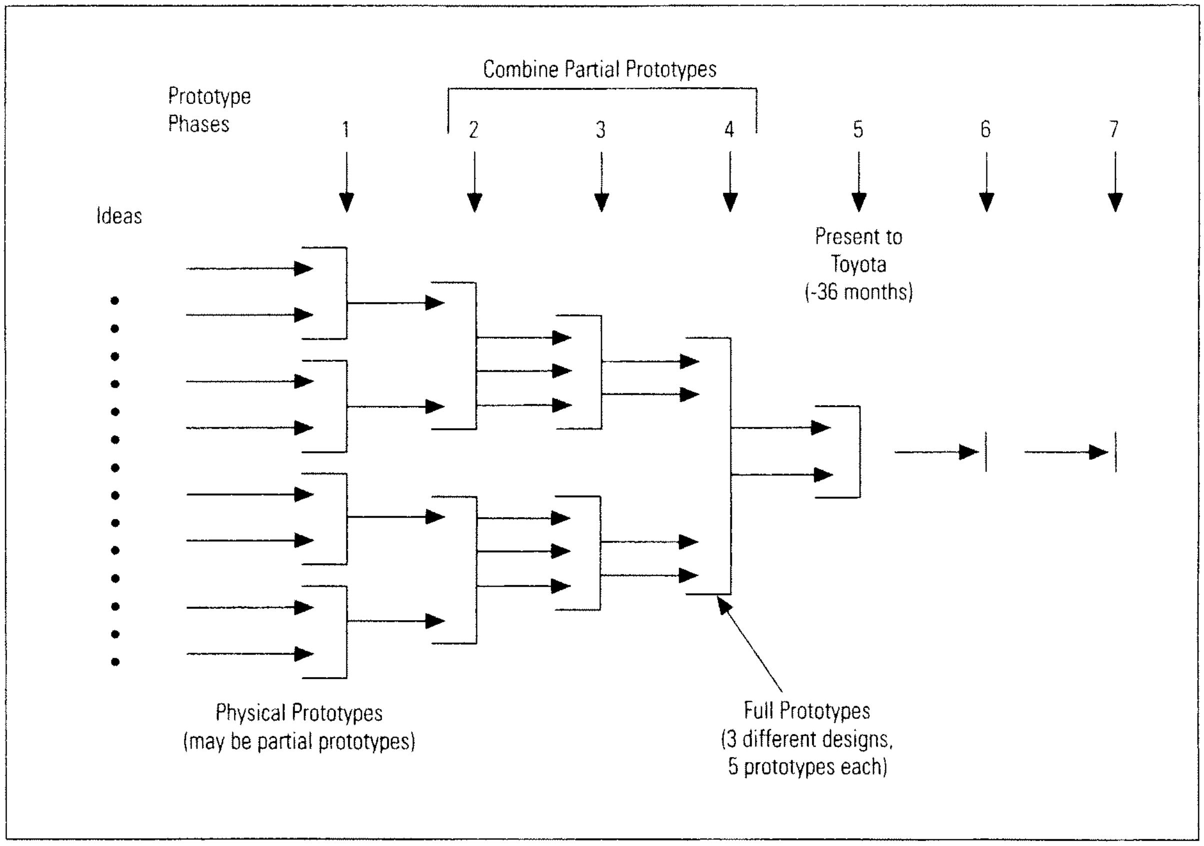
Figure 5 Nippondenso's R&D Process



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.

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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