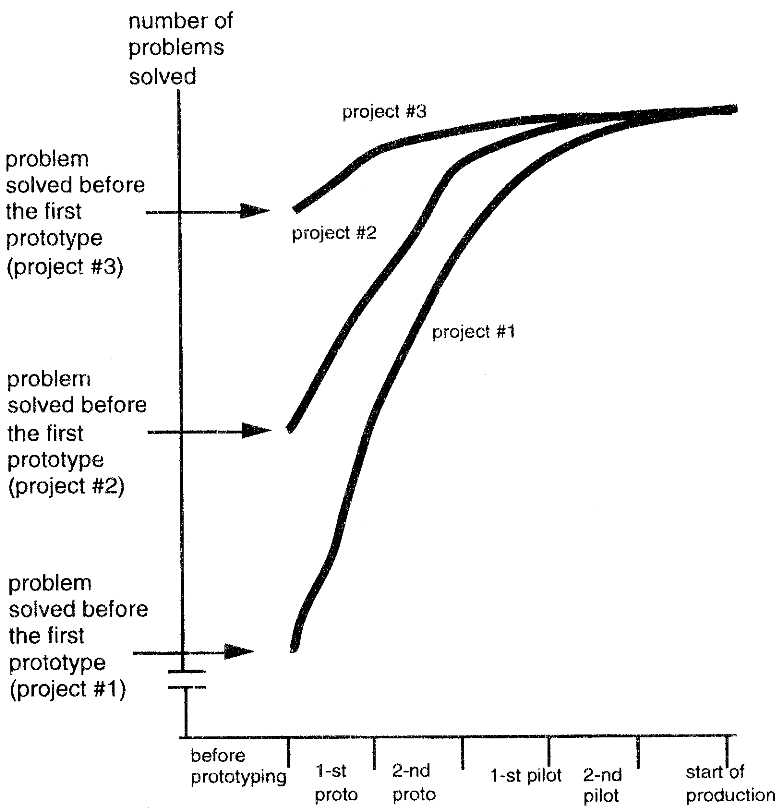


As the figure indicates, lead time reduction for a model change project can be reinterpreted as the shift of the cumulative problem-solving curve to the left. For this purpose, the project would try to (i) maximize the number of prior problem solving, (ii) minimize the problems unfound, (iii) shift the cumulative problem-finding curve, (iv) minimize the time lag between the problem-finding curve and the problem-solving curve, and (v) minimize the problem unsolved at the end of the project. In this way, the cumulative problem-solving curve is shifted to the left, and lead time reduced without sacrificing product quality or cost.

It is important to note that lead time reduction is an effect of capability-building in product development (i.e., shift of the problem solving curve). One manager of an effective lead-time-cutting company, for example, warns that **lead time reduction itself should not be treated as the goal -- it is a consequence of an enhanced capability**. Thus, the management attentions should be first focused on capability, rather than lead times themselves. In a sense, cutting lead time can be dine overnight if deterioration of initial product quality and increase in product cost is allowed: what is difficult is to cut lead times without sacrificing initial quality and project costs, and it is possible only with enhancement of organizational capabilities in problem solving.

There is no systematic data collection on the problem solving curves of the auto product development, but figure 14 may provide a preliminary evidence.

Figure 14 Shift in Problem Solving Curve (Company A, Japan)



Note: All the three projects were completed in the mid 1990s in the order of 1, 2, and 3. For simplicity, it is assumed that the number of problems to be solved are the same in all three cases, and that all the problems are solved by the start of production. The curves are rough approximation of real cases.

The curves were reconstructed by the author based on the number of problems solved at each stage of product development (from the first prototypes to start of production) for three project in one of the lead-time-cutting company in Japan. The shift of these problem solving curves from project #1 to #3 indicates that the absolute number of the problem solved at the first prototype stage and thereafter was reduced dramatically between the projects #1 and #3 in a few years. If we can make a rough assumption that these three projects potentially had the same number of problems to be solved, as the figure 14 implies (i.e., the same end point for the three curves), then we can reinterpret this figure that more and more problems are solved prior to the first prototype phase (see starting points of the curves). Such prior problem solving would be partly because of inter-project learning (transfer of prior knowledge) and partly because of early problem solving prior to the prototyping (there is no way to separate the two effect in this chart), but it would be reasonable to infer from this chart that knowledge front-loading and/or activity front-loading was actually happening in some lead-time-cutting firms of the mid 1990s.

6. Summary and Future Research

This paper examined the improvements of product development performance in the 1980s and 1990s. The Japanese advantages in the 1980s were explained by a set of mutually complementary routines (For historical explanation on how these routines emerged, see Fujimoto, 1994). Our data in the early 1990s also indicated that the western auto-makers achieved a significant catch-up vis-à-vis the Japanese in product development performance partly by adopting the organizational routines that we identified in the 1980s study as a complementary set of capabilities. Finally, this paper made a preliminary analysis on the case of recent re-intensification of the capability-building competition, in which some Japanese firms again reduced lead times between design fix to start of sales from the previous 30 months to about 20 months or even less.

Through the present analysis, it was indicated that the set of routines-capabilities for effective automobile product development that the earlier Harvard study identified (Clark and Fujimoto, 1991), as well as the problem solving framework behind such routines, can explain at least a part of the patterns of capability-building competition in this field during the 1990s.

It was pointed out in this paper that the issue of lead time cutting should be analyzed as that of early problem solving, and forward shift of problem-finding curves and problem-solving curves and engineering work load curves. It was also argued that what companies do for this purpose is not lead time cutting per se but capability building for early problem solving, and that the former occurs as a consequence of the latter.

The competition of capability building is an endless "industrial marathon" (Clark and Fujimoto, 1994). Whereas the western auto-makers are rapidly catching up the Japanese in many areas of product development performance and routines, some Japanese are also starting to renew its efforts to improve their performance as of the mid 1990s. While such see-saw game continues, I predict that the regional differences (i.e.,, the Japan effect) that we observed during the 1980s may become obscure in the long run, and capabilities of individual firms will increase its relative importance. Mutual learning between the competing firms will continue, as the capability-building competition intensifies. To analyze such dynamics of the new industrial competition, we have to continue consistent data collection and analysis in the long run toward the first part of the next century.

Reference

Aoshima, Y. "XXX." Unpublished Ph.D. Dissertation, Massachusetts Institute of technology.

Clark, K. B., Chew, W. B., and Fujimoto, T. (1987). "Product Development in the World Auto Industry." Brookings Papers on Economic Activity, 3: 729 - 771.

Clark, K.B. and T. Fujimoto. "The Power of Product Integrity." Harvard Business Review. November - December, 1990. pp. 107 - 118.

Clark, Kim B., and Takahiro Fujimoto (1991). Product Development Performance. Boston: Harvard Business School Press.

Clark, K. B. and Fujimoto, T (1989a). "Lead Time in Automobile Product Development: Explaining the Japanese Advantage." Journal of Technology and Engineering Management, 6,1989. pp. 25-58.

Clark, K. B., and Fujimoto, T. (1989b) "Overlapping Problem Solving in Product Development." Harvard Business School Working Paper, 1987. Also in Managing International Manufacturing, edited by Ferdows Kasra. Amsterdam: North-Holland, 1989.

Clark, K. B. and Fujimoto, T. (1994). "The Product Development Imperative: Competing in the New Industrial Marathon." Duffy, P.B., ed., The Relevance of a Decade. Harvard Business School Press.

Ellison, D. J., Clark, K. B., Fujimoto, T., and Hyun, Y. (1995) "Product Development Performance in the Auto Industry: 1990s Update." Harvard Business School Working Paper 95-066.

Fujimoto, T. (1989) "Organizations for Effective Product Development -The Case of the Global Automobile Industry-." Unpublished D.B.A. dissertation, Harvard Business School.

Fujimoto, T. (1993a) "Information Asset Map and Cumulative Concept Translation in Product Development.' Design Management Journal, Vol. 4, Number 4, 34-42.

Fujimoto, T. (1994a) "The Dynamic Aspect of Product Development Capabilities: An International Comparison in the Automobile Industry," in Goto, A. and Odagiri, H., ed., Innovation in Japan. to be published from Oxford University Press, forthcoming)

Fujimoto, T. (1994b) "Reinterpreting the Resource-Capability View of the Firm: A Case of the Development-Production Systems of the Japanese Auto Makers." Paper Presented to Prince Bertil Symposium, Stockholm, June.

Fujimoto, T. (1996a) "An Evolutionary Process of Toyota's Final Assembly Operations - The Role of Ex-post Dynamic Capabilities." Dissuasion Paper, Tokyo University Faculty of Economics. 96-F-2. (Presented at Third International Workshop on Assembly Automation, Ca' Foscari University of Venice, October 1995).

Fujimoto (1996b) "Capability Building and Over-Adaptation -A Case of 'Fat Design' in the Japanese Auto Industry-." INSEAD Euro-Asia Centre Working Paper.

Fujimoto, T., Clark, Kim B., and Aoshima, Y. (1992) "Managing the Product Line: A case of the Automobile Industry." Harvard Business School Working Paper 92-067.

Fujimoto, T., Iansiti, M., and Clark, Kim B. (1996) "External Integration in Product Development." in Nishiguchi, T., ed., Managing Product Development. Oxford University Press, New York. 121-189.

Nobeoka, K. (1993). "Multi-Project Management: Strategy and Organization in Automobile Product Development." Unpublished Ph.D. Dissertation, Massachusetts Institute of technology.

Nobeoka, K., and Cusumano, M. A. (1995). "Multi-Project Strategy, Design Transfer, and Project Performance: A Survey of Automobile Development Projects in the IS and Japan." IEEE Transactions on Engineering Management, 42. 4.

Nobeoka, K. and Fujimoto, T. (1996). "XXX", Presented at International Motor Vehicle Program, Massachusetts Institute of Technology, 1996 Sponsors Meeting. Sao Paulo, Brazil, June

von Hippel, E. "Task Partitioning: An Innovation Process Variable." Research Policy. 19 (1990): 407-418.

Thomke, S. (1995) The Economics of Experimentation in the Design of New Products and Processes." Unpublished Ph.D. Dissertation, Massachusetts Institute of technology.

Thomke, S. and Fujimoto, T. (1997). "Front Loading for Shortening Product Development Lead Times." Harvard Business School Working paper, forthcoming.

Ulrich, K. and Eppinger, S. (1994). Product Design and Development. McGraw-Hill, New York.

Watkins M., and Clark, K.B. (1992) "Strategies for Managing Multiple Projects." Harvard Business School Working paper.