The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster

Allen Ward • Jeffrey K. Liker • John J. Cristiano • Durward K. Sobek II

ALTHOUGH ON THE SURFACE, TOYOTA'S DEVELOPMENT PROCESS SEEMS EXTRAORDINARILY CUMBERSOME, IT IS A MODEL OF HOW TO MAKE BETTER CARS MORE quickly and cheaply. Toyota's engineers and managers delay decisions and give suppliers partial information, while exploring numerous prototypes. The authors examine what they call "set-based concurrent engineering," a method prevalent at Toyota but not at other Japanese and U.S. automakers. Toyota designers think about sets of design alternatives, rather than pursuing one alternative iteratively. They gradually narrow the sets until they come to a final solution. Through extensive research, case studies, and interviews, the authors present their argument — that this apparently inefficient system has made Toyota the fastest and most efficient developer of autos.

Allen Ward is assistant professor, mechanical engineering and applied mechanics; Jeffrey K. Liker is associate professor; and John J. Cristiano and Durward K. Sobek II are doctoral candidates, industrial and operations engineering, at the University of Michigan.

During the past decade, Japan's major source of competitive advantage in the global automotive industry has been its ability to bring new, high-quality products rapidly to market. Simultaneously designing a product and its manufacturing system (often referred to as concurrent or simultaneous engineering of overlapping tasks) is generally seen as the salient characteristic of this competitive edge; Toyota, the most successful Japanese automotive company, is credited as one of the originators of concurrent engineering (CE).[1] To compete, U.S. companies have implemented CE, largely through organizational design, creating highly structured design processes and multifunctional, often collocated, design teams, with intense communication among team members, including supplier engineers.[2] Several U.S. companies (most notably, Chrysler and Ford) have reduced the length of the product development cycle, in part through such organizational changes.[3]

Our research has found, however, that Toyota uses a relatively unstructured development process, its multidisciplinary teams are neither collocated nor dedicated, and, in the case of suppliers, Toyota communicates intensively about product development with a smaller portion of its supply base than do U.S. auto companies (but Toyota suppliers give their customer higher marks for communication effectiveness than U.S. suppliers give their automakers). Moreover, while in most cases CE seeks to freeze specifications quickly, Toyota's engineers and managers try to delay decisions and provide their suppliers with hard specifications very late in the process. And, while conventional concurrent engineering reduces the number of prototypes, Toyota's suppliers seem to multiply prototypes, in some cases to an apparently absurd degree.

The Second Toyota Paradox

In our view, the first Toyota paradox is its production system, which includes delivering just-in-time; breaking production into lots far below "minimum economical order quantity"; having each worker, rather than professional inspectors, check the previous worker's results; allowing any worker to stop the line and installing automatic line stops; adding many tasks to a single workstation; and encouraging workers to redesign their own jobs, rather than having trained industrial engineers break the work down and prescribe procedures. Few guessed that these methods would prove compatible with, and perhaps essential to, factory efficiency well above Japanese companies' already high average.

Toyota's use of what we call set-based concurrent engineering is the *second* Toyota paradox. We believe that Toyota's development innovations may be nearly as important as the Toyota production system — and as confusing at first glance. The second paradox, in brief, delaying decisions, communicating "ambiguously," and pursuing excessive numbers of prototypes, enables Toyota to design better cars faster and cheaper. Certain aspects of Toyota's development process seem to range from mildly conservative to grossly inefficient. However, they are entirely coherent when seen as a different development paradigm. While the formal concept of set-based concurrent engineering is not Toyota's — Ward and Seering developed it in automating design processes — we have found something approaching a coherent, company-wide, set-based philosophy only at Toyota.[4]

Some background on our definition of set-based CE will help frame our arguments. In this approach, designers explicitly communicate and think about sets of design alternatives at both conceptual and parametric levels. They gradually narrow these sets by eliminating inferior alternatives until they come to a final solution. This approach contrasts with the common practice of iterating — making modifications or improvements in series — on one alternative until a satisfactory solution emerges. We call the iterative approach "point to point" design, since the state of the design moves from point to point in the "design space."

To understand why set-based CE can be efficient, consider one simple problem — selecting a meeting time. The meeting organizer selects the time and date most convenient for himself and starts inviting people. The first person may not be able to attend then; together, they select a new time. However, the third person may not be able to make the new time and suggests an alternative, forcing a check with the first person, and perhaps another change. For large, busy groups, convergence to a satisfactory time for all parties can require lengthy communications — the disadvantage of a point-to-point search in which no individual has all the required knowledge.

There are two common strategies for shortening the search yet retaining the point-to-point model. First, the group can have a meeting to decide when to have a meeting: this accelerates the communication, at the cost of some members' time. The corresponding strategy in automobile development is to collocate and dedicate the engineers and require them to meet more often, increasing their communication. Second, some powerful member(s) of the group can set a time and force everyone else to comply, generally producing a suboptimal solution, albeit quickly. Similarly, auto development teams often seek to freeze specifications early in the development cycle.

A third, set-based approach to planning a meeting requires all participants to submit the times that they are available, perhaps with preferences. A convenient time can quickly be found by taking the intersection of all the sets of available times, a process now often automated.

Set-based meeting design is easy because it is simple to represent and test sets of meeting times. But sets of automobile designs are difficult to represent and take time to develop and test, so the set-based approach often leads to apparent inefficiencies. Yet our observations suggest that Toyota stands apart from its Japanese and U.S. counterparts in the degree to which it uses a set-based approach — and Toyota is arguably the fastest and most efficient developer of automobiles.

We have emphasized in this introduction some dramatic (and extreme) examples of broad exploration of solutions at Toyota. However, set-based concurrent engineering refers to a deliberate effort to define, communicate about, and explore sets of possible solutions, rather than modifying a point solution — and, in some cases, these sets may be deliberately more constrained than common industry practice. Toyota uses engineering checklists or "lessons learned books" (our term) to represent sets of manufacturable designs in order to constrain the styling process — for example, requiring the stylists to avoid some extreme body curves. Just as in the meeting example, where each participant identifies infeasible times, each functional group in Toyota has identified infeasible designs and systematically records these in the checklists. Thus set-based concurrent engineering suggests exploration of sets of alternatives, but within clearly defined sets of constraints. In some cases, there are few constraints and the search is quite broad (as in a brand new vehicle like the original Lexus), and, in others, the search is highly constrained (as in a minor model change in which most parts are carried over from the previous model). We describe both kinds of practices in this article. We have been impressed in our interviews at Toyota with the ability of engineers and managers to intuitively identify when broad exploration is warranted and when a narrow, constrained search is preferable.

The purpose of our research was to test empirically whether high-performing companies use a more set-based approach than their lower performing counterparts. We looked for evidence of set-based methods in the Japanese auto industry because of its reputation for rapid development of high-quality products. We visited U.S. automakers and some of their parts suppliers and Nissan, Mazda, and Toyota and their parts suppliers.

Next we describe our data collection methodology, Toyota's contribution to CE, and the basic concepts of conventional and set-based concurrent engineering, and then we outline the stages of Toyota's development process. Case examples provide data for three kinds of communication: between stylists and body engineers, between body engineers and manufacturing engineers, and between original equipment manufacturers (OEMs) and suppliers. Finally, we explain the paradox between inefficient steps and an efficient overall process and discuss implications for managers and future research.

Data Collection Approach

Our study is based on case data, which has inherent limitations in proving causality. In the beginning, we recognized the difficulties in measuring the degree to which a particular company uses "set-based design" — particularly since this is a relatively new concept. We understood the principles in theory but had not identified specific practices and sorted them into relative degrees of set-based versus point-based. We also saw the difficulties in measuring product development efficiency and effectiveness comparably across companies making different products. We hoped that by comparing Japanese automakers, known for excellence and efficiency in product development, with their U.S. counterparts, we might see a contrast in approaches associated with the U.S./ Japan differences in efficiency and effectiveness.

Our initial hypothesis was that Japanese auto companies were both more concurrent and more set-based in their design approach than U.S. automakers, and that this helped account for their rapid development cycles and high-quality results. To our surprise, the U.S. and other Japanese companies we investigated appear fairly similar, but strikingly different from Toyota: Toyota and its suppliers alone fit our concept of set-based concurrent engineering.

That fit is neither perfect nor uniform, since the Toyota culture includes many companies and individuals. Unlike the Toyota production process, the Toyota development process has not had a Shigeo Shingo to formalize and popularize it, or a Taichi Ohno to enforce it; it is growing slowly and organically. We have tried to report accurately the cutting edge of practice at Toyota and its suppliers, while identifying the most important areas where our data are ambiguous.

Concurrent engineering is inherently about horizontal coordination across functions (e.g, managing the interfaces of subsystems), and longitudinal coordination across development stages (e.g., the interface between product design and manufacturing system design). For this study, we focused on the interface between automakers and their parts suppliers. Japanese automakers outsource about 70 percent of the vehicle content to suppliers.[5] They also give their suppliers relatively large influence on the product design.[6] The customer-supplier interface provides an excellent opportunity to explore set-based design, as communications on the design tend to be formal and deliberate. We asked questions about the requirement-setting process and how suppliers develop prototypes and communicate potential solutions to customers. We also asked about the body styling and engineering process and the interface between body engineering and manufacture. (Body styling and engineering is a complex CE process. The body design inherently constrains the design of all other vehicle subsystems, and many different body panels must fit together accurately.)[7]

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We interviewed managers and engineers of U.S. and Japanese automotive companies and their suppliers.[8] We asked respondents to describe their development process from the early concept stages through production and then probed with standard questions to understand the degree to which their process is set-based. The results of the initial interviews with Toyota were so surprising that we returned to Japan twice for follow-up interviews that confirmed the paradox apparent at first.

Toyota and Concurrent Engineering

Managers told us that Toyota began moving to concurrent development in the 1960s; Mazda, in the late 1970s; and Nissan, not until the mid-1980s. Toyota's process continues to be far more concurrent than other companies': for example, Toyota begins designing and building body-stamping dies before all drawings are finished,

Table 1 Toyota Compared with Other Auto Companies on Selected Design Features

Area	Other Companies	Toyota & Suppliers
Number of 1/4 or 1/5 scale clay models developed	Japanese OEM: 3 to 5	Toyota: 5 to 20
Body hardpoints	U.S. OEM: fixes before full-sized clay model, avoids changes.	Toyota: as much as 2 cm. design tolerance* at first stage of full-sized clay model, fixes at second stage.
Exhaust system specifications	Japanese supplier: receives hard specs and test data; argues if impossible to meet.	Toyota and supplier: specifications are approximate targets until second prototype.
Number of exhaust system designs prototyped	Japanese supplier: 1	Toyota supplier: 10 to 50
Cooling fan specifications	Japanese OEM: provides hard spec at full-sized clay model.	Toyota supplier: design tolerance – 30% at first prototype 5% at second prototype
Number of fans prototyped	Japanese OEM (about supplier): 2 or 3	Toyota supplier: average of 4 to 5, 30 maximum

*Design tolerance is the amount of flexibility remaining in the design (e.g., *x* ±20 percent).

something neither Nissan nor Mazda does. That Toyota should be different is not surprising. Historically, Nissan has imitated U.S. practice, while Toyota, geographically and perhaps culturally isolated even in Japan, has sought to develop distinctive practices.[9]

We cannot trace in detail the causal links between Toyota's concurrent engineering practices and Toyota quality, efficiency, and market success, but Toyota is doing something right. Toyota's world market share grew by 25 percent in the past decade; in both 1993 and 1994, of the ten cars at the top of J.D. Power's initial quality survey, Toyota had six.[10] Despite dramatic changes in exchange rates, Toyota's U.S. market share is still growing. Much of its success is certainly due to Toyota's production system, but it is widely believed that manufacturing efficiency and product reliability are strongly influenced by design and, therefore, by development processes.

Toyota's development processes seem extraordinarily efficient. "Concept approval," the formal start of a car program in most companies, occurs twenty-seven months before start of production. This is slightly earlier than Nissan, which takes twenty-nine months, and much faster than most U.S. companies; the Chrysler team that designed the LH line took thirty-seven months. A Toyota team has, at peak, only about 500 people, as opposed to 750 or so dedicated at peak to the LH.[11] We have not compensated for vehicle complexity, the degree of reengineering, the quality of results, or the degree of supplier involvement, but Toyota's development process seems to require 50 percent fewer person-years than Chrysler's LH. (The Neon team may have been more efficient, since vehicle development time was reported to take thirty-two months, but so may Toyota's most recent efforts.)[12] This efficiency helps Toyota produce about forty-five different models.

Ironically, however, Toyota's success cannot be attributed to some of the concurrent engineering mechanisms U.S. companies consider essential, such as collocated, dedicated multifunctional teams, a highly structured development process, and frequent meetings with suppliers. First, Toyota does not use collocated, dedicated teams; most development personnel are organized in the traditional "chimney" structure. Toyota has a matrix organization housed within a number of platform divisions (e.g., front-wheel drive, rear-wheel drive, etc.). The general manager of a functional group (e.g., body engineering), in consultation with the chief engineer (*shusa*) for a car platform, assigns engineers to a vehicle program as they are needed. A handful of engineers will stay with the vehicle program throughout its duration, but most work on the program full-time only during the peak period (in the prototype stages), then move on to another vehicle program, often reporting to a different *shusa.*

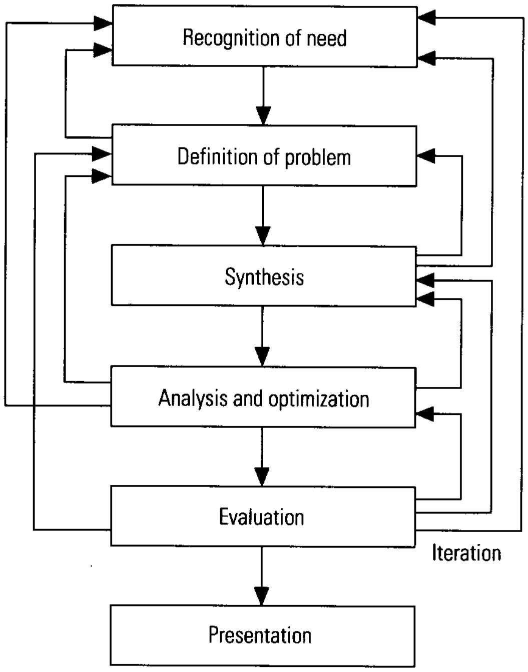
In the United States, Chrysler has reorganized around four platform teams for large cars, small cars, minivans, and light trucks/jeeps.[13] Each team has a high-level general manager (who reports at the vice president level), and the majority of development staff report solely to one platform team head and work on one project at a time. Chrysler considers dedicated platform teams to be essential and matrix management approaches that combine program managers with functional organizations to be ineffective. But Toyota is able to combine an emphasis on teamwork, communication, and consensus with a matrix organizational structure.

Second, while Ford and GM have created staff sections to develop extensive, detailed, development process plans (e.g., G.M.'s four-phase and Ford's world-class timing programs), Toyota has established its reputation for short and rigidly enforced milestones on the basis of project leaders' very simple plans. As in the kanban system on the factory floor, subteams are responsible for deciding when to start work. Suppliers and manufacturing teams, for example, have major deadline goals, such as the start of full production or the first vehicle prototype.[14] As long as the groups can meet the deadline while satisfying the customer, Toyota does not care, or track, when the groups begin work. The suppliers (or manufacturers) initiate when to obtain the information they need to meet the deadline. Some have a "guest engineer" at Toyota; others fax or phone. The wall charts and thick process manuals so popular in the United States are reduced to a few pages at Toyota and its suppliers.

Third, while Toyota is thought to have superb communications between parent company and suppliers, data show that a smaller percentage of Toyota suppliers reported communicating at least weekly with their OEM about design than the average in either the United States or Japan: most Toyota suppliers spend *less* time communicating with the parent company than is the case in the United States.[15] Further, the suppliers are significantly less likely to design their parts jointly with Toyota — either Toyota designs the parts and provides blueprints, or Toyota uses its design-in process to give suppliers the autonomy to do their own design, subject to Toyota's specifications and constraints. (Of course, Toyota has partial ownership of and long experience with its suppliers — but so do other Japanese companies.)

There are some similarities between Toyota's methods and other aspects of U.S. conventional practices, including multifunctional teams and powerful development leaders, and the differences we found do not imply that recent U.S. changes will be harmful. Toyota may not need dedicated, collocated teams because its corporate culture allows effective communication between chimneys. U.S. companies may need more structured processes because they are trying to change rapidly. Toyota's suppliers may need to communicate less because of their long association (the explanation they gave us most often). Toyota may even simply lag U.S. practice, though few U.S. automotive managers seem to think so.

Figure 1 Shigley's Model of the Design Process



Source: J.E. Shigley and C.R. Mischke, *Mechanical Engineering Design*, fifth edition (New York: McGraw-Hill, 1989).

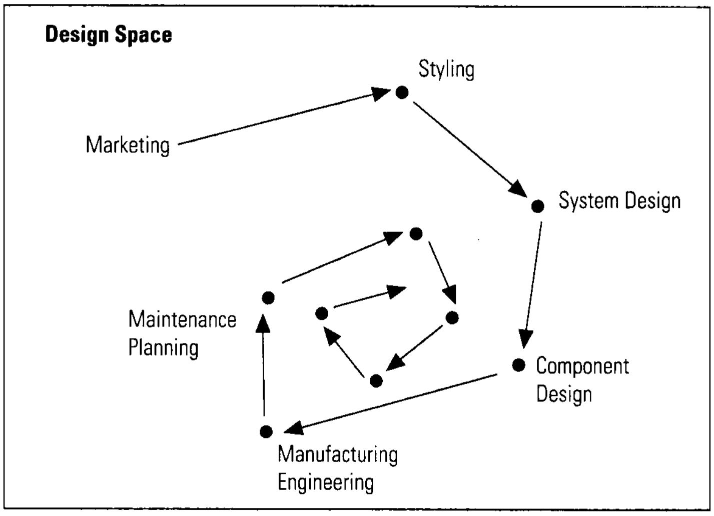
But there is another possible explanation for the differences. Each U.S. practice incurs costs. Dedicating and collocating teams can, in the long term, degrade the company's technical expertise as specialist organizations disappear or become moribund. Detailed process manuals can be cumbersome. Communicating through frequent meetings is expensive; U.S. engineers often complain they spend too much time in meetings, and not enough on creating and analyzing. The set-based concurrent engineering process, as we will show, may allow significant concurrency without incurring these costs. It also explains the more surprising, even seemingly irrational differences we describe in the next section.

Apparent Inefficiencies

The central paradox of the Toyota development process is that, despite its obvious effectiveness, many steps appear extraordinarily inefficient (see Table 1). Compared to the competition, Toyota and its suppliers:

- Explore a larger number of possible concepts in 1/4 or 1/5 scale clay models and expend more resources. Toyota's general manager of styling commented that they "prefer lots of torpedoes to a single sniper bullet."

Figure 2 A Point-Based Concurrent Engineering Process



- Delay fixing body hardpoints (key dimensions that determine body shape), thereby increasing the design team's uncertainty and decreasing the time for the stamping die designers after the body shape is fully determined. According to Toyota's general manager of body engineering, "The manager's job is to prevent people from making decisions too quickly."
- Delay releasing final specifications to suppliers until relatively late in the design process. This conscious decision is based on supplier capability. Toyota sees certain suppliers as less technically capable and provides hard specifications earlier. But Toyota managers report that they provide approximate specifications, or targets, to their more capable suppliers. Approximate targets give the supplier latitude to explore alternatives and are deliberately set to challenge suppliers to excel.
- Develop prototypes of an extraordinary number of different designs for subsystems.

This evidence might suggest a slow, wasteful process, a management that has difficulty making decisions, and a thoroughness that seems completely inconsistent with the speed, economy, and effectiveness of Toyota's development process. Engineers at one of Toyota's leading Japanese competitors reacted to the evidence with polite incredulity. Their own process, it seemed to them, must be more efficient. They could not imagine that one of the world's strongest automakers would waste so much time and effort.

Explaining the Paradox

From a mass production perspective, the lean production process seems highly inefficient. Similarly, the Toyota design process would seem inefficient if viewed from the conventional development model. But Toyota is not following this paradigm, and its practices make perfect sense within its paradigm. Here we summarize the conventional design process model and then outline our interpretation of Toyota's approach.

The Conventional Model

An engineering design text widely used in the United States for the past several decades, Shigley's *Mechanical Engineering Design* prescribes a process that iterates through a sequence of steps in which a designer first understands a problem and then synthesizes a solution (see Figure 1).[16] The designer then analyzes and evaluates the solution; based on the analysis, he or she tries a new solution (and maybe modifies the problem definition). This is often described as a hill-climbing process: each successive solution is another step toward the best possible design at the top of the hill. Because the process moves from point to point in the realm of possible designs, we refer to it as point-based design. Figure 2 illustrates this point-to-point search.

Partly because a majority of automotive engineers were trained to use the Shigley method, this view of engineering design is pervasive in engineering thinking. U.S. engineers, authors, and researchers often emphasize "speeding up the iterative loop" by increasing communication among team members through collocation or sometimes computer support or by providing more powerful analytical tools. They emphasize "reducing the number of iterations," by "taking a prototype out of the design cycle," "doing it right the first time," or "freezing specifications early." In our experience, when shown Figure 1, U.S. line engineers respond immediately, "That's the way we do it," often mentioning improvements that leave the basic model intact, sometimes vaguely implying that there must be a better way.

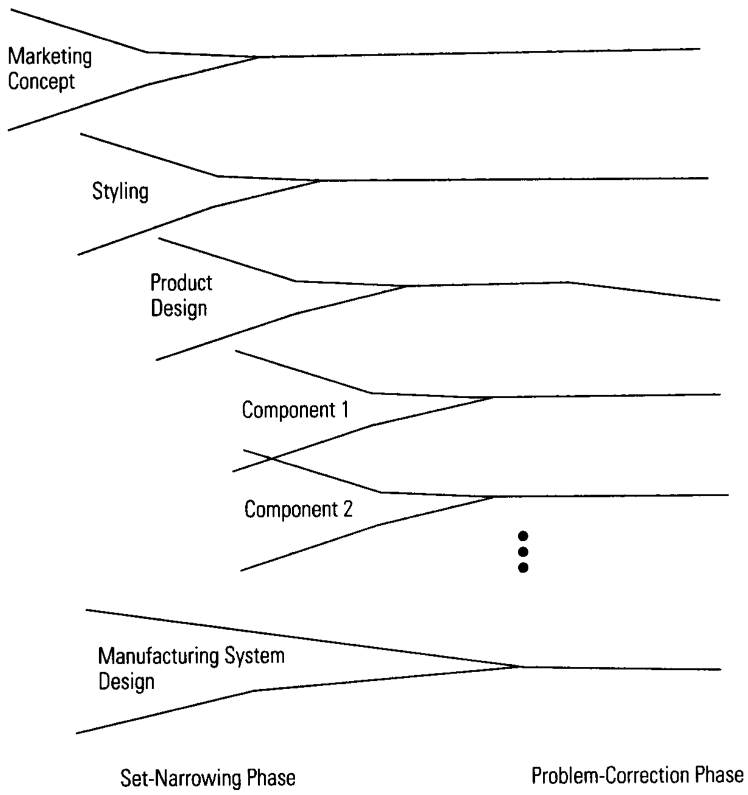
Why does Toyota go through so many iterations, generating different designs? Why does Toyota take so long to synthesize the first solution, providing the starting point for modifications?

The Toyota Model

Toyota's development process looks expensive, clumsy, and inefficient to outsiders (including other Japanese companies) if they view it as a badly run version of their own point-to-point search. Toyota does not conduct a point-to-point search but follows a version of set-based concurrent engineering (see Figure 3):

1. The team defines a *set* of solutions at the system level, rather than a single solution.
2. It defines sets of possible solutions for various subsystems.
3. It explores these possible subsystems in parallel, using analysis, design rules, and experiments to characterize a set of possible solutions.
4. It uses the analysis to gradually narrow the sets of solutions, converging slowly toward a single solution. In particular, the team uses analysis of the set of possibilities for subsystems to determine the appropriate specifications to impose on those subsystems.
5. Once the team establishes the single solution for any part of the design, it does not change it unless absolutely necessary. In particular, the single solution is *not* changed to gain improvements — to climb the hill.

Figure 3 Toyota's Parallel Set-Narrowing Process



Note: Based on a sketch by Toyota's general manager of body engineering in 1993.

There are several aspects of set-based concurrent engineering evident in the approaches of Toyota and its suppliers: First, design authors have long advocated examining a number of concepts, and Pugh developed sophisticated methods for gradually narrowing the "development funnel."[17] The "method of delayed commitment" is well established, but Toyota differs in this aspect from other auto companies in the number and depth of concepts it explores.

Second, "design for robustness," including Taguchi's techniques, considers a set of possible environmental conditions.[18] Toyota and other companies use these methods, but, as we will see, Nippondenso has carried the concept to a higher level, simultaneously designing a set of products to cover a set of possible customers on a single production line.

Third, the deliberate use of ranges in specification provides freedom and focuses effort on exploring regions of the design space so that they can be narrowed rationally. This idea is loosely connected to "interval constraint propagation," but Toyota is not restricted to using intervals to define sets.[19]

Fourth, Toyota extensively uses what we call "lessons learned" books, not simply to record lessons but to define the space of manufacturable designs to product engineers. Toyota uses them in an unusually effective way (as we describe later).

Fifth, Toyota's rigorous effort to avoid changes that expand, rather than contract, the space of possible designs, ensures that communications and decisions remain valid through the project's life. This notion has been used by automated "partial planners."[20]

While none of these concepts is new, a set-based philosophy in concurrent engineering extends well beyond the sum of the parts. We argue that the philosophy explains Toyota's unusual practices. By communicating a whole set of possibilities simultaneously and avoiding changes that move outside the set, Toyota can reduce the frequency of communication, eliminate the need for dedication and collocation, and reduce supplier communications for a simpler process structure. The large number of prototypes and alternatives is not a consequence of rapid changes in the design concept, but an effort to explore broad regions of the design space simultaneously. The "ambiguity" in Toyota's specifications to suppliers is actually great precision: Toyota provides only the degree of constraint in which it is confident, avoiding future changes. The philosophy may represent a new model that explains Toyota's success.

Next we give examples of set-based concurrent engineering in practice to provide insight and evidence for our conclusion that Toyota follows a different design strategy, and suggest ways in which the philosophy may be implemented. We outline the major milestones in the Toyota vehicle development process, describe a case study on body and die design at Toyota, and give several case studies of Toyota's suppliers. We also provide contrasts with point-based design in other companies.

Vehicle Development at Toyota

The major milestones in Toyota's generic development process are depicted in Figure 4. The timing of an actual Toyota program will vary somewhat depending on how much of the vehicle is new and changing and even on the particular chief engineer running the program. Also, some Toyota sources described two prototype stages, while others described three, which may also vary by project. The important point is that the fundamental structure of projects is quite similar and structured around key milestones rather than detailed breakdowns of activities. At each milestone, a physical product integrates the work of all parts of the company, compelling teamwork. Team members begin preparation for milestones whenever they need to. The vehicle development cycle begins with an evaluation of the current model, customer reactions to the current product, and predicted market conditions. In the concept, the *shusa* describes the target customer, vehicle characteristics, important competitive features, performance targets, qualitative descriptions (e.g., "fantastic styling"), etc. Approximately thirty-two months before mass production, the most promising styling sketches are selected to be made into 1/5 scale models; a subset is chosen for full-scale modeling. Finally, about twenty-six to twenty-seven months before production, the final theme is approved. This is generally when the auto industry starts to report development cycle times.

While the stylists are exploring various styling alternatives, other functional groups such as interior body design and body engineering are working on what Toyota calls design structure plans (in Japanese, *kozokeikaku,* or K4 for short). The K4 is a document that each functional department prepares to work out the main features of their designs. The document contains many sketches and drawings with dimensions. For example, a cross-section of an A-pillar (the column between the windshield and front doors) would be sketched with dimensions, a cavity for a wire harness, the location and dimensions for the rubber door seal, etc. The engineers also include larger planning issues, such as where the wire harness ought to run and about how much space it requires, and even the stamping and assembly order of interior panels.

Once the engineers for each functional group's K4 have conferred and reached agreement with the appropriate groups, the K4 is widely circulated for as many as eighty signatures. This process allows for a great deal of intensive communication and negotiation across functional groups and with outside suppliers when the design structures are still fluid and there are no major investments in time-consuming CAD databases.

K4 finalization occurs approximately two months after concept approval. At this point, a substantial portion of the design has been decided (though many important issues remain open), and engineers begin detailed drawings based on the K4 (the K4 itself is not updated). Since the K4 begins before management has selected a final body styling theme, in some cases, two K4s are developed simultaneously (e.g., one for sashless doors and one for full-panel doors). The K4 can then help inform the final selection of a full-scale clay model.

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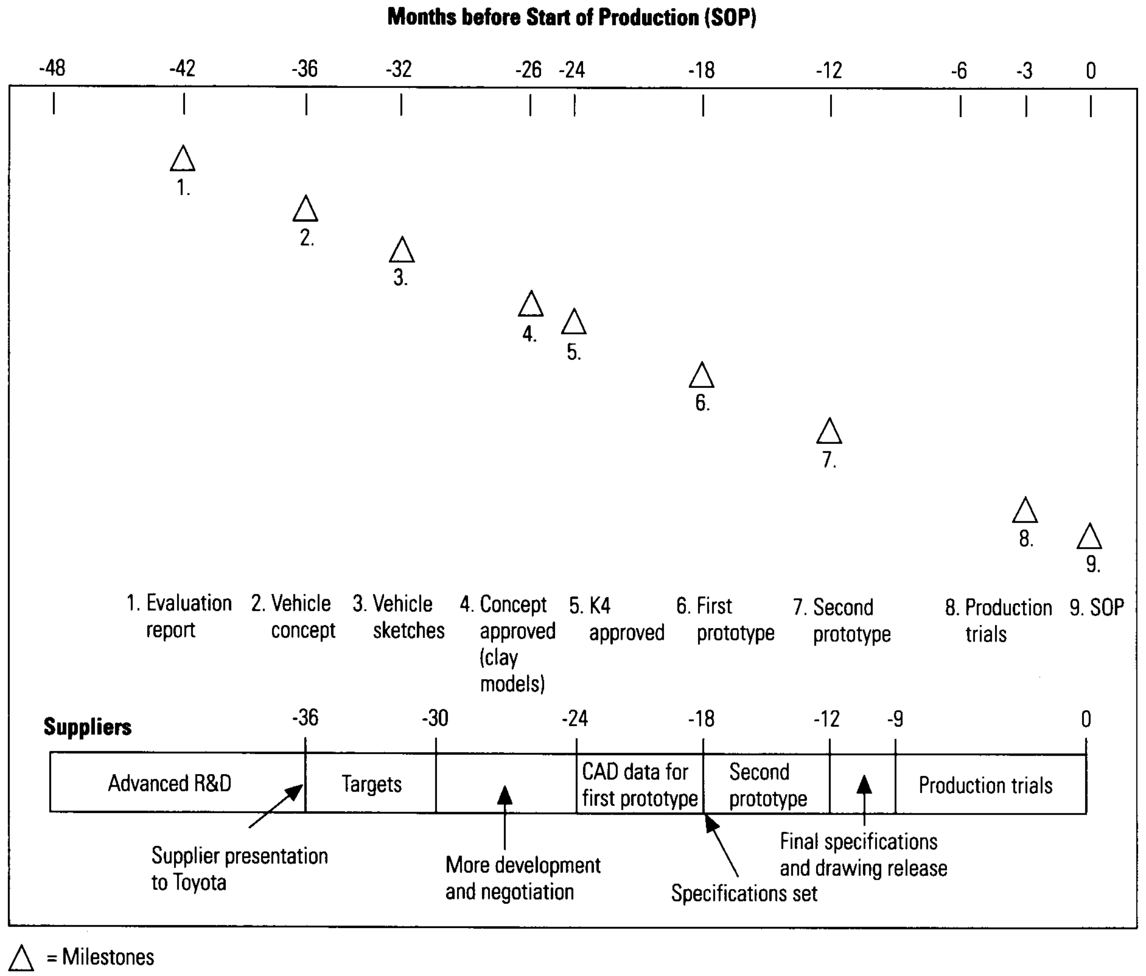
Throughout these stages, Toyota communicates with its suppliers. During concept development, it gives suppliers feedback on parts in the current model, and the suppliers provide information on their new technical developments to Toyota. During this time, Toyota also initiates a negotiation process with suppliers for target setting and eventual specification. We discuss the negotiation process in greater detail later.

Following theme approval, Toyota functional groups issue K4s, and work begins on the first vehicle prototype. They hone targets, exchange CAD data internally and with suppliers, and order component prototypes from suppliers. Partial prototypes may be made to test specific features. Based on test results from the first pro-

Figure 4 Toyota's Generic Development Process and the Supplier's Role



totype, the second prototype is developed and built, approximately one year before the start of production. Next Toyota conducts two stages of production trial runs and then ramps up into full production.

Throughout our description of Toyota and its suppliers, we have emphasized the set-based nature of product development. But we do not mean to imply that Toyota is widely exploring all possible design options for all parts of the vehicle simultaneously. Toyota has a reputation as a conservative company for good reason. Getting a high-quality vehicle on the market very quickly is a top priority, and Toyota realizes that excessive experimentation will make this impossible. So it intentionally uses a "rapid inch-up" strategy to keep many of the subsystems and components essentially the same, while selectively innovating.[21] Engineers who want to make major changes must provide hard evidence through data that the new design is a major improvement over the existing design. Many of the design decisions we have described as set-based are, in fact, incremental fine-tuning for the sake of fit and finish, marginal performance improvements, or weight/cost reductions.

With this framework in mind, we now discuss several detailed case studies.

Styling, Body Engineering, and Die Development

After many sketches and drawings of possible designs, Toyota makes from five to twenty 1/5 scale clay models, all different.[22] (Of course, twenty is the extreme. Even five models exceeds the average three models that many U.S. and other Japanese automakers produce.) The team studies the drawings and models based on customer input and feasibility and begins the full-scale clay model process in two phases, intermediate and final.

At the intermediate stage, two rough models are created that differ as much as two to four centimeters on critical dimensions (e.g., a model from the California studio and one from Japan). Interviewees had different opinions on the role of the two models: some stated that the final design was usually close to one of the models, implying that they represent two discrete options. Others implied that the models represent a continuous range of different design alternatives, with the final solution falling somewhere between. In contrast, another Japanese OEM uses a rough and a final clay model in sequence; some U.S. companies use only a single full-size model.

When the models are complete, there is a meeting of approximately 100 participants from different Toyota areas such as body design, stamping, product planning, die design, and so on. Each functional area audits the intermediate clay designs, using its own lessons-learned books (called "engineering check sheets" at Toyota) that describe the current company capability, including feasibility ranges. For example, a Toyota die designer showed us a lessons-learned book for a fender design. The book, ten to twelve pages long, contained approximately sixty to seventy different ranges of specifications that would ensure the fender design's manufacturability (e.g., intervals of acceptable curvature radii for angles). Developed during the past fifteen years, these books of every body part give a very detailed definition of what can be done from each functional area's viewpoint.

Each deviation from the lessons-learned books is noted on an audit sheet, the primary communication between affected groups. These sheets give the nature of the problem, a countermeasure suggested to alleviate the problem, the suggesting department, and a sign-off for the affected functional areas. Often the suggestions resolve the problem to all parties' satisfaction. However, if they are unable to find a common ground, a functional group (say, die design) may develop a new technology or process advance to make the design feasible, and then revise the lessons-learned book.

This strategy defines the set of manufacturable designs. From a theoretical standpoint, for any given design problem, there is a true, yet unknown, "design space" that includes all possible values for all the parameters. Within the design space, if the problem indeed has a solution, there are combinations of parameters that represent feasible designs. And, within the set of feasible designs, there are combinations that are more or less optimal than others. The lessons-learned books map (in figures and parameter ranges) the known areas of the feasible design space. The audit compares the designer's ideas to the known set of possibilities from each function's viewpoint. In some cases, the intersection of these sets constrains the ultimate design. In other cases, technological developments expand the known feasible region.

The set-based approach enables the audit to be efficiently performed in two ways. First, stylists, body engineers, and production engineers each maintain their own version of the lessons-learned books as guidelines for manufacturability in design and audit. Second, if the two clay models establish bounds on what is acceptable to the stylists, other functional groups can quickly identify the intersection between this set and the set acceptable to them; there is no need for a prolonged series of suggested changes, which must in turn be examined by the other functional groups.

The general manager of body engineering remarked that delaying the decision on critical dimensions until the last possible moment is necessary to ensure that customers' expectations are fully understood, that they will be satisfied by the body design, and that the design is also manufacturable. He described preventing engineers from making premature design decisions as a critical part of his job. In contrast, managers at two U.S. companies told us that the key to achieving manufacturable designs quickly was to freeze the hardpoints early (in at least one case, *before* development of the full-size model), thereby giving manufacturing more time to respond, but risking a suboptimal solution.

Engineering and Building Dies

At Toyota, refinements continue on both intermediate clay models until a final model is selected approximately twenty-seven months before the start of production. Toyota engineers have just over two years to go from concept approval to full volume production, which hinges on early development of the manufacturing process, that is, die design and production. Die design begins long before the critical dimensions are fixed. In some cases, castings are ordered and die production begins while "design tolerances" (implied or actual ranges for the final design parameters as distinct from manufacturing tolerances that are set much later) are still maintained on the critical dimensions.[23] Process engineers are able to perform preliminary work on the dies because they are confident that the ultimate body design will not depart from the design tolerances given them. Thus process engineers can do all the work they want, as long as they maintain enough flexibility to accommodate all possibilities within the tolerances.

As the tolerances narrow, engineers can continue with further die development. Most often, they do this by fixing some parts and designing their dies, while other parts retain a tolerance. Production engineers prefer complete information and, if possible, wait until the last possible minute for the fixed dimensions before building the die. In contrast, U.S. die makers tell us that they routinely lowball bids on dies, knowing that they will be told to make changes after the die has been constructed that they can charge a premium for.

Finally, Toyota body engineers routinely omit most manufacturing tolerances on body-part dimensions. The overall length of the body must be held within a standard two centimeters of the dimension on the drawing. This huge tolerance (Toyota holds critical stampings to .5 millimeters) arises because the customer does not care precisely how long the car is, as long as all the parts fit. The body designers thus define the acceptable set of cars, allowing the manufacturing engineers to make the parts fit, within the wide tolerance bands. The manufacturing engineers typically build dies on the nominal dimensions and make a series of parts, which they assemble into a "screw body" or "functional build" to check for fit.[24] They then adjust the most easily changed dies to make the parts fit. In contrast, U.S. companies normally force the die maker to make parts match the tolerances on the blueprints. This process is much more expensive and does not produce as good a fit.

The set-based nature of this approach facilitates simultaneous product and process development. All auto companies use sketches, drawings, and 1/5 scale clay models to explore design feasibility, but Toyota develops more alternatives with models to explore the space more deeply. Throughout each stage, Toyota continues to compile information on the environment, the market, and various constraints and trade-offs between alternatives. Even through the full-scale model stage, flexibility, often in the form of explicit parameter ranges, is maintained on the body hardpoints until the final model stage. These ranges represent sets of design alternatives.

> Even through the full-scale model stage, flexibility, often in the form of explicit parameter ranges, is maintained on the body hardpoints until the final model stage.

The lessons-learned books are another way of representing feasible design alternatives from a manufacturing perspective. There are few conflicts between design and manufacturing engineers, because they need find only some intersection of the preferred regions for both. Process engineers can start early on die planning because such ranges on the hardpoints place bounds on anticipated changes downstream in the design process; they design for the set of possible solutions.

A functional build approach also suggests a set-based approach. Rather than treat each sheet-metal part as the final design that the die should precisely reflect, this approach assumes that the blueprints are guidelines. What counts is how the actual parts fit together. Some variance in parts is expected, but as long as the resulting body is acceptable, the stamped parts become the final design. The CAD database is then updated to reflect the stamped parts, rather than the dies being adjusted to match the original CAD database.

U.S. Auto Body Development

A development team leader at a U.S. automotive manufacturer provides a starkly contrasting example of more traditional, point-based body development. The manufacturer's design and development process consists of concept development, prototype, production tooling, and production phases.[25]

In the early concept development phase, a small group of project designers work on a number of different sketches representing body design alternatives, evaluate the alternatives, and choose the best one. They lay out the vehicle architecture based on this design. This process is typically completed four to five months into the concept development phase, approximately forty-three months before production. Manufacturing is brought into the development loop only after the base design is defined, although manufacturing was recently collocated with the product design team to bring its considerations into the design.

Next, manufacturing and other functional areas evaluate the design and propose changes to a plastic model. The manufacturing engineers' critique is based on their experience and intuition. The changes, wherever feasible, are incorporated into the design, and a second scaled plastic model is developed for further evaluation. After three to four models, this iterative process results in a final body architecture thirty-six months before production. Hardpoints are fixed as early as possible and changed only if manufacturing discovers that the design is impossible to make, or crash testing determines that it does not meet government standards. Subsystems and components are optimized using a similar strategy: establish one basic design and "iterate like mad" to improve it.

This is classic point-based design. A single design solution is selected early in the development cycle and then modified from different functional perspectives (such as body manufacturing) to achieve an acceptable result. There is little opportunity to address the unique combination of customer demands and manufacturing problems posed by the design. If the stylists or body engineers define a difficult design, it must be changed according to manufacturing's critique, which may drive further changes.

The Supplier-OEM Interface

A talented, high-quality, well-coordinated supplier network is crucial to successful vehicle development. Japanese auto companies are famous for their *keiretsu,* efficient networks of companies that maintain very long-term relationships, and Toyota is no exception.[26] We found that not only are its best suppliers set-based in communicating with Toyota, but at least one has carried set-based development beyond the levels we saw at Toyota itself.

Several Toyota managers explained that they vary suppliers' design responsibility, depending on capability. We developed a three-level hierarchy from our observations, based on the influence of the suppliers in decision making, particularly on the component specifications. The relationship level appears to be determined by the supplier's engineering capability, past performance record, complexity of the part, the degree to which the part interfaces with others, the stability of the technology, and so on.

The first-level relationship is a partnership. This type of supplier greatly influences not only the detailed design of the parts it makes but also the concept. Such suppliers do extensive development well before Toyota decides on its own vehicle concepts, often presenting Toyota with a wide range of alternatives early in the process. Toyota may then choose one or more of the options.

The second-level, mature suppliers wait for Toyota to define its needs for a specific vehicle concept before beginning development. However, they work with Toyota in a process that goes far beyond conventional negotiation to determine part specifications (including cost).

At the third level, which we call "parental," all the major decisions are made by Toyota, with little influence from the supplier. The supplier may design to specification or simply manufacture a Toyota design.

The companies we studied and the levels of their relationship are summarized in Table 2. In the next section, we examine partnership, mature, and parental relationship suppliers in detail.

Table 2 Hierarchy of Toyota Design Relationships with Suppliers

Level of Relationship	Number of Companies	Engineers of:
Partnership	1	Radiators Alternators
Mature	4	Power steering Fan clutches and fan blades Automatic transmission Catalytic converters Exhaust systems
Parental	1	Gear shift levers

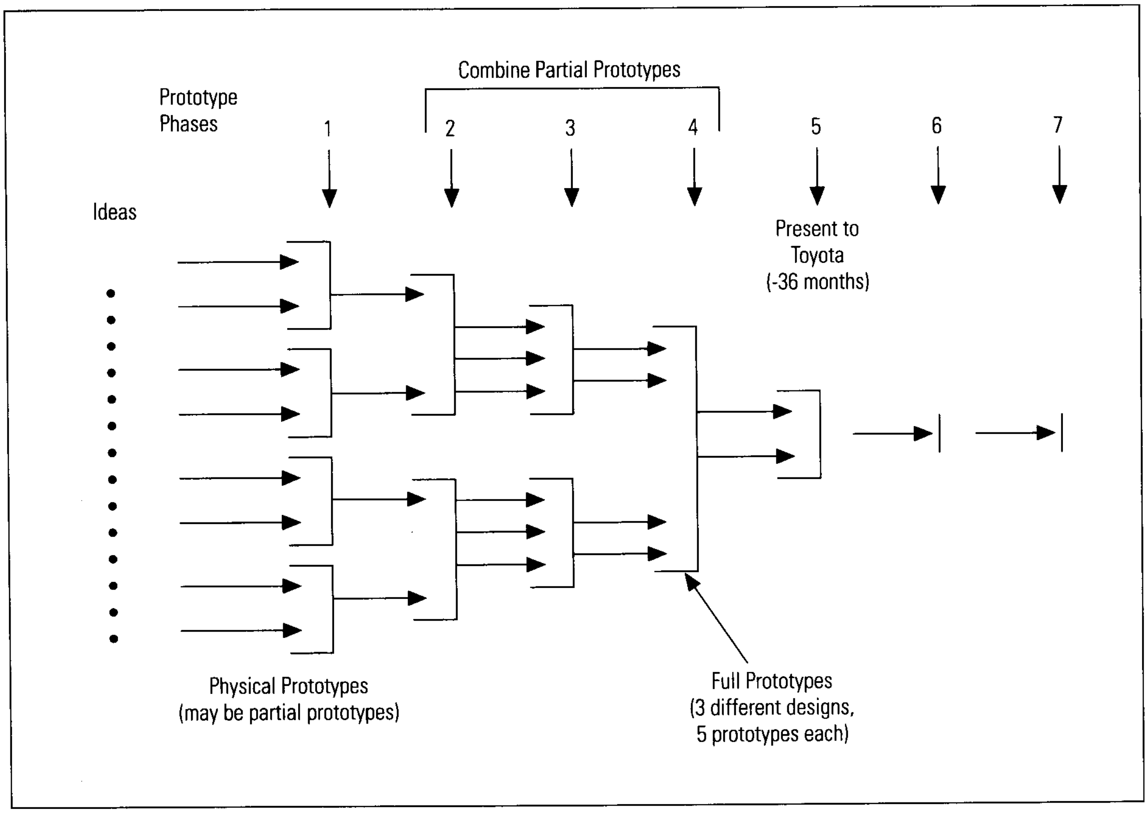
Advanced R&D

All the suppliers we interviewed performed advanced product research and development, which ranged from developing radically new product families, to incorporating new technologies, to modifying an existing product. Nippondenso, a world leader in radiators and alternators, was the only case we classified as a partnership. Its alternator group described an eight-year internal development cycle. At the beginning, the suppliers' engineers establish targets for parts characteristics (size, weight, performance, etc.), generate many ideas, and by the end of the first year, create prototypes. These full or partial prototypes are used to evaluate the engineers' design ideas. Next there is further development by combining partial prototypes, modifying and improving designs, and adding new ones. Nippondenso experiments extensively but also relies heavily on charts, graphs, test data, past experience, and professional judgment to decide which designs to continue. Four years into development, about three different designs remain, with five prototypes each. By the end of the fifth year (three years from start of full production), the engineers are fairly confident about one design. Figure 5 illustrates the converging process.

Nippondenso's radiator group members described a similar process of creating prototypes early to evaluate designs, then gradually narrowing the possibilities over time, creating and testing prototypes at each step. The elimination process continues until a single, superior design concept remains. This process produced a radiator that, when it was introduced into the market, was ten years ahead of competitors' models in weight and performance.

This partnership-level supplier deliberately develops a set of designs for a set of automobiles, not a single design for a single model. That is, while developing targets for its new designs, it explicitly defines the set of automobiles in which the new product can be used. It gathers information on all prospective Toyota car models (and to a lesser degree at other customers) and the anticipated require-

Figure 5 Nippondenso's R&D Process



ments. It then designs a product family around a single concept, producible on the same line. Nippondenso offers its customers more than 700 different alternators, providing customers with a wide variety of products while standardizing the production process; it calls this approach "standardized variety."[27] For example, the development group will develop a modularized plan to standardize the various components of the alternator to meet all requirements. It might develop three different body types, nine different wire specifications, four different regulators, etc., all mutually compatible.

Far from pursuing the incremental improvement widely attributed to Japanese companies, Nippondenso deliberately seeks radical breakthroughs. In setting targets for the radiator design, for example, the Nippondenso team graphed performance-to-weight ratios of radiators built during the past several decades. They then projected this data and set targets to beat the competition in the next decade, which required a 50 percent reduction in radiator weight. As Whitney points out, Nippondenso treats product and process development expertise as a strategic business weapon; technological breakthroughs can have equal, if not more important, impacts on profits and long-term viability of the firm as compared to financial and marketing strategies.

Nippondenso's advanced R&D efforts result in a catalog of components that covers most of its customers' needs. The customer picks from the catalog, and Nippondenso designs interface components if necessary and manufactures the full range of needed parts on a single production line. For several reasons, Toyota usually chooses from the set of possible solutions rather than asking for a custom design: First, Nippondenso anticipates its customers' future needs. Second, its technology is often years ahead of its competitors. Third, the standardized components offer significant cost savings. Fourth, variety is so large and carefully designed that tailored products offer few advantages.

The standardized variety concept is fundamentally set-based. The company treats its customers as a set and develops aggregate requirements that will satisfy all likely requirements. It then designs a set of products to meet such requirements and offers discrete product combinations to customers. Standardization cuts costs, while variety meets the customers' needs.

The mature-level suppliers have a similar, though shorter, process, but they usually design a single product for a single automobile. The development cycle for these companies' products is about five years. The advanced R&D process, about two to three years, is driven by Toyota's long-range goals and improvements, the suppliers' own long-range goals, and feedback from Toyota on existing parts.

The companies begin by generating many ideas for improvement, then choose four to five full prototypes, and test and evaluate along all critical dimensions. Designers use matrices, graphs and charts, and professional judgment in evaluation, then make decisions about whether to continue with certain designs or to combine parts into a superior design. They make more prototypes. By three years from the start of full production, the designers have narrowed the possibilities to one, two, or three designs.

This strategy — using sets of prototypes that are narrowed over time for a new design — clearly has set-based underpinnings: these companies not only consider but build and test a wide variety of designs. The engineers recognize that, even though they are familiar with this product, they cannot know everything about it. There are subtle relationships between parts of the system that can be explored only through tests of real prototypes. In set-based terms, experimentation is a way of exploring the design space. Decisions are made only after such experimentation. Although the mature suppliers' engineering level seemed quite high, they apparently do not believe that computational models are sufficient to capture the subtleties.

> Before Toyota starts making decisions about the vehicle, at least about detailed specifications, it is gathering suppliers' information and data.

Unlike the partnership and mature suppliers, the parental-level supplier (of gearshift levers) does not use a set-based approach. This supplier's R&D effort begins with the existing design. Internal evaluations and Toyota feedback expose weaknesses in the current design, and the supplier generates ideas to improve the design. The engineers interviewed did not describe a set-narrowing process but a process of starting with one design, moving to the next, then the next, in a point-to-point serial fashion. This process is consistent with the "rapid inch-up" approach that Clark and Fujimoto observed in their study of Japanese auto companies.[28] Factors that would make this product conducive to a point-based approach include technological stability, limited interface with other components, and relatively simple geometry. Toyota specifies the gearshift lever height, and the supplier makes all other dimensions the same as the current model. Some of Toyota's specifications, like the mounting bolt position and size, have not changed in twelve years.

Presentations to Toyota

All the Toyota suppliers we interviewed present their latest relevant developments to Toyota about thirty-six months before the start of new model production. They may show one, two, or three concepts, with suggestions about which is most promising. The presentations include working prototypes and a great deal of test data, with comparisons to existing and/or alternative designs. Suppliers commented that the Toyota engineers, all knowledgeable about their particular product, often discuss how the designs can be improved.

In every case, the presentations precede any specific information or statements from Toyota about the new model, but the suppliers are able to proceed because of their long relationship with Toyota and knowledge of current trends. For example, during the energy crisis in the 1970s, fuel efficiency was a concern, so suppliers knew weight reduction would be a high priority. With the decline of the Japanese economy in the 1990s, weight reduction has been displaced by cost reduction as a priority.

In contrast, the U.S. manufacturer develops a list of specifications in-house (perhaps in consultation with suppliers), then sends the specifications to prospective suppliers and asks for proposals. Then the suppliers make proposals, and the parent company chooses its supplier, often the lowest bidder. In the United States, specifications are set before the supplier presentations. At Toyota, final specifications are decided approximately two years after supplier presentations.

This difference is subtle but significant because the Toyota practice appears to be more efficient from the perspective of the set-based model. Before Toyota starts making decisions about the vehicle, or at least about detailed specifications, it is gathering suppliers' information and data. It is finding out the latest developments, the newest innovations and features, the degree of improvement over existing products, approximate cost figures, and more. It also understands the possibilities — sets whose endpoints are the current product at one end and the latest developments at the other. In essence, Toyota is updating and refining its map of the design space before making decisions. The U.S. manufacturer, on the other hand, does not expend the same energy to understand its constraints. Thus it appears the Toyota process compensates for the costs of its system by facilitating a well-informed decision-making process.[29]

Target Setting and Negotiations

Supplier presentations play a critical role in Toyota's ability to set reasonable targets for its suppliers. Toyota uses a prolonged target-setting process to further explore the design space and improve the vehicle. For the first target, the supplier is always trying to maximize or minimize certain product aspects. For example, a radiator supplier tries to minimize size and weight while maximizing cooling. The customer, Toyota, will never be dissatisfied with reduced weight, provided the cooling effect is sufficient. The second type of target is a bull's-eye in which deviations in more than one direction may be undesirable. An example is an exhaust system in which noise reduction characteristics vary for different models; a luxury sedan may need a very quiet ride, while a sports coupe may require more noise and throaty timbre.

The mature-level suppliers told us that Toyota gives them targets shortly after the thirty-sixth month presentation (about thirty-two months). Usually, maximum/minimum targets already meet the performance limitations in the previous design, so Toyota asks for a modest improvement. Approximate maximum/minimum targets are generally expressed in terms of improvements over an existing product or the prototype in the presentation: Toyota is likely to want *gurai* 4 percent reduction in cost, or *gurai* 5 percent improvement in power output. (*Gurai* roughly translates as "about"; supplier engineers told us that its exact meaning depends on the atmosphere of the meeting. If the meeting is tense, *gurai* means Toyota really needs the target to be met, i.e., the bounds around the target are tight. If the meeting is more relaxed, so are the target boundaries.) During the months that follow, the suppliers diligently strive to meet the targets through design improvements. If the targets are met or exceeded, this eventually becomes the specification; if not, in negotiations, the supplier demonstrates with test data that the target is impossible, and the two sides compromise on a target.

Bull's-eye targets offer an opportunity to improve the system performance by carefully selecting the target. Toyota gives basic requirements that are expressly vague — an anticipated change of 20 percent to 30 percent — and asks suppliers to explore the areas around the requirements by building and testing prototypes or by computer simulation. After evaluating trade-offs and comparing with interfacing components, Toyota refines the requirements more specifically. The implication is that a small change is still likely; sometimes the targets are explicitly expressed in terms of intervals.

A general manager at Toyota described the process of using *gurai* targets and intervals to focus suppliers on exploring all possibilities around a given target. Even the targets of the maximum/minimum variety are at implicit intervals — the specification will be between current levels and target levels — which represent sets of possible designs. As the targets are refined, the sets are narrowed until a design solution is attained. The general manager commented that this process "allows the *shusa* to understand trade-offs and set targets to produce the best possible design."

Another Toyota general manager of engineering explained that they typically set targets on each component higher than really necessary by as much as 20 percent. They realize that, with production variations, this ensures a comfort zone so parts out of tolerance will actually be quality parts. They also want the supplier to stretch; if the target is too easy, the supplier will relax and not try to continuously push possible boundaries. If the supplier cannot achieve the very challenging goal, there is still room for negotiation.

> Toyota uses a prolonged target-setting process to further explore the design space and improve the vehicle.

For parental relationship suppliers and less critical aspects, like the mounting holes for the gearshift lever, Toyota often does not change the design from model to model. If a supplier can suggest changes that will reduce cost or weight, the dimensions will be modified in a point-based process.

- **Target Pricing.** Along with target specifications for a component's space and performance, the customer gives suppliers a target price. This important difference between U.S. and Japanese companies has been discussed at length elsewhere.[30] In short, the automaker decides what price the market will bear for the total vehicle and works back, roughly allocating costs to major subsystems and components. It then gives that cost to the supplier as a target at the beginning of the design process. The supplier has a great incentive to design the part so it can meet that price and still make a profit.

There seems to be less flexibility in the target prices than in other component specifications, although suppliers show Toyota graphs of performance-weight-cost trade-offs and, in some cases, try to sell Toyota on the higher price to achieve better performance or lower weight. In the traditional U.S. system, suppliers design parts to specifications and negotiate price later, sometimes competing with suppliers that were not involved in product development.[31] In the Japanese system, there is much greater opportunity to explicitly consider trade-offs between cost, performance, and weight in the early design stage, before commitments are made. As in other aspects of design, Toyota seems to be more flexible and waits longer to set a firm price than other Japanese automakers. Thus, to a degree, Toyota is using a more set-based approach to target pricing.

Vehicle Prototypes

Suppliers typically receive CAD data for their prototypes twenty-four to twenty months before the start of production, along with specifications (targets) for other aspects of the parts and orders for the first prototype. Usually Toyota orders one prototype design for each component, but some suppliers reported that, half the time, it orders more than one part ("Give us power steering design A and power steering design B, and we'll see which works best"). Again, Toyota delays its decision until it is convinced of the best option.

After the results of the first prototype, Toyota issues revised specs for all components. According to the suppliers, specifications are not likely to change much after this. Next Toyota orders parts for the second vehicle prototype, which is completed twelve months before start of production, and the last modifications are made. Only after the second vehicle prototype has been built and tested are final specifications issued. Toyota and suppliers then negotiate price, which has been discussed but not settled.

> Toyota has the highest degree of concurrency in its engineering process of any company we visited, yet it neither collocates nor dedicates its development teams.

Production Trials and Startup

The official design release occurs approximately nine months before full production, at the start of the first production trials. The supplier has agreed on all the information in the design release. Two stages of trial runs occur in the final year before ramp-up to full production. Generally, only minor changes are made to component specs during this time, so suppliers can concentrate on improving production and value engineering to drive down costs.

Advantages of Toyota's Approach

We have argued that the set-based paradigm explains the contrast of Toyota's apparently inefficient steps with a highly efficient overall process. We have explored practices that, at first glance, seem wasteful but that yield high efficiency and performance. Here are some potential advantages we see in the set-based approach to design:

1. *Set-based concurrent engineering enables reliable, efficient communication.* In the conventional, point-to-point search, *every change that part of an organization makes may invalidate all previous decisions.* Since designs are highly interconnected in obscure ways, it is generally impossible to tell whether a particular change alters decisions already made. Nor will changes necessarily converge. Conversely, in the set-based approach, all communication describes the whole set of possible solutions. As the set narrows, the earlier communications remain valid but are supplemented with further, more precise information.

Set-based communication seems to have a number of consequences for Toyota. Most obviously, it eliminates work on solutions that must later be changed. Toyota's body designers waste little time on detailed designs that cannot be manufactured because the manufacturing personnel can precisely define the set of bodies that are manufacturable, using the lessons-learned books, and structural decisions have been made concurrently through the K4 process before detailed design begins.

Second, it reduces the number and length of meetings. In the conventional approach, every change requires a new, lengthy meeting. Toyota's engineers and suppliers can work relatively independently, because each meeting communicates information about an entire set of designs. Toyota has the highest degree of concurrency in its engineering process of any company we visited, yet it neither collocates nor dedicates its development teams. And Toyota suppliers report the best communications with the parent company of any surveyed but less time spent communicating than others.[32] These suppliers are less likely to report shared design activity between their design engineers and Toyota's; that is, they are more likely to work independently.

Third, set-based communication's reliability eliminates a major incentive to delay work. With a point-based approach, members of the team may delay getting started because their information is subject to change. Toyota's suppliers know the amount of design tolerance in their specifications at any point in the process and therefore know to what extent they can commit themselves. This may be a major reason why Toyota can allow parts of a team to get started when they want, rather than forcing them to follow a rigid schedule.

Finally, set-based communication can increase trust in working relationships. If a supplier knows, early on, about a planned solution before there is enough data, it knows the plan will probably change. But if the supplier has a lot of information and is informed in advance about the set of possible changes, trust will build in the partnership.

2. *Set-based concurrent engineering allows for greater parallelism in the process, with more effective, early use of subteams.* In the conventional model, planning the manufacturing process before the product is defined makes little sense. But in the set-based paradigm, the manufacturing processes that might apply to the set of possible products can be planned, early on. Thus innovation in the manufacturing process may drive innovation in the product design, as described in Whitney's discussion of the Nippondenso *jikigata* designs.[33] The manufacturing team can focus on a new part of the product design space and assume that the product will be designed as much to fit the new manufacturing system as the manufacturing system to fit the new product.

3. *Set-based concurrent engineering bases the most critical, early decisions on data.* The earliest decisions about designs have the largest impact on the ultimate quality and cost, but these decisions are made with the least data.[34] Powerful engineering analysis tools, such as finite element analysis, are difficult to apply until the design has been detailed. Consequently, major changes made later in the design process are expensive, and many organizations try to reduce them by instructing engineers to "do it right the first time." This is equivalent to telling them to try harder and be more careful, not particularly useful advice. Toyota explores the space of possible designs before making important decisions.

4. *The set-based process promotes institutional learning.* Designers are notoriously resistant to documenting their work, partly because they sense documentation is generally useless. Describing the process of changes leading to a design's final configuration is equivalent to providing directions to your current location. Since the next design uses the current design as a starting point, the directions will be useful only if the team backtracks.

Conversely, the Toyota process helps team members form mental maps of the design space, since a larger fraction of the space is systematically explored. For example, the lessons-learned books at Toyota are updated to reflect Toyota engineers' experiences with the manufacturability of various body designs. From the start, body designers know which angles can be manufactured and which are difficult to make, without even talking to manufacturing engineers. Hence, Toyota team members start with a far better picture and then refine it through further exploration.

5. *Set-based concurrent engineering allows for a search of globally optimal designs.* Nippondenso, far from following a "rapid inch-up" process, routinely pursues radical design breakthroughs. Rapid inch-up can find only "local optima" — the best possible design based on the current fundamental concept. Set-based concurrent engineering, conversely, explores many concepts in depth and can potentially find better solutions based on radically new concepts. It also allows a company to pursue radical improvements with a fair degree of safety: if one idea does not work out, another is likely to.

Further Research

Each advantage of set-based CE described earlier represents a hypothesis — that there is a causal relationship between Toyota's success and its use of set-based CE. An important task for further research is therefore to demonstrate this causal link more carefully. Unfortunately, such causes are difficult to show in complex organizations. In a separate survey of U.S. and Japanese auto parts suppliers, we found that the set-based approach is associated with more concurrent engineering experience, use of quality function deployment, and interdependent parts development.[35]

We also found that set-based design is more prevalent among Japanese than U.S. companies. Evidence of a relationship between set-based methods and concurrent engineering is encouraging, assuming that companies learn from experience what works well. But we have yet to show a relationship between set-based concurrent engineering and hard performance outcomes.

We also do not know enough about how set-based concurrent engineering is or should be performed. Toyota's approach is not well defined or documented; researchers may have to construct much of the methodology of set-based concurrent engineering and test it in other companies, before formulating a complete theory.

Implications for Management

Toyota has introduced a new model into development that allows effective concurrent engineering while minimizing costs. Recent changes in U.S. companies, such as Chrysler's improvements through the platform team approach, may hit a plateau below Toyota's as Toyota learns to exploit this philosophy more fully. At the same time, because Toyota has not fully formalized the paradigm, companies that do may gain a competitive edge over Toyota.

But there are significant barriers. Set-based CE could become an excuse for poor decision making and imprecision, wasting both money and time. Since there is no proven formal methodology, learning the process will be slow and error-prone. Toyota has had decades to teach everyone what *gurai* means; a U.S. company would have to develop a more formal approach.

Further, what is right for Toyota may not be right for every company. Toyota has a long-standing relationship with highly competent suppliers that put in extra effort for the set-based approach, function on long-term relationships rather than contracts, and understand Toyota's informal communications about design sets. U.S. suppliers may not be willing to work on an interval specification to be narrowed later.

Perhaps most important, Toyota has unusual engineering expertise. Toyota engineers serve a minimum of fifteen years before reaching management positions, have extensive hands-on experience, undergo frequent training, and are vigorously encouraged to think about their jobs and technologies by managers who are themselves technical experts. Set-based concurrent engineering seems likely to require more skill and judgment than the simpler, point-to-point approach; its adoption by companies with lower average skill levels might be difficult.

We cannot therefore recommend crash programs to develop set-based concurrent engineering. Rather, companies that want to gain this new competitive edge should experiment in developing concrete techniques, while carefully pondering the philosophical implications and management of suppliers and personnel. We suspect that many U.S. companies' efforts to adopt concurrent engineering through cross-functional teams and structured development processes that focus on designing the right product in the concept stage are important steps. We believe these CE approaches will inevitably move companies in the direction of set-based concurrent engineering. ◆

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8. We questioned fifteen different suppliers about eighteen different product lines (two of the Toyota suppliers and one of the non-Toyota suppliers in Japan about two different product lines). We also interviewed Toyota's general managers of styling and body engineering, an ex-general manager of body engineering, senior managers in stamping and welding development, and about fifteen line engineers. Respondents at other OEMs were generally less senior, and the total number of interviews at other OEMs combined is only slightly larger than the number at Toyota. For each kind of development, we have data for Toyota or a Toyota supplier and at least one other company, so we can clearly contrast Toyota with other companies along the critical axes, but we cannot compare other companies with each other.

We conducted the interviews in Japan primarily in English, although a Japanese translator with substantial engineering expertise was usually present. Since the Japanese companies sent only English-speaking managers and engineers to the interviews, translation was rarely necessary.

9. M. Cusumano, *The Japanese Automobile Industry: Technology and Management at Nissan and Toyota* (Cambridge, Massachusetts: Harvard University Press, 1991).

10. *Toyota Annual Report* (Tokyo, Japan: Toyota Head Office, 1994).
11. Smith (1992).
12. The LH line is Chrysler's "cab forward" midsized and large cars, including the Dodge Intrepid, the Chrysler Concorde, New Yorker, and Eagle Vision. They were the first vehicles designed using Chrysler's platform team organization and, at the time, held a record for fast development time in U.S. automotive practice.

Comparing companies on vehicle development time is a complex matter. For example, are the starting points comparable? In our interviews, Toyota engineers claimed that Chrysler engineers on Neon and LH had worked twice as long on body development before getting management approval (the official time the stopwatch starts) and had complete math data in their CAD system, while Toyota got management approval based on the clay models, and the CAD data still needed a great deal of correction to catch up with the clay models.

13. Smith (1992).
14. Kamath and Liker found this to be generally true of major Japanese automakers in dealing with suppliers involved in design. Toyota, Nissan, and Mazda all have simple, one-page development processes and focus on end dates for key events that then pull the supplier's activity toward concrete milestones. See:
Kamath and Liker (1994).
15. J.K. Liker, R. Kamath, S.N. Wasti, M. Nagamachi, "Supplier Involvement in Automotive Product Design: Are There Really Large U.S./Japan Differences?" *Research Policy*, forthcoming.
16. Shigley's textbook is admittedly an old, very traditional view of engineering design. More contemporary views such as Wheelwright and Clark and Pugh depict far more concurrent processes closer to a set-based view. But students of mechanical engineering were less apt to be exposed to these books than Shigley, which decades of practicing engineers were raised on. See:
Wheelwright and Clark (1992); and
S. Pugh, *Total Design* (Reading: Massachusetts: Addison-Wesley, 1991).
17. Pugh (1991);
J.E. Shigley and C.R. Mischke, *Mechanical Engineering Design*, fifth edition (New York: McGraw-Hill, 1989).
18. G. Taguchi and D. Clausing, "Robust Quality," *Harvard Business Review*, January-February 1990, pp. 65-75.
19. G. Sussman and G. Steele, "Constraints — A Language for Expressing Almost Hierarchical Descriptions," *Artificial Intelligence* 14 (1980): 1-39.
20. D. Chapman, "Planning for Conjunctive Goals" (Cambridge, Massachusetts: Massachusetts Institute of Technology, Artificial Intelligence Laboratory, Technical Report 707, 1985).
21. Clark and Fujimoto (1991).
22. The body design process described here is composite information collected during interviews with the general manager of body engineering at Toyota, the general manager of styling design, a group of body and design engineers (eight in total), and a former general manager of body engineering who is a currently a vice president in Toyota's U.S. operation. Our example focuses on the design and development process in the clay model stage.
23. There was some disagreement on this point among different groups of engineers we visited. Some claimed they do not intend to delay fixing hardpoints so that castings are ordered before they are fixed, and would only do so if the program was behind schedule.
24. Hammett et al. (1995).
25. Although the information in this example reflects only the specific experiences of the interviewees in one large division, the descriptions are consistent with reports from other areas and other companies.
26. Smitka (1991).
27. D.E. Whitney, "Nippondenso Co. Ltd.: A Case Study of Strategic Product," in Liker et al. (1995).
28. Clark and Fujimoto (1991).
29. This has significant implications for non-Japanese auto parts suppliers which want to break into the Japanese market, especially with regard to Toyota. They need to aggressively pursue presentation time at Toyota to introduce Toyota engineers to its products, and also provide large amounts of data on their product.
30. Nishiguchi (1993); and
J.H. Dyer and W.G. Ouchi, "Japanese-Style Partnerships: Giving Companies the Competitive Edge," *Sloan Management Review*, Fall 1993, pp. 51-63.
31. This is rapidly changing in the United States at Ford and Chrysler, with movement toward the Japanese practice of target pricing. General Motors still uses a more traditional competitive bidding system. See:
Liker et al. (forthcoming).
32. Liker et al. do not show separate data for Toyota in this publication. The results reported in this paper are based on a separate unpublished analysis done for Toyota comparing their suppliers to the average for other Japanese companies and U.S. companies.
33. Whitney (1995).
34. Clark and Fujimoto (1991).
35. See J.K. Liker, D.K. Sobek, A.C. Ward, and J.J. Cristiano, "Involving Suppliers in Product Development in the U.S. and Japan: Evidence for Set-Based Concurrent Engineering" (IEEE Transactions on Engineering Management, forthcoming).

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