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NIPPONDENSO CO. LTD.: A CASE STUDY OF STRATEGIC PRODUCT DESIGN

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Abstract

Nippondenso Co. Ltd. (NDCL) is Japan's foremost manufacturer of automotive components. It faces the challenge of manufacturing mass-production-volume products in unpredictable model mix in order to meet the high variety Just In Time (JIT) production requirements of its customers, notably Toyota. Over the past 25 years it has increased its ability to meet this challenge and indeed has made the conquest of variety a prime corporate goal. Although flexible manufacturing of this type is usually attacked as a problem involving factory floor operations, NDCL has defined and solved it primarily as a problem of product design. For the most part, production flexibility is accomplished by manipulating the assembly process, which in most cases is highly automated. Close coordination of top management objectives, product design, and production technology are required in order to carry out this approach. As a result, it can be said that NDCL has taken Concurrent Engineering well beyond the goal of improving fabrication or assembly. Instead, NDCL has learned how to use design to achieve the essentially strategic goal of meeting the demands of its dominant customer.

In pursuit of this approach, NDCL has categorized the problems of assembly automation into distinct classes, identified applicable solutions for each class, and successively attacked and solved increasingly difficult problems. This paper describes this approach, gives examples of its evolution, and indicates how NDCL has managed production technology, notably robots, as part of the overall attack. NDCL's approaches to Concurrent Engineering

(CE) and new product risk management are also described. The paper is based on seven personal visits to NDCL during the period 1974 to 1991, including extensive interviews with NDCL engineers and managers, plant tours, plus papers published by NDCL and interviews with their authors.

Background

Nippondenso Co. Ltd. (NDCL) is one of the world's great manufacturing companies. It makes automotive components for Toyota and other Japanese and foreign car companies. Its main challenge is to manufacture high volume products in unpredictable variety in a Just-in-Time (JIT) environment, and do so efficiently. NDCL sells to other manufacturers and, to stay in business, must manufacture economically to meet their product performance specifications, cost targets, and ordering patterns. This is a *strategic business* challenge, which NDCL has met by raising product design and manufacturing engineering to the company strategic level.

The core of NDCL's response has been to design its products so that it can automate its production to a high degree while at the same time maintaining flexibility, an extremely difficult combination. Since automation of the *fabrication* of individual parts is required in the car industry due to high production rates and is achievable in many proven ways, the innovation here has focused on automating the *assembly* of such items.

This challenge is normally considered a problem of designing and operating factory floor facilities. NDCL's approach is totally different. The solution has been found in the product design office. NDCL has learned how to design products so that it is relatively easy to manufacture them in high production volumes, in a JIT environment, with little or no changeover time. Furthermore, the product and its parts are designed "intelligently" so that flexibility is achieved during assembly. Often the assembly technology itself is very ordinary and not robotic or high tech. A technique I call "assembly-driven manufacturing" has emerged.

It is essential to recognize the holistic nature of NDCL's response. Many companies see the need to implement product design using computer-aided design (CAD), or to improve the ability to assemble products efficiently using design for assembly (DFA). Fewer see the need to be able to manufacture their products in unique ways, much less to be able to build in-house the specialized equipment necessary to do so. Fewer yet are those that see the need to write their own CAD software to tie together their own carefully groomed product-process design methodology. And fewest of all are those that see the need to do all of these together. [Whitney 1992 indicates that the majority of them are Japanese.] NDCL is one of the most advanced in understanding that all must be done together in a systematic way. This combination of skills gives NDCL the ability to use design of products and processes in a strategic way, that is, so it can meet the needs of its customers in ways that other companies cannot.

Venkatesan [Venkatesan] discusses core competencies in terms of make/buy decisions, indicating that firms should buy when they find others who can do portions of their business better than they can in-house. NDCL has identified the following list of core competencies of a responsive, innovative, high volume-high variety manufacturer:

- knowing how to use engineering design to create products that can easily be made in many models, and, as a result, that can often be made efficiently in high variety by less sophisticated manufacturing equipment than is commonly believed necessary to achieve this capability

- being conscious of the need to learn over many years how to accomplish this kind of design, and of the need to develop a step by step procedure for learning and growing the skill

- being willing to take responsibility for simultaneously growing the ability to make key manufacturing equipment and design software in-house and to integrate those skilled in their development with those skilled in product design, including supporting advanced production engineering and CAD development at the corporate level

Researchers currently lack adequate theories of the "value of knowledge" as well as the value of the synergy of many "islands of knowledge" into a system. Many of NDCL's make/buy choices in technology (as well as those of other large Japanese firms) often seem uneconomical or indicative of a not invented here attitude. An engineer at another Japanese firm put it bluntly: "You learn by trying, not by buying." This statement indicates that learning is the valued commodity, rather than any of the individual skills, and that this commodity is considered almost beyond conventional economic measure in such companies.

This paper describes NDCL's evolution in some detail, as seen by this author during seven visits over the period 1974-91, plus interviews with NDCL engineers and managers, plant tours, reading of NDCL publications, and interviews with their authors. It is a fascinating story, revealing construction of a multi-decade strategy and a deliberate sequential plan to identify feasible targets and achieve them one at a time before moving on to more difficult ones.

The approach was driven by NDCL's main customer, Toyota, which developed JIT in the late 1940s and extended it to its suppliers in the early 50s. As Japanese car makers broadened their product offerings in the 1980s, and as NDCL began selling to more customers, its problems with high variety model mix production grew, making automated flexible production even harder. NDCL's systematic approach and its experience with simpler problems in simpler circumstances helped it with the harder problems.

An important feature of the approach has been avoidance of complex assembly technology such as "intelligent dexterous" robots. Instead, NDCL has put as much of the "intelligence" as possible into the product itself by focusing the *design process* on supporting high volume mixed model JIT automated assembly. Large numbers of robots are indeed used in NDCL, some quite innovatively, but they and other complex technology are not the core of the approach. This fact should be of interest to managers of technology as well as to academic researchers interested in Concurrent Engineering, production automation, and product design.

The difficulty of achieving high volume model mix JIT automated production can be put in the context of a generic and long-standing conflict in manufacturing: the *flexibility-efficiency tradeoff*. Here we define efficiency loosely to mean low unit cost, high percent of utilization, or any other congenial metric that benefits from elimination of waste. Flexibility is also loosely defined (see below for more precise definitions that NDCL has evolved) as the ability to alter important operating characteristics of the equipment or features of the item it is making. It is commonly assumed that flexibility and efficiency are basically counteracting characteristics in manufacturing, inasmuch as efficiency has in the past been obtained by using rigid, simple, fast equipment coupled tightly to parts transfer equipment. In this way, neither time nor motion is wasted, but making the equipment do something else, either short-term or long-term, is difficult or impossible. Rigid equipment avoids "wasters" that normally accompany flexibility, such as changing tools, dies, or fixtures, making adjustments to accommodate different product models, making measurements and decisions, and so on. Typical flexible equipment such as robots, in addition to requiring some of these "wasters," also tends to be slower and more expensive than simpler, more rigid machines, further lowering its efficiency by most measures.

While the flexibility-efficiency tradeoff appears alive and well in most factories, it can be beaten in two basic ways: by designing equipment so that "wasters" are small,[1] and by designing products so that "wasters" are not needed. This paper shows how NDCL has used the second method: embedding flexibility in the product during the design process and, with notable exceptions, using substantially traditional factory equipment.

It is also worth noting that NDCL is shown here as focusing on one aspect of flexibility, namely the ability to respond to a mostly known set of possible operating conditions. Other authors and companies have sought in "flexibility" an antidote to the consequences of making a wrong decision, such as failing to guess the future course of the market. This may be a vain hope. Some of NDCL's methods indeed provide some cushion against unpredictable events, but most are planned actions against fairly well anticipated ensembles of challenges. Indeed, some of the actions cited below involve deliberately investing design effort to eliminate unpredictable events so that no "flexibility" to meet them is needed at all.

Another way to view what NDCL has done is to recognize that it achieves its flexibility goals by designing fairly ordinary parts and then employing unusual methods to assemble them. That is, model mix and JIT can be addressed much more easily and economically during assembly than during fabrication. In fact, only one of the items described below requires

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[1] The classic example is [Shingo].

novel fabrication techniques. (In some cases, however, more than usual attention to tolerances may be required.) The ability to manufacture flexibly and efficiently is starting to be more widely recognized as a strategic competitive strength. Because assembly has particularly strong power to address these goals, it is getting more attention earlier in the product design process than it did in the past. [Whitney 1988]

Relevant Literature

The fact that manufacturing can be a competitive weapon when wielded strategically has been known for a long time. A typical analysis of the potential may be found in [Skinner]. This study and most others lack detail and usually cite the same factors, ascribing them to several companies. The literature cited below on Japanese manufacturing methods in particular is extensive and focuses on management approaches such as Concurrent Engineering, implementation of project management methods, and introduction of computer-aided design (CAD), computer-aided engineering (CAE), and Factory Automation (FA). Most of these studies are general in the sense that they assert the use of one or more practices at several "successful" companies. There is little detail concerning specific engineering or design actions taken within each company in response to particular circumstances.

The special class of literature known as case studies typically concentrates on one company and circumstance, and is found exclusively in the management literature. With notable exceptions, the topics covered are strictly management-oriented.

The engineering design literature, on the other hand, tends to focus on technical issues exclusively and rarely notes the relation between the way a product is designed and such management environments as marketing strategy or the dominant customers' ordering patterns. An interesting exception is [Mather], where the idea of "design for logistics" is presented. An example is arranging the design and production sequence of a complex product so that customer-unique or long lead items can identified early in its build sequence but are not needed until late. Similarly, the product, its subassembly boundaries, and its assembly sequence might be designed so that customer-unique parts are attached last, or on the outside, causing the bulk of the process to be the same (thus less error-prone) regardless of unique features.

Many authors deal with the general product deployment strategies of Japanese manufacturing companies. [Abegglen and Stalk] observe that up to the time of publication (1985) most successful companies limited the variety of their product lines, saving money and reducing complexity. The authors also note the emergence of wider ranges of offerings in the mid 1980s; presumably cost and complexity should have risen. However, the authors do not describe the methods employed to achieve more product variety or the way the associated costs and complexities are avoided.

Other authors discuss design process management and improvement in general. The project management methods of Toyota are described in [Meyer] and [Clark and Fujimoto]. These methods comprise overlapping tasks during design, involvement of suppliers in the design and engineering processes, incremental rather than revolutionary progress from one design to the next, and close communication between designers and engineers. The aim is to shorten the product development cycle, an important competitive weapon. In [Sasaki] one learns of the importance of analyzing the various stages of the design process in order to improve it, especially by finding computer tools that speed up one stage or another. Various authors [Hayes, Robb, Shina, Perry, and van Dierdonck] stress Concurrent Engineering in one form or another, the goal being to combine project management with strong design-manufacturing communication so that problems are discovered during design rather than on the shop floor. Other authors recommend specific technologies or approaches, including statistical quality control (SQC) [Box, et al, Modarress and Ansari], flexible manufacturing systems (FMS) [Attaran, Huang and Sakurai], forward cost predictions [Worthy], CAD/CAE [von Hassell], Just-In-Time manufacturing [Zipkin], or some combination of these [Atkinson]. [Whitney 86] discusses the fact that attention to design can reduce the complexity of assembly technology.

Business school case studies of manufacturing tend to deal with the management issues and rarely deal with design. For, example, internal debates at Sony regarding the advisability of setting up a separate Manufacturing Engineering Division are described in [Wheelwright and Gill

1]. These authors also analyze the operation of the well-regarded Motorola Bandit Pager manufacturing system, which can make individual pagers to order with the same unit cost regardless of batch size [Wheelwright and Gill 2]. The only HBS case studies which focus on the relationship between what happens on the factory floor and how the product is designed are by Jaikumar. For example, [Jaikumar] describes design strategies taken by Yamazaki Mazak Machine Tool company to ensure that its FMSs operate efficiently. The most important of these is the "defined tool method," under which product designers must assume the availability of a limited set of cutting tools and must design each part so that this set will be sufficient to make it. Similar techniques are common in the electronics industry, in which a limited set of standard, quality-certified, easy-to-insert parts must be used by designers to the exclusion of all others.

In the above literature, two gaps appear: with the exceptions noted, there is little detail on the actions taken within the recommended policy frameworks. "Form teams, involve suppliers, communicate with manufacturing, employ CAD" and so on are general prescriptions. Second, again with exceptions noted, there is little to indicate that design practices (CE, CAD) and manufacturing practices (JIT, SQC) are related or that the former can affect the ability to accomplish the latter. Instead they are treated as separate worthy practices whose aims are narrow and only technical: avoid or find problems early, make processes more efficient, reduce cost, and so on.

The aim of this paper is to show in detail how one company linked these two sets of practices effectively for the purpose of achieving a specific positive strategic corporate goal, and to indicate some of the methodologies it used. No specific study of Nippondenso has come to the author's attention, except for those published by NDCL itself, such as [Kawai]. This paper sets out the need for automating assembly for quality, cost, and speed reasons, and shows how product redesign is used for this purpose. The difficulty of doing this in the face of increasing product variety and model mix is made clear. The paper also indicates that NDCL recognizes the importance of automating not only "the flow of things" but also of "the flow of information." Both tend to be discrete in nature but the objective is to make them "flow as smoothly as if they were fluids." Thus NDCL found it important to develop in-house ability to create both product designs and factory automation systems together with the required information systems.

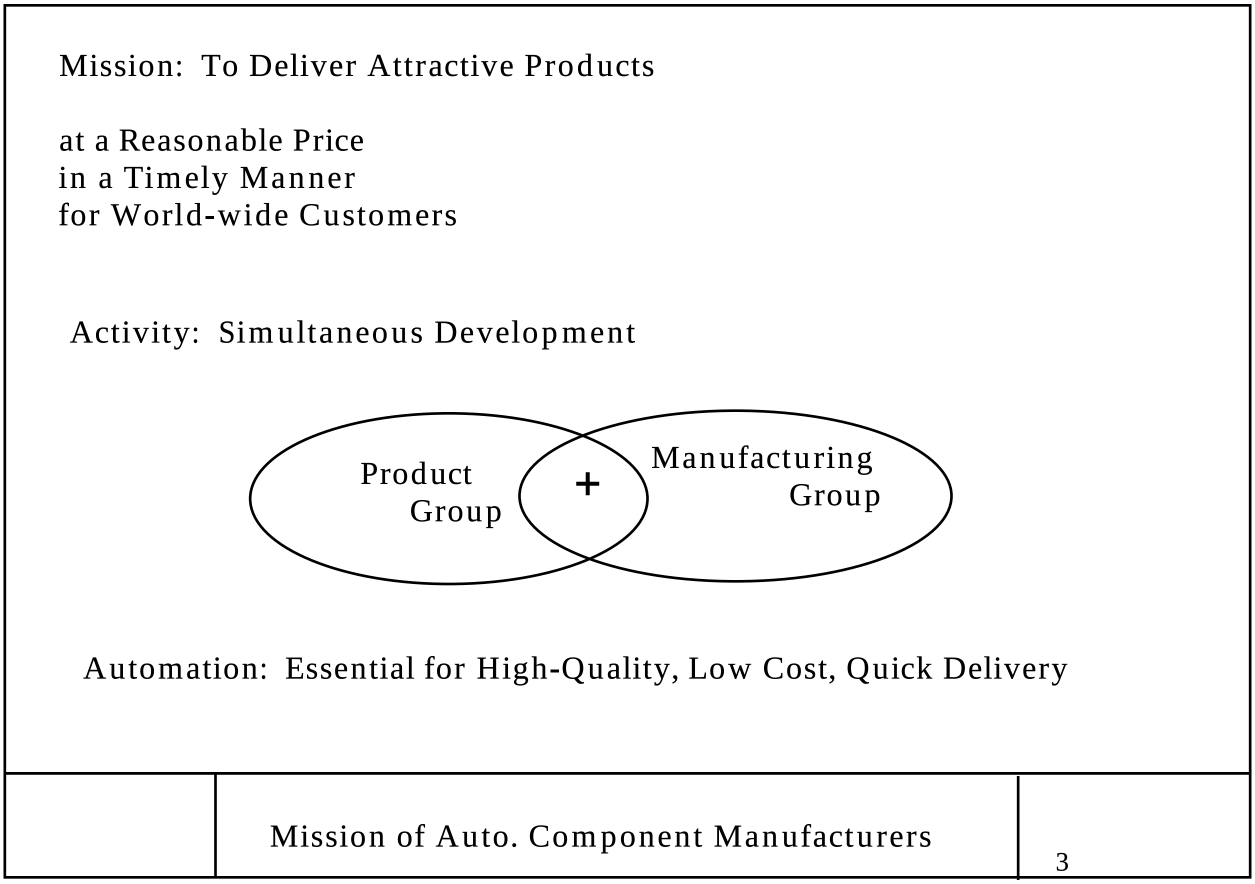
As mentioned above, NDCL is a first tier supplier to Toyota and other car makers. While Toyota has heavily influenced the way NDCL manages day to day manufacturing, which in turn influences design as described here, Toyota apparently has little other influence on the way NDCL designs or makes its products. NDCL is a good example of the system engineering supplier, as identified in Chapter XX by Liker, Kamath, and Wasti: it is given the overall requirements for a system and left alone to design it. While NDCL maintains resident engineers at Toyota, I have no personal evidence of the set-based approach to design described in Chapter XX by Ward, Christiano, Sobek and Liker. This method may indeed be used, but it affects product performance rather than those aspects of design that support JIT manufacturing which are the focus here.

History of NDCL and Evolution of Its Approach to Design and Manufacturing

NDCL began as the electrical and radiator department of Toyota in 1937. It was spun off as an independent but partly owned affiliate of Toyota in 1949. A strategic alliance with Bosch in 1953 brought NDCL access to Bosch's fuel injection patents and brought Bosch an equity stake in NDCL. Toyota and Bosch still own stakes but they are smaller than in the past. NDCL moved rapidly into international markets, opening its first US operations in 1971 and its first European operations in 1973. It now operates 20 plants in 15 foreign countries in addition to 10 plants in Japan. With 43000 employees worldwide (1991) it is almost half Toyota's size and the largest company in Toyota's supplier group. NDCL itself has 18 domestic affiliates and subsidiaries with another 18000 employees (1991). In 1989, total sales were ¥1230 billion (over $10 billion at 1992 exchange rates).

NDCL's products comprise automotive parts not considered part of the drive train, chassis, body, interior, or trim. This leaves air conditioners and heaters (over 35% of sales), electrical equipment (about 25%), entertainment (15%), plus meters, radiators, diesel components, filters, brake systems and controls, and so on. In air conditioning and most electrical equipment, it is the market leader, often dominating market share, technology and/or price. Practically speaking NDCL often takes higher technology approaches to both products and production methods than its main customer Toyota. This is an exception to the usual *Keiretsu* pattern in Japan in which the upper strata of the supply chain teach the lower strata. Here the exchange is more equal, with Toyota supplying the JIT methods and NDCL providing the product design and production technology. For example, Toyota buys nearly all its robots whereas NDCL makes nearly all of its in-house (and sells none).

Many companies make excellent use of manufacturing technology or have innovative product designs. NDCL is interesting because, as an original equipment manufacturer (OEM), its large industrial customers rely on objective criteria when evaluating its products: performance, delivery, price, reliability, and service. These characteristics (except for service) are driven totally by design, engineering, and manufacturing. Therefore, NDCL is a "pure play" on factors that are objective and easy to evaluate, unmixed with any that can be capricious, such as product esthetics, advertising, or consumer tastes. The result is that one can focus on a facet of the company which has clear cause-effect properties and learn a great deal. The fact that NDCL sees itself relying entirely on its engineering design and production capability to stay in business may be observed in Figure 1.



Mission: To Deliver Attractive Products

at a Reasonable Price
in a Timely Manner
for World-wide Customers

Activity: Simultaneous Development

Automation: Essential for High-Quality, Low Cost, Quick Delivery

Mission of Auto. Component Manufacturers

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Figure 1. "Mission of Auto. Component Manufacturers." Courtesy Nippondenso Co. Ltd. Used by permission.

NDCL's approach to product design and manufacturing has evolved toward greater and greater interaction between these design/engineering and manufacturing functions. Much of this seems to be due to the influence of one man, Mr. K. Aoki, who retired in 1984. At that time he was a nationally recognized figure and Vice President of Engineering (**all** engineering: product, process, field service, plant construction and maintenance, etc.), having moved up through the ranks of the production side of the firm. He was responsible for NDCL's technology strategy, including the decision in 1968 to begin building robots in-house. Since few companies have taken this decision (and none at all in the US), the story is important and is sketched in a later section.

The major feature of NDCL's approach to manufacturing can only be described as relentless and pervasive automation. Much of this automation is quite conventional, although in places it is very innovative, even compared to some university research efforts. Advanced and complex automation has been applied selectively, however.

In almost every case, the non-traditional or ground-breaking automation (robotics, plant communication systems, automated guided vehicles, top-down factory control) has been implemented by in-house teams using in-house technology. More conventional automation is also often designed and built in-house due to claimed cost advantages, quality limitations of outside vendors, or (at least in the high growth 80s) outright unavailability of outside vendors.[2]

Support for this activity comes from the Production Engineering Department and the Machinery and Tools Department. Both are part of the central corporate structure and report directly to the Board of Directors. (See Figure 2) These departments provide expertise, equipment designs, and equipment to the product groups and their factories. The product groups provide product engineering and production engineering. This arrangement permits corporate support for costly innovations, retains and grows a corporate resource of skills, and keeps the partnership going: Neither corporate nor the divisions can provide the products or factories by themselves. As mentioned above, these corporate functions do not sell equipment outside NDCL and as far as I know are not looked on as profit centers.[3]

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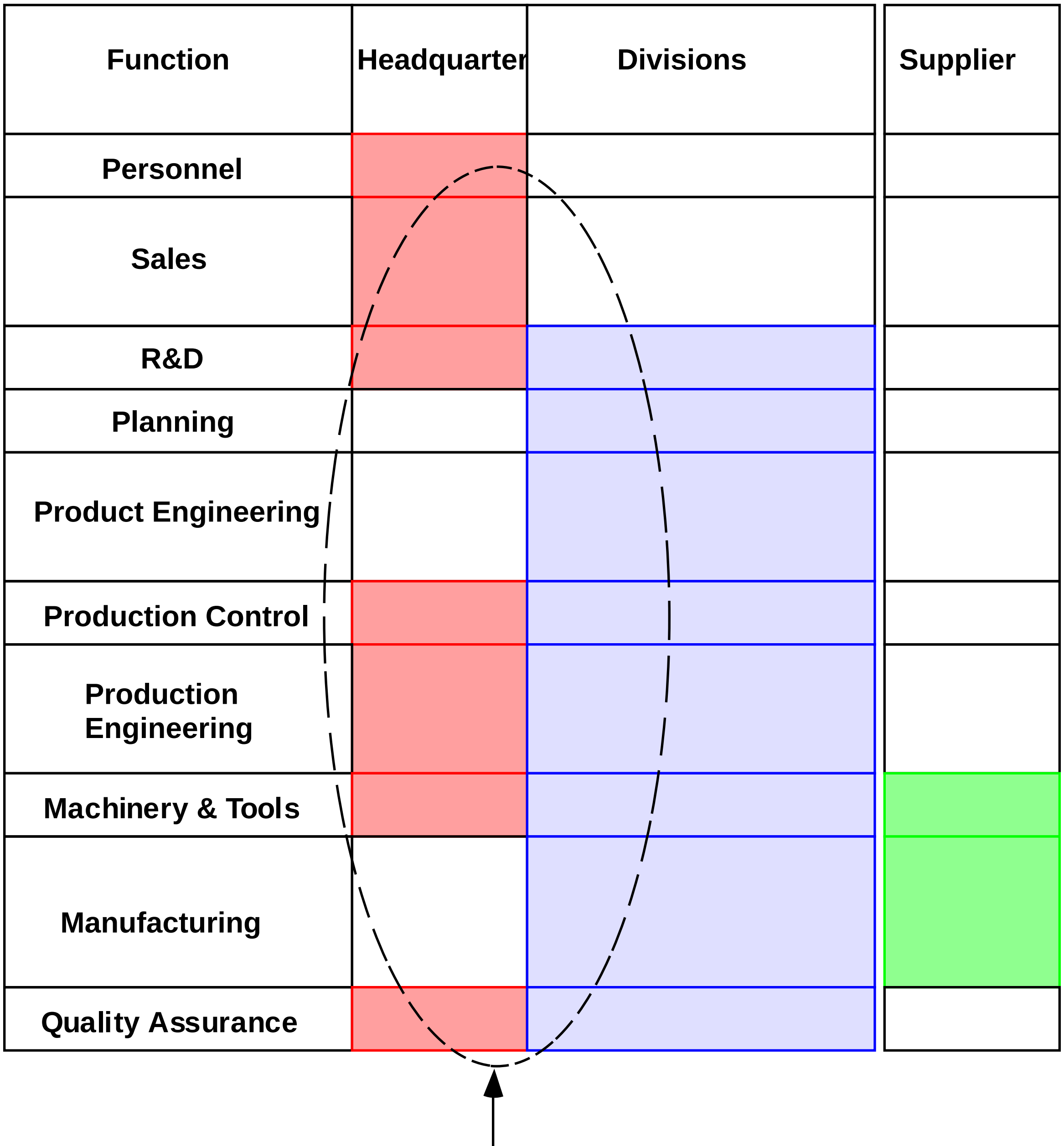
[2] Mr. Koichi Fukaya, Assistant General Manager, NDCL Production Engineering Department, private communication, August, 1990.

[3] However, I have anecdotal evidence that NDCL sometimes sells automation system design and installation services. Apparently it assisted General Electric with its breakthrough dishwasher plant in the early 1980s.

Organizational Structure in Nippondenso

Distribution of Staff Between Headquarters and Divisions in Each Function



Function	Headquarter	Divisions	Supplier
Personnel	🟥		
Sales	🟥		
R&D	🟥	🟦	
Planning		🟦	
Product Engineering		🟦	
Production Control	🟥	🟦	
Production Engineering	🟥	🟦	
Machinery & Tools	🟥	🟦	🟩
Manufacturing		🟦	🟩
Quality Assurance	🟥	🟦	

"Cooperative Activity with Priority in Big Development"

Figure 2. "Organizational Structure in Nippondenso" provided by NDCL. Used by permission. Shaded regions indicate which divisions, inside or outside the company, participate in which of the functions listed at the left. This structure illustrates the partnership between corporate and divisional

levels in NDCL that provides production knowledge, technology development, and factory systems.

The forceful role played by Toyota in this evolution must also be recognized. Imagine the phone ringing each day at NDCL and a voice from Toyota saying, "We want 4316 of meter type A, 301 of type B, 1633 of type C, and 4 of Type D, tomorrow morning. Thank you, Good-bye." The next day totally different distributions might be ordered. One cannot possibly respond to this type of customer by order-picking from a warehouse or by adjusting fabrication patterns. But this customer at one point accounted for 90% of the business and still commands over 50%. NDCL says it has adopted the slogan "Conquer Diversity." One could say the slogan is "Never Say No to Toyota." Either way, top management recognized what the required focus was, and engineering responded, as will be described below.

Strategy Alternatives

Before proceeding to specific examples of NDCL's methods, it is worth considering different ways companies might respond to the challenges posed by Toyota. Even granting that a technological response (rather than, say, aggressive pricing or creative advertising) is appropriate, most companies respond by trying to buy those technologies that are not in their line of products. NDCL, the pure play on technological response, has decided that, in order to win competitively, it must have internal control over the main hardware, software, and design technologies required to design and produce its products. Only by doing so does it feel it can gain tight product-process integration and successfully resolve difficult tradeoffs (for example to improve flexibility by means of a clever design attribute or an innovative piece of production equipment).

In its choice to develop and keep production technology in-house, NDCL has followed a strategy that is frequently found in Japan. Not only do companies like Honda and Matsushita maintain production engineering departments with several thousand employees, but they also have production technology development units that create new capabilities. In a similar fashion, a number of the largest Japanese manufacturers, among them Sony, Toyota, Nissan, and Nippondenso, have spent the last 15 years developing their own CAD software and allied engineering analysis and data management programs.[4]

Behind both the hardware and software decisions lie several basic attitudes. First, the Japanese are well-known for putting high priority on process capability. Developing new manufacturing technologies along with the ability to put them into the factory are parts of this trend. Second, advanced companies also see product design as a process analogous to manufacturing, and they recognize the need to have in-house skills to support it as well. The design process is usually carefully cultivated and idiosyncratic to each company, and it is tightly linked to, and drives, the capabilities of the supporting software. Hence many of these companies have opted to supply design software as well, rather than rely on outside vendors who often lack sufficient understanding of design and manufacturing in general or the particular company's design methods. The disadvantage is that the companies must devote considerable resources to software support.

US and European companies take different approaches. US companies are most likely to leave both manufacturing technology and design process software to outside vendors. These decisions reflect a desire to focus on "core competencies" combined with a failure to recognize process skills (design and manufacturing) as strategically important. It was not always this way. GE had a large automation development division that was disbanded in the early 80s when it was unable to perform as a profit center. GM developed an industrial robot and a 3D CAD system in the 60s before either were commercially available, but abandoned both because "its business is cars." Both Ford and GM today have design software that is an uncomfortable hybrid of older in-house packages and newer commercial programs.

In Europe, a mixed strategy has been adopted by many companies. Having long recognized manufacturing technology development as strategically important, they maintain this skill in-house. However, software is still mainly purchased from the outside, though in some companies it is augmented by significant tailored add-ons that contain proprietary data or

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[4] [Whitney 1991] discusses the strategies of several Japanese companies regarding in-house development of CAD capabilities and their relation to product development methodologies in general.

specialized programs. The main problem is to "explain to the CAD vendors what we want," a deeper problem than just maintaining software.[5]

A recent article [Venkatesan] discusses the pros and cons of relying on suppliers, indicating rightly that the "strategic" things should be kept in-house. The different decisions made in the US, Europe, and Japan indicate that Japanese firms tend to consider more things strategic than other firms do.

In sum, NDCL has decided that the ability to manufacture in high volume and high variety is an essential core competence, and that design is an essential component of this ability. It has also decided that to achieve a high level of this competence it must carry in-house capability farther than most companies have. The following sections give some specific examples, not only of what NDCL did but how it learned how to do it.

The Elements of Nippondenso's Approach

NDCL has responded to the challenge of efficient model mix JIT production automation in four distinct ways by developing

- a focus on integrated product/process development (IPPD) capability as a strategic weapon,
- new product design methodologies that capitalize on IPPD,
- in-house capability for implementing these methodologies using in-house design and manufacturing equipment, and
- an intellectual framework for understanding and developing the necessary skills and methods which includes classification of problems and solutions, design and process simplification, and the use of the assembly process as the main vehicle for flexible high variety high volume production.

These will be described briefly, followed by examples.

<u>New product design methodologies</u>

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[5] The status of design methodologies and strategies regarding computer aided design in European companies are discussed in [Whitney 1993]

The methodologies span the range from the obvious to the sophisticated. The first is to attack product diversity directly by standardization. This requires analyzing the product's requirements and functions, studying the parts lists of similar products to discover opportunities to eliminate redundancy, and negotiating with the customer to trim off low volume members of the model mixed set. In one case, a small relay, originally designed to have either three or four poles, was replaced by one with four poles. A price discount was offered as an incentive, and NDCL apparently cut off the extra wire terminals on those "4s" that its customer wanted to use as "3s."

Next in increasing level of sophistication has been to identify time and money wasters in product design or production methods, including barriers to assembly automation. NDCL has been careful to include in these studies the impact of product diversity, the main challenge. As one interesting result, NDCL's Design for Assembly (DFA) methods now include demerit points for a design that is difficult to change over from one version to another. This is quite a departure from conventional DFA, which focuses more on part count reduction and predicting the time and ease of manual assembly of individual parts outside of the context in which the product is being made.

For the reasons cited above (need to automate, desire to use assembly strategically), NDCL must solve many difficult assembly technology problems. Figure 3 contains specific examples of how NDCL has used design rather than complex production technology to solve these problems. The approach starts by classifying assembly automation problems into "dexterous/intricate" and "large variation." These two are different in NDCL's eyes, although they are often treated as the same by others. Once they are seen as different, the tendency to attack both by massive application of complex technology can be replaced by more rational approaches suited to each class.

"Dexterous/intricate" implies that the capabilities of people would normally be required to perform the assembly. Here it has been attacked mostly by redesigning the products. The large plastic air conditioner cases shown on the left vary too much from one "identical" case to the next to permit conventional robot assembly. (Sometimes the left sides contact first and the right sides miss, while at other times the left sides contact and the right sides miss.) Instead of applying robot vision sensing, for example, NDCL redesigned the shape of the interface between the upper and lower case halves so that, for a given robot trajectory, one side of the top half always contacts the lower half first regardless of how the cases' shapes vary from normal. A deterministic robot trajectory can then be used, removing the need for sensing. On the other hand, the method utilized for attaching seals between air conditioner case halves (called "sponges" in Figure 3) required development of a novel but deterministic articulated robot gripper; when models change, the robot changes grippers.

"Large variation" is normally thought of as a natural target for robots because they can change from one product to another "just by switching software." However, NDCL's time/cost study showed that part feeding and preparation is the cost driver in high variety situations. Having a robot at the workstation had little effect on the cost and little to contribute to the solution. Several attacks on this problem are now under way, in addition to the modification of DFA noted above. These include quick-change pallets loaded with different kinds of parts, plus robot grippers that can be changed quickly to permit the different kinds of parts to be gripped. This approach is similar to Sony's APOS vibratory pallet filling technique, described in [Nevins and Whitney 78].

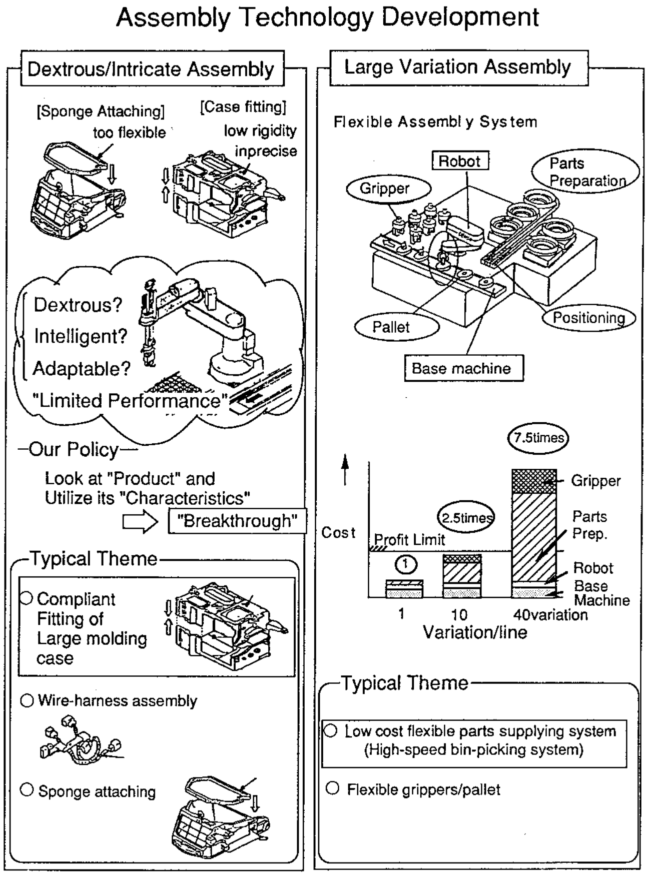


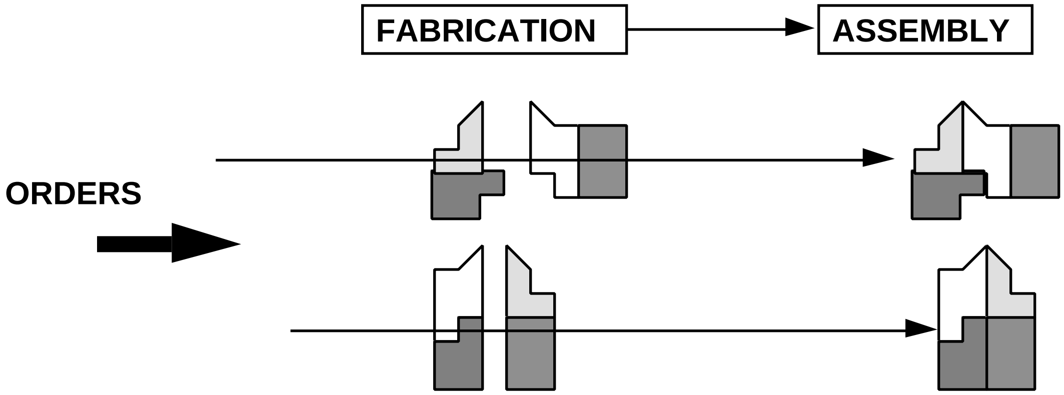
Figure 3. "Assembly Technology Development" Courtesy Nippondenso. Used by permission. This figure shows that NDCL has partitioned development of assembly automation into two classes: dexterous/intricate assembly and large variation assembly. The former involves difficult physics which may be easy to identify, while the latter mainly involves part logistics and changing conditions that may not be obvious without further analysis. NDCL notes in this figure that one can attack the dexterous/intricate problems by requiring robots that have the intelligence and dexterity of people, or by assuming that robots cannot do such tasks, or finally by redesigning the product slightly but meaningfully so that it will be easier to assemble by robot. The last approach has been taken, resulting in products that, despite their difficulties, can be handled effectively by relatively ordinary robots. NDCL attacks the large variation problems by direct economic analyses, focusing attention on the cost-drivers. These may or may not pose technological challenges, in contrast to the dexterous/intricate cases. The solutions may require only better organization or communication; or they may require new part feeding methods or cleverly designed robot grippers.

The next product design method used by NDCL to make efficient model mix production feasible is to deliberately design the product for quick changeover from one version to another. Two common barriers to changeover are the logistics of the parts themselves and the logistics of jigs and fixtures that are unique to each version. Fixtures can sometimes be the larger challenge. They are costly, so fixture investment rises with the number of versions supported. The number of fixtures also rises with the production rate; it is not uncommon for there to be 300 or more identical fixtures filling the pipeline of a high volume assembly process. Second, when a changeover is required, all the old fixtures must be swept out of the production line and new ones swept in, a procedure that can take a long time and encourage "economic lot size mentality." Third, fixtures can be a psychological barrier to process improvement since they represent a large investment. In the example discussed below, manufacture of radiators, fixtures have largely been removed from the process via redesign of the product. There is no such thing as an economic order quantity (EOQ) any more, and any quantity or mix ordered can be made at the same unit cost as any other.

The last and possibly most sophisticated approach I have labeled the combinatoric method. Product variety is created by having several versions of each part in the product. The product is designed so that physical and functional interfaces between parts are the same for all versions of each part. The result is that any combination of part versions can be assembled into a working unit. The interfaces between the parts and the assembly equipment are similarly standardized so that differences between part versions are transparent to the automated equipment. The dashboard panel meters described below are a good example.

In a larger sense, the combinatoric strategy reflects an advantage to using assembly rather than fabrication to make things different. Relying on fabrication to express model differences means producing complex parts having different features that express the differences. Complex parts are harder to make, more costly, require more inspection, fail more often in test or use, and so on. Fabrication also has a longer lead time than assembly by one to two orders of magnitude (hours to days vs. seconds to minutes). This means that changing from one model to another can take a long time. By contrast, the combinatoric method utilizes simpler parts but possibly more of them per product unit to achieve the same function. Assembling a larger quantity of simpler parts presents its own problems, mainly logistical, but it is easier to change models quickly and on an individual step basis is simpler and faster than fabrication. In most of the examples below, NDCL has employed assembly to express model differences. Figure 4 sketches these ideas, which are discussed in more detail in the example of the panel meter.

FABRICATION-DRIVEN MANUFACTURING



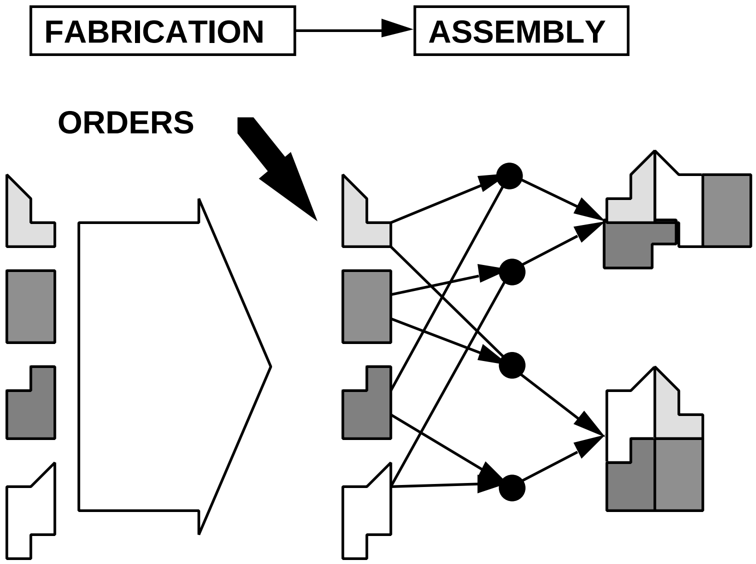
RELIES ON FABRICATION TO EXPRESS MODEL MIX AND ACHIEVE FLEXIBILITY:

IN RESPONSE TO ORDERS, COMPLEX PARTS ARE MADE AND THEN ASSEMBLED INTO FINAL ITEMS.

THIS IS A LOW BANDWIDTH METHOD BECAUSE FABRICATION TAKES SO LONG.

FIGURE 4A

ASSEMBLY-DRIVEN MANUFACTURING



RELIES ON ASSEMBLY TO EXPRESS MODEL MIX AND ACHIEVE FLEXIBILITY:

SIMPLE PARTS ARE MADE TO STATISTICAL TRENDS. IN RESPONSE TO ORDERS, ITEMS ARE ASSEMBLED.

THIS IS A HIGH BANDWIDTH METHOD BECAUSE ASSEMBLY HAPPENS SO QUICKLY.

FIGURE 4B

Figure 4. Comparison of Fabrication-driven Manufacturing and Assembly-driven Manufacturing. In fabrication-driven manufacturing, the order stream enters prior to fabrication, which makes a few complex parts to differentiate models of the product. In assembly-driven manufacturing, the order stream enters prior to assembly, which assembles a larger number of simpler parts to create different models. Parts are fabricated according to statistical trends in the order stream instead of the actual order stream. Fabrication-driven manufacturing is a low-bandwidth process compared to assembly-driven manufacturing since fabrication takes relatively longer than assembly, and changeover also takes longer. Assembly-driven manufacturing can be a good strategy if the parts are small and not too expensive. Inventory

risk is small because parts are members of more than one model and hence have several chances to be used.

In-house capability for implementing these methodologies

In-house capability has been established in three areas: the methodology for forming and operating product-process design teams and the associated risk-management methods; the engineers and shops that build and maintain automation machinery; and the system integration area where chains of machines are linked and the necessary local and wide area networks, computer control, scheduling, communication, quality monitoring, and display technologies are brought together. Both model-mix JIT production and on-line quality control are intensely information-driven as well as design-driven. Thus all three are considered strategic and tightly linked to each other. The discussion in [Kawai] makes it clear that NDCL was acutely aware of these issues over a decade ago. Of these in-house capabilities, the product-process team methodology is sketched here and discussed in more detail later in the paper.

Product-process design teams are composed of high level representatives from corporate Production Engineering, Machinery and Tools, and divisional Product Engineering departments. Teams are small at the beginning of a project and are chaired by top managers from those departments. As the project matures from the concept to the detail design stage, the teams enlarge. They follow the development and risk-management plan worked out at the concept stage. An important feature is the willingness of NDCL's top management to step in if a serious problem arises. When a quick crucial decision is needed, top management is there to make it.

Several methods have been adopted to shorten the design cycle. As illustrated in Figure 5, a parallel approach is used to overlap some of the design steps, both between the two major activities of product design and production design as well as within each. To aid the overlapping of adjacent tasks, "early sourcing" is used to feed forward to the next task advanced information on the coming information before it is finalized. Each downstream task provides "front loading" back to the ongoing previous task in the form of commentary and suggestions based on the advance information.[6] Where-ever possible, computers have been introduced to shorten each of the design tasks. Finally, having production technology and system integration skills in-house shortens many crucial communication loops, contributing to faster product design and introduction. As illustrated later in the paper where a new alternator is described, in-house production technology capability created a more tightly integrated product-process design than would likely have been possible if product and process were designed separately by different companies.

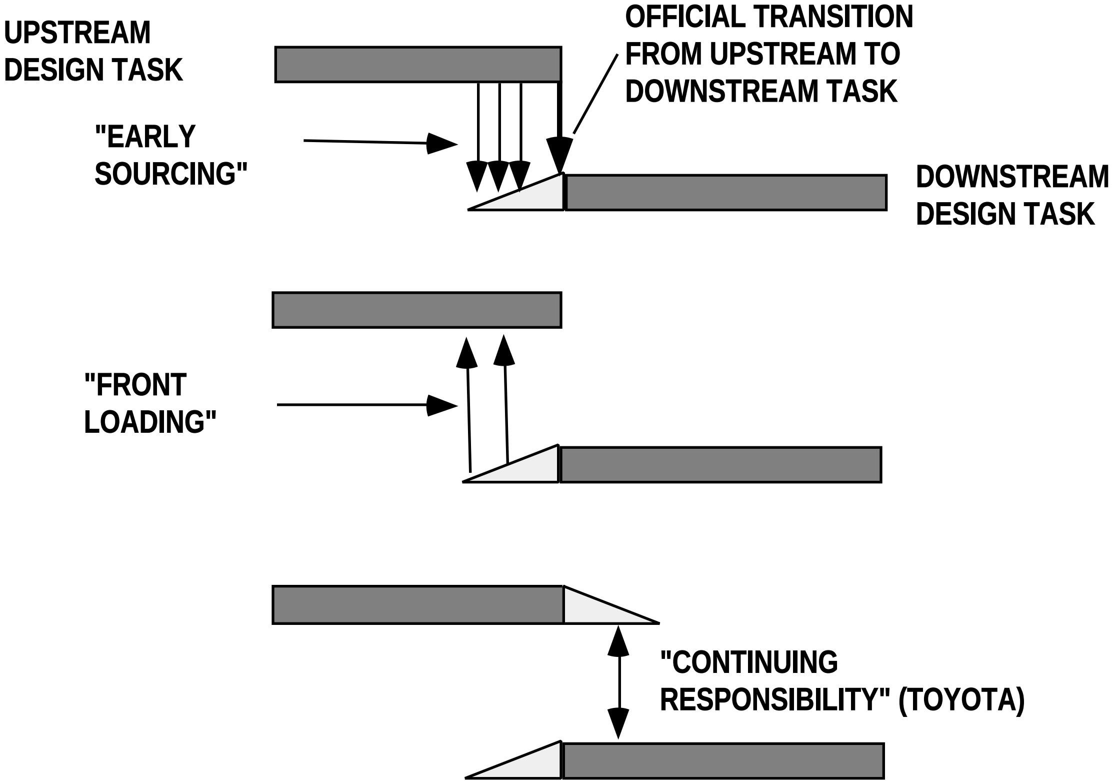


FIGURE 5

Figure 5. NDCL's Methods for Streamlining the Product Design Process, with Comparison to Toyota's. Both companies overlap successive design tasks, using strong communication between the end of an upstream task and the start of its successor. NDCL employs "early sourcing" to warn

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[6] See [Whitney 1992] for a description of Toyota's overlapping tasks method of product development.

downstream tasks of impending design information, and employs "front loading" to provide feedback to the upstream task. At Toyota, "early sourcing" is called "flying start." However, Toyota also identifies an element called "continuing responsibility," in which each upstream task keeps an eye on those downstream and fixes errors it was responsible for. This element was not described explicitly by NDCL. On the other hand, "front loading" is an integral part of "flying start" at Toyota and is not called out as a separate element.

An intellectual framework

From an academic point of view, the intellectual framework is probably the most interesting aspect of the story, in part because many companies have followed a number of the methods described above. What one sees at NDCL is repeated attempts to classify problems, classify solutions, prioritize, find the right combination of problem and solution, and attack one at a time, starting with the simplest. Classification is at least as old as Aristotle and is usually found only in academic environments. NDCL has developed useful classifications of automation, flexibility, and products. The combination of these classes and selection of items from each class drive the implementation of the strategy. The reason is that each kind of flexibility and product demands a different response, and each kind of automation represents a different level of difficulty.

We can see these points by example if we reconsider Figure 3. Barriers to economical assembly automation are here shown to fall into two classes normally lumped together simply as suitable targets for "flexible robots." But NDCL sees them as two separate problems distinguishable as two different kinds of flexibility. On the left is what might be called "within-task flexibility," arising from the apparent need to adjust the actions of the robot because the progress of a task cannot be predicted in advance due to tolerances or part differences. On the right is what might be called "between-task flexibility," arising from the need to redirect the robot to a new product model, an entirely predictable event. The former cannot be planned for; NDCL has chosen to eliminate it at the source by redesigning the product so that the unpredictable events do not occur. The latter can be planned for, and is attacked as shown in Figure 3 by economic analysis which leads NDCL to focus on designing better means of part preparation, which is not a function of the robot at all.

"Within-task" and "between-task" are two specific types of flexibility that occur at a single automated workstation. For a broader view, refer to Figure 6, where NDCL has identified three broad classes of flexibility. Within each are several subclasses representing different levels of difficulty. Volume change and product variation are day-to-day issues imposed by the customers. Design change in the past represented minor improvements but has evolved into the most difficult challenge, namely how to avoid total factory reinvestment when the next generation product arrives. Examples later in the paper show how NDCL responded to volume and product size changes and uncertainties.

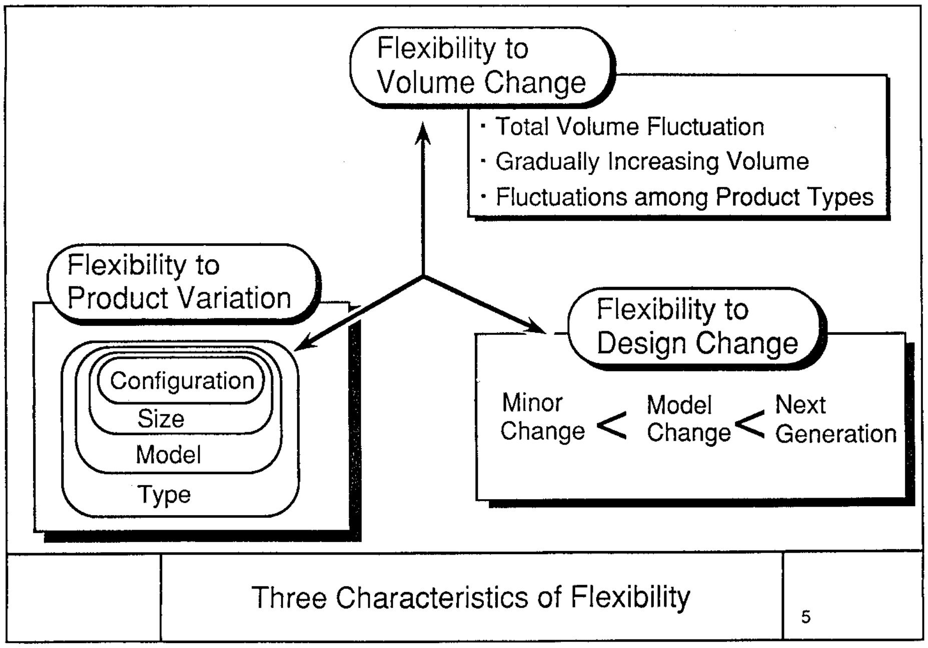

Figure 6. "Three Characteristics of Flexibility." Courtesy of Nippondenso. Used by permission. Three classes of flexibility have been identified, each concerning a different time scale, source, and class of technological challenge. Volume change is often end-user market driven, can occur over weeks to years, and can comprise overall change or redistribution of demand within a product line. Design changes are often in the hands of NDCL and can be frequent and minor or be a switch to a new generation that occurs every half decade. Product variation is usually driven by the OEM customer and comprises the kinds of variants wanted, which depend on each kind of product.

Classifications of automation systems and products may be seen in Figure 7, which gives a 40 year snapshot of NDCL's evolution in automation ambitions and achievements. The various terms (spot, line, FMS-0, FMS-I, etc.) are NDCL's names for successively more complex levels of automation. Spot refers to a single automated workstation; line refers to a series of such stations integrated into a line; FMS-0 is an integrated set of stations in a single machine complete with limited ability to make a variety of models; FMS-I is such an integrated system with much wider ability to accomplish model mix assembly using the combinatoric method; FMS-II can accomplish the combinatoric method even when different models have different parts complements; FMS-III can do so even when the different models are of somewhat different size. These differences are associated with product examples in a similar timeline presentation in Figure 8.

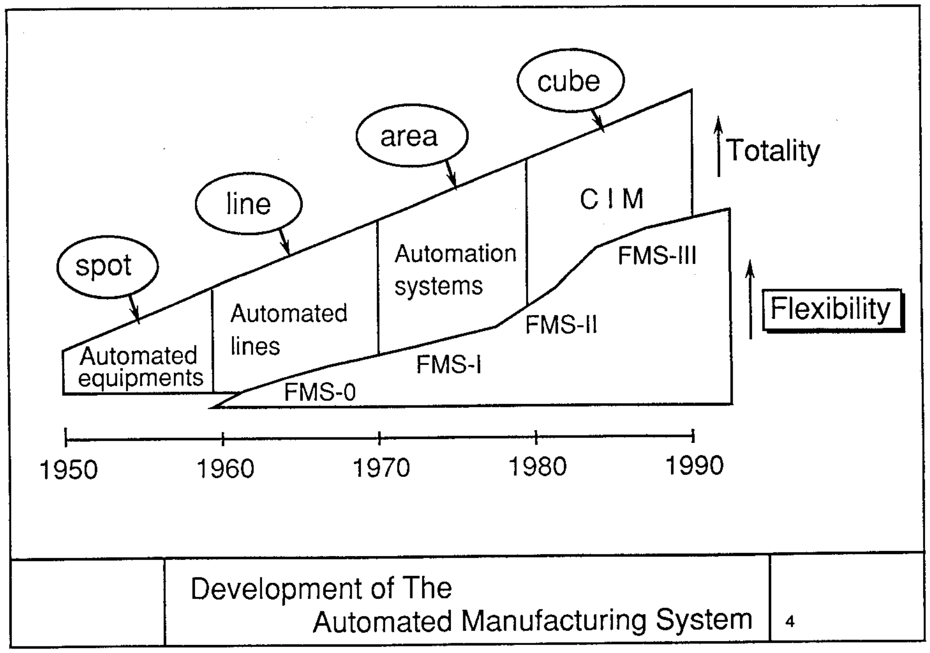

Figure 7. "Development of the Automated Manufacturing System." This chart shows that NDCL has tried to conquer a series of increasingly difficult automation problems, each of which presents a more difficult variety or changeover problem than the one before. Starting with islands of automation in the 1950s, the progression has also been toward more integration. For the 1990s, the goal is to be able to bring a new design of the product into an existing factory. Courtesy Nippondenso. Used by permission.

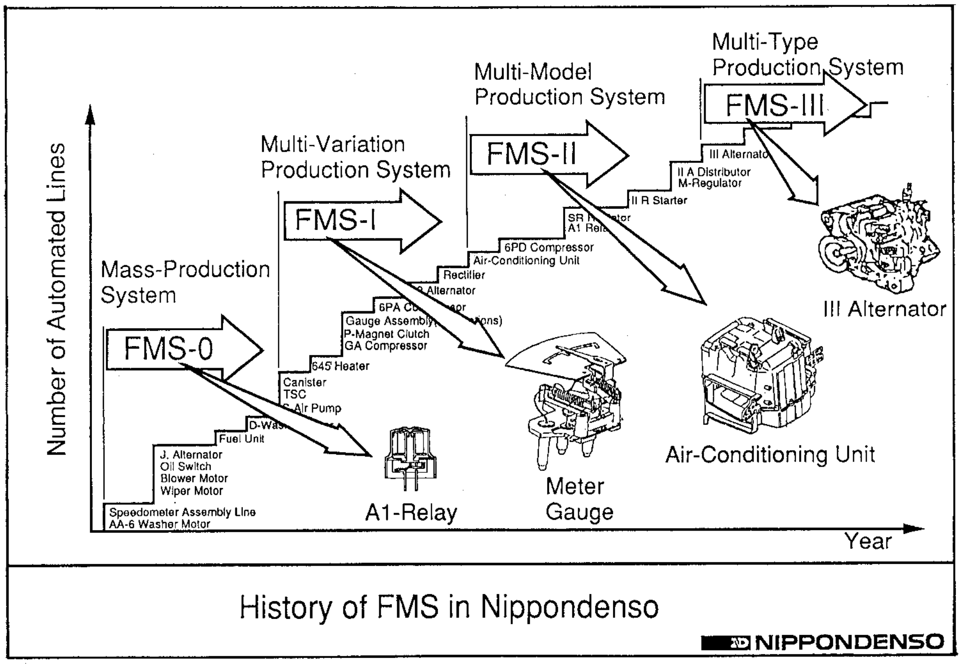

Figure 8. "History of FMS in Nippondenso" Courtesy Nippondenso. Used by permission. Over the time span of the 1960s to 80s NDCL has automated more difficult production situations. The relays have minor variations and comprise mass production. The meters have arbitrary variation within a fixed part count and function suite. The air conditioners are large and differ considerably in features from one model to the next. The alternators vary in size as well as features and present the most challenging problem so far.

The categorization of automation systems indicates not only increased size and sophistication of the systems but also the ability to respond to more difficult levels of flexibility as defined in Figure 6. The products in Figure 8 may be classified as follows: (See Table 1)

PRODUCT	**SIZE AND SIZE:MODEL RELATIONSHIP**	**PART COUNT AND COUNT:MODEL RELATIONSHIP**	**PERIOD WHEN AUTOMATED ASSEMBLY WAS ACHIEVED**

RELAY	VERY SMALL AND SAME FOR EACH MODEL	SAME FOR EACH MODEL	EARLY 1970s
METER GAUGE	SMALL AND SAME FOR EACH MODEL	SAME FOR EACH MODEL	MID 1970s
RADIATOR	LARGE AND SAME FOR EACH MODEL	SAME FOR EACH MODEL	EARLY 1980s
A/C UNIT	LARGE AND SAME FOR EACH MODEL	DIFFERENT FOR SOME MODELS	EARLY-MID 1980s
ALTERNATOR	LARGE AND DIFFERENT FOR EACH MODEL	SAME FOR EACH MODEL	MID-LATE 1980s

Table 1. Classification and Properties of Several Products Whose Model Mix Assembly Was Totally or Mostly Automated at NDCL. (The radiator does not appear in Figure 8. It is shown schematically in Figure 10.)

It is well-known that the easiest items to assemble automatically are small and have the same number of parts in each model. On the other hand, the difficulty and cost rise with product size, and providing the option to omit or include parts based on model type adds more difficulty. The most difficult among those in this table is the provision for different size items on the same assembly equipment. Thus Table 1, whose downward order corresponds to the time history of automation at NDCL, is in the order of increasing difficulty, indicating that NDCL picked its targets systematically. Note, too, that production and assembly equipment is typically 100 to 1000 times the size of the product itself, with equipment cost being a very strong function of size. Thus careful combined product and production system design becomes more crucial as product size increases.

Specific Examples of NDCL's Methods

The following sections of the paper give examples of

- technology management in the form of in-house robot development

- several strategically designed products that attack different kinds of flexibility problems:
    - panel meters (flexible production of a small product with the same part count and part type in each model)
    - radiators (flexible jigless production of a large product with the same part count and part type in each model)
    - alternators (flexible production of a large product with the same part count but different size in different models)

These examples illustrate aspects of NDCL's general approach in the areas of technology management, make/buy decisions, application of classification, use of assembly to express model variety during production, and so on.

Robots at NDCL

In the mid 1960s, Mr. Aoki purchased a Versatran robot from the US. After some testing, it appeared to lack sufficient reliability, so Mr. Aoki assigned a new hire, Mr. M. Hattori, to redesign it in 1967. Mr. Hattori used a new technology, powerful electro-hydraulic stepper motors from Fujitsu-Fanuc, to drive this large robot. The robots were therefore more costly than desired but they were strong, fast, and reliable. By 1974, 40 of them were at work in a shop unloading die casting machines.[7]

In 1977 Mr. Aoki introduced me to Mr. Hattori, who showed me an assembly machine for building dashboard panel meters. (The panel meter is shown in Figure 9 and discussed in the next example.) He called attention to the simple "robot" at the first workstation of this machine, whose task was to choose between several types of casing or base plate and load it into the machine. He also pointed out that the machine could make several varieties

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[7] 1974 was the date of my first visit to NDCL. Other visits were in 1977, 1980, 1983, 1986, 1990 and 1991.

of panel meter. I did not understand the significance of this for the company's business environment until 1980.

In that year, NDCL had about 200 robots, all designed by Mr. Hattori and built in his department. Several of the types commonly used in industry were represented. (As the years went by, Hattori built all the types in common use.) Just before my 1980 visit, I had listened to one of the first public descriptions in English of the Toyota production system (including JIT). NDCL production engineers gave me a very lucid explanation of how they implemented JIT, noting that trucks full of alternators and panel meters left for Toyota plants (about 10 to 20 miles away at most) "every hour."[8] I also showed a film to a large audience of engineers illustrating a research demonstration of robot assembly of alternators executed in our laboratory.[9]

In 1983 NDCL had about 500 robots, all designed and built in-house.

In 1986 NDCL robots with tool-changers were assembling the cases and some simple internal parts of air conditioners.

In 1987 NDCL had about 1500 robots. Among these were several involved in assembly of alternators. Another group assembled the more difficult plumbing parts of air conditioners, resulting in a complete end-to-end automated assembly system. This system included robot vision to help the robot locate threaded pipe ends relative to each other and join them, as well as the articulated "sponge" attachment robots discussed above.

In 1991 NDCL had 2500 robots, and the number was planned to increase at about 1000 per year for the next year or two.

Throughout the period '74 - 91, Mr. Hattori was my host, discussing problems of robot technology as he rose in responsibility. His constant concerns were cost and speed. Conventional economic considerations were

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[8] I observed at that time that traffic jams in Aichi Prefecture seemed to consist almost entirely of trucks. By 1990 I was joking that JIT means "jammed in traffic." By 1991 the Japanese government was asking Toyota and other companies to reduce the frequency of deliveries and, in the case of Toyota, to take steps to improve the infrastructure in Aichi.

[9] [Nevins Whitney 1978]

always taken into account, just as they are in US companies, when deciding whether to automate. However, the required payback periods were much longer, typically three to four years. Even so, robots were not economical compared to manual assembly unless quite large production volumes were anticipated, usually over 500,000 per year. "Forget low volume applications for robots," he said in 1986.

An important reason why robots were economical at all was that in the early 80s a breakthrough in electric actuators occurred: direct drives. These powerful motors were less expensive than the early electro-hydraulic steppers. Whereas most assembly robots supported cycle times no less than about 6 seconds in the 1970s, cycle times of 2 seconds were realistic for robots with less than 1 meter reach by the early to mid 80s. The combination of lower cost and higher speed was a powerful impetus, and robot assembly applications multiplied.

The fastest such robots employed a configuration known as SCARA, which provided only horizontal motions (except for vertical motion of a light gripper at the end).[10] This arrangement relieved the motors of the task of supporting the arm against gravity, permitting more of their torque to be used to generate speed. Today, nearly all assembly robots are of this configuration, and the race for a one second cycle time is on.

However, the configuration can make only XYZ moves, requiring that the product be designed so that this limited repertoire is sufficient. Most NDCL products can be designed this way, although it takes some discipline and understanding. Sony's products, by contrast, are much more complex, so it must augment its SCARAs with innovative grippers and tools.[11]

In choosing to make its own robots, NDCL has identified three main justifications. First, it has control over the technology and can create what it needs to match the requirements of its products. Second, it claims it can produce the robots for lower cost than it can buy them, quoting in 1991 an

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[10] Prof. H. Makino, the inventor of the SCARA, gives a technical description of it in [Makino]

[11] Photos of these tools and a description of how Sony uses SCARAs may be found in [Nevins and Whitney 1989]

effective in-house cost of about $30000 vs. a price of nearly $80000 for a similar US-made SCARA, both equipped with a vision system. Third, it keeps control over maintenance and repair and can muster service personnel 24 hours per day, something that was unavailable from outside vendors during the 1980s when every company was stretched very thin.

Of these justifications, the ability to retain control over the technology undoubtedly is the most important. Not only can NDCL integrate product design and robot assembly system design, but it can leverage its other corporate technologies, such as micro-electronics, software, and sensors, into advancing the state of the art of the robots it makes, which are as fast, accurate, and reliable as any on the market.

Specific Examples of Products Designed for High Volume-High Variety Manufacturing

Three products will be discussed, indicating how they were designed for manufacturability to meet the OEM-JIT selling environment imposed by Toyota. In each case, design for manufacture (DFM) and design for assembly (DFA) were not utilized in the conventional way, namely to make fabrication and assembly easier or faster. On the contrary, they were used as enablers for the larger strategy of using design to meet customers' varying demands. Additional technical details about these products and their production equipment may be found in [Kawai.]

Panel Meters

The panel meters are shown in Figure 9. As mentioned above, the method is combinatoric. The figure shows that a meter has 6 parts (in rare cases, only 5). Prior to implementing the combinatoric method, some varieties of each part were eliminated. Then each type of each part was redesigned so that its mating features to its neighbors were identical for all parts of that type. Similarly, the surfaces where the assembly machine's feeder tracks or grippers touched each type were also made the same. The result is that any combination of the 6 parts will fit together and function as a meter, and furthermore the machine can assemble any of the 288 types.[12,13]

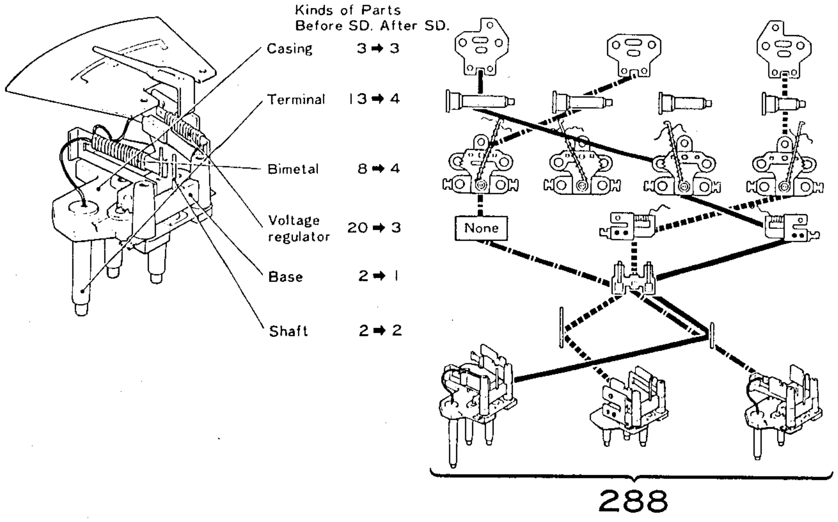

Figure 9. A Panel Meter (left) and the Combinatoric Strategy (right). Each zig-zag line on the right represents a valid type of meter, which is assembled by following the path from top to bottom. "SD" stands for standardized design, an effort that reduced the number of variants of each part as shown. The production rate is 32000 per shift. A "catalog" of only 16 parts is sufficient to support production of 288 different kinds of meter. If all the 288 possible paths at the right were drawn, one would see that each part is a member of many possible types of meters. Thus to first order most parts will be used regardless of the pattern of the order stream, so there is little inventory risk in making the 16 kinds of parts. If each different meter type were created by a few parts that were special to that type, a shift in the order pattern would require a large and awkward shift in part fabrication schedules, which could not be accomplished as quickly as the assembly machine can be switched. Also, feeding the hundreds of different kinds of parts needed to support so many varieties of meter would be very awkward. These are some of the reasons why expressing variety during assembly is easier than doing so during fabrication. Courtesy of Nippondenso. Used by permission.

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[12] The panel meter machine and NDCL's quality strategy are described by Mr. Aoki in [Aoki]

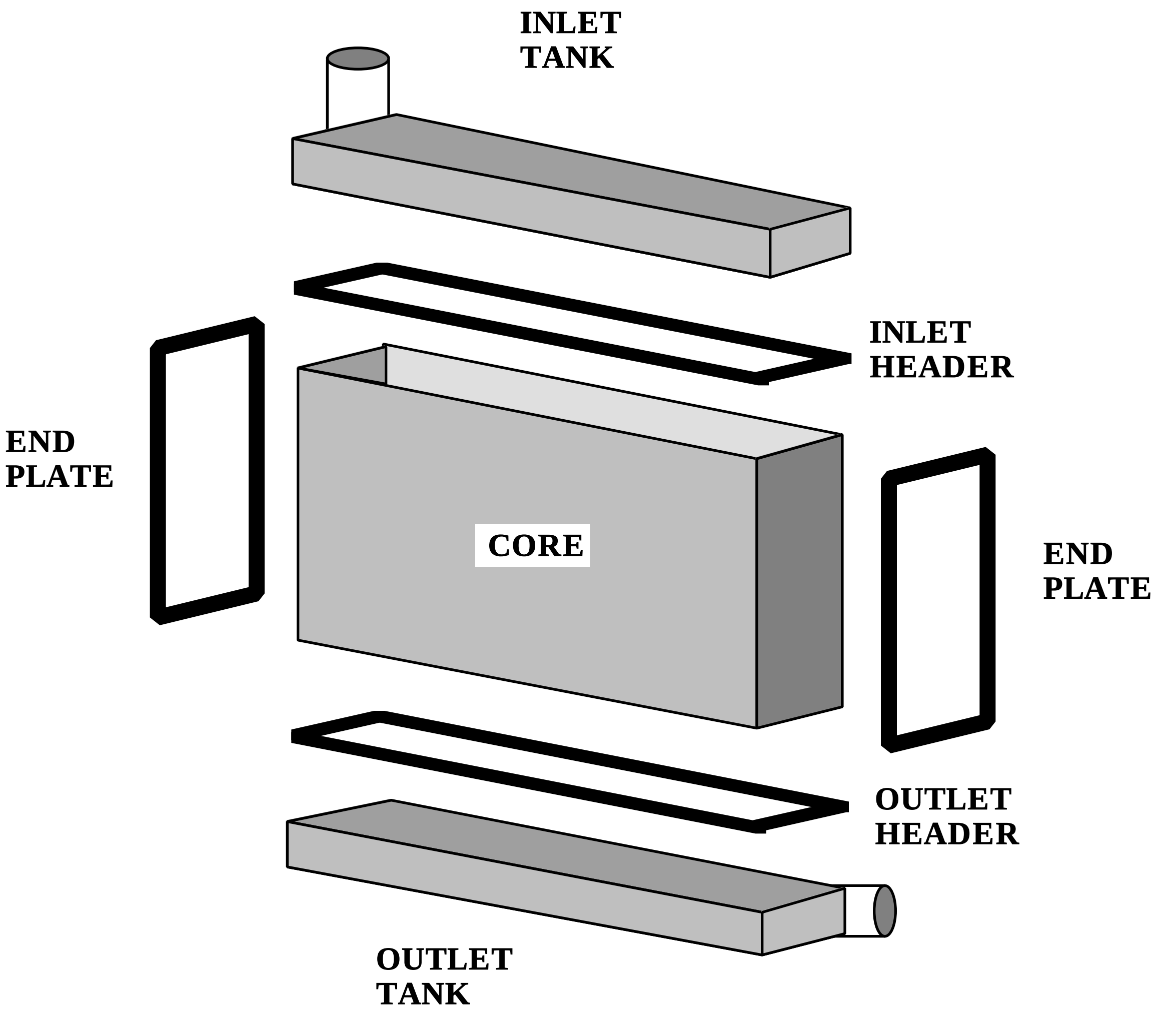
[13] [Kawai] discusses the small relays at length and indicates that they are made in 8 varieties using a restricted version of the combinatoric strategy. Before product simplification, 114 varieties were needed to meet all customer requirements.

The assembly machine functions as follows: The machine's control panel has thumbwheels into which the foreman can dial the required quantity for each of up to 40 types of meter. The machine itself is a serial system consisting of a conveyor that runs past several workstations. The stations all operate simultaneously, and each cycle of the machine produces a finished meter. At the first station, a robot picks up the correct casing and places it on the conveyor. This casing serves as the assembly base during subsequent steps. Casings follow each other along the conveyor with no empty space between them. When a case gets to the workstation where terminals are installed, a feeder track delivers a terminal to a simple gripper, which installs it. The casing visits each subsequent workstation and receives the remaining parts, one at each station.

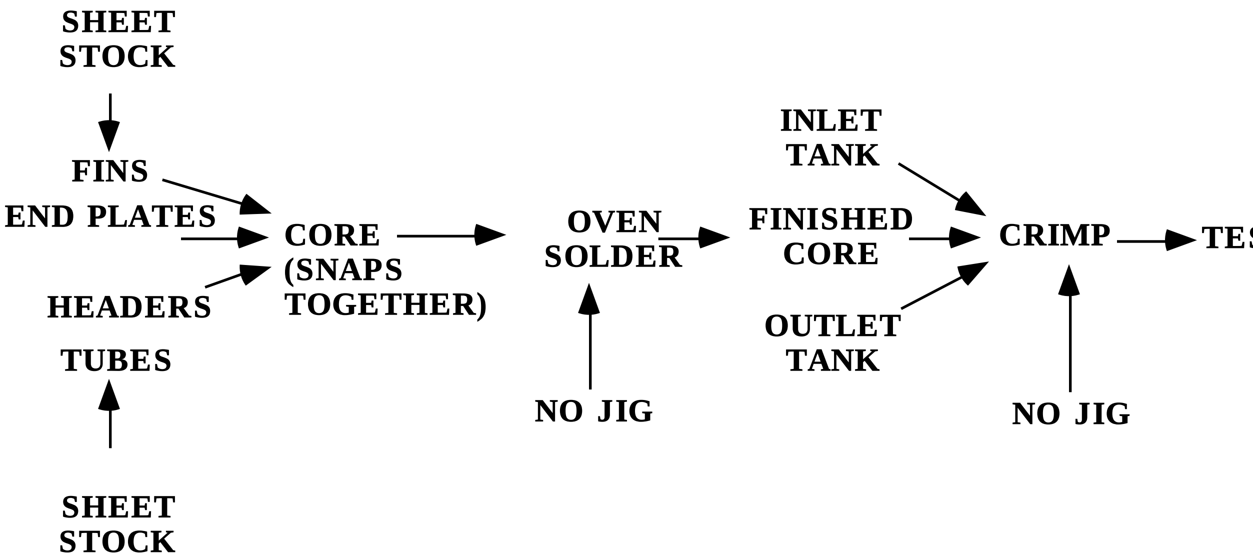
The machine builds one type of meter in this way until the counter on the control panel indicates that the day's (or shift's) need for that type has been filled. The robot then places a dummy casing on the conveyor. This casing acts as a signal beacon, tripping a sensor as it enters each workstation. The gripper at the station does nothing, but the feeder track is moved by a simple air piston so that it feeds another type of part. The next casing after the dummy is a real one, so the station resumes operation after losing one cycle as the dummy passes through. Following this pattern, the machine builds solid batches of each type ordered until the orders are all filled.

Radiators

Radiators are many times larger than panel meters, so the "machine" is in fact an entire factory. In a conventional radiator factory, the radiators are carried around in fixtures that hang from an overhead conveyor. The fixtures hold several metal items together (See Figure 10); these are the core, two end plates, and two headers. The cores are quite springy and would pop apart if not securely held by the fixtures. The parts are soldered together in a large oven, through which the conveyor travels. Then the radiators are removed from the fixtures and placed in a crimping machine where the plastic inlet and outlet tanks are crimped securely into place. Typically this is done with a large press die that is shaped to conform to the tank. When a new type radiator is to be made, the factory must switch over. Depending on the EOQ, this switch may occur every few hours. A lot of time is lost while one kind of fixture and press die is exchanged for another. Possibly hundreds of fixtures are involved in the switch.



RADIATOR PARTS



PROCESS FLOW

Figure 10. The Radiator, Showing its Main Parts and General Sequence of Construction. The radiator is made by cutting and folding arbitrary lengths of flat brass stock, snapping them together to make a core, and oven-soldering the core into a rigid structure. Top and bottom tanks are added by a self-configuring crimping press. The use of arbitrary stock lengths, the snap-together core design, and the self-configuring press together permit one of a kind production at mass production unit costs. There are no fixtures, so there is no changeover time, hence no EOQ.

The new design, created in the early 1980s, dispenses with fixtures because the parts snap together securely enough to be soldered, after which the assembly is quite rigid.[14] Any correctly shaped combination of core, end plate, and header will easily snap together into a valid unit. Thus a version of the combinatoric method is in use here. The redesigned press die consists of several pressure points rather than one continuous press face. Each pressure point looks like a piano key and is inserted by its own air piston. Keys that are inserted cause a tab to be crimped when the machine presses. A bar code on the tank tells the press die which pistons to activate. In this way the system conforms to the shape of the tank. Thus each tank can be different and the machine can crimp it.

Unlike the panel meter machine, this factory can make a batch size of one as easily as 100. When I first heard Mr. Ohta describe this factory in public in 1986, he was asked "How much did this factory cost?" "Strictly speaking," he said, "you have to include the cost of redesigning the product." That is, it's simply not a factory unless the product has been designed correctly.

Alternators

Alternators, like radiators, are completely unglamorous items. To radically change one's market share for such a product, one must do something dramatic in price or performance. In the early 1980s, NDCL chose to attack price, which meant not only automating but doing so for much less cost than before. The fact that alternators are made in about 250 varieties, in three different outside diameters, complicates the problem because typically automation works on items of one size only. Different sizes are made on

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[14] The radiator design and factory are described in [Ohta and Hanai]

different machines. In this case, as with radiators, "machine" really means factory, and each additional factory means hundreds of millions of dollars of additional investment.

Here again, NDCL classified the problem into different challenges of different levels of difficulty. Some of those pertaining to individual parts are shown in Figure 11. Dealing with different size stators was judged the most difficult challenge.

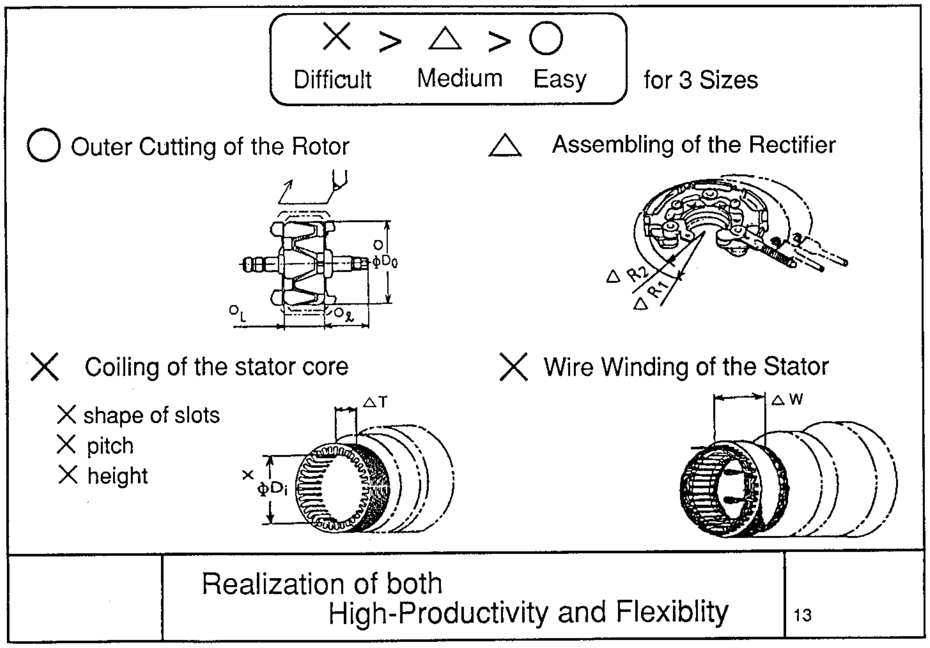
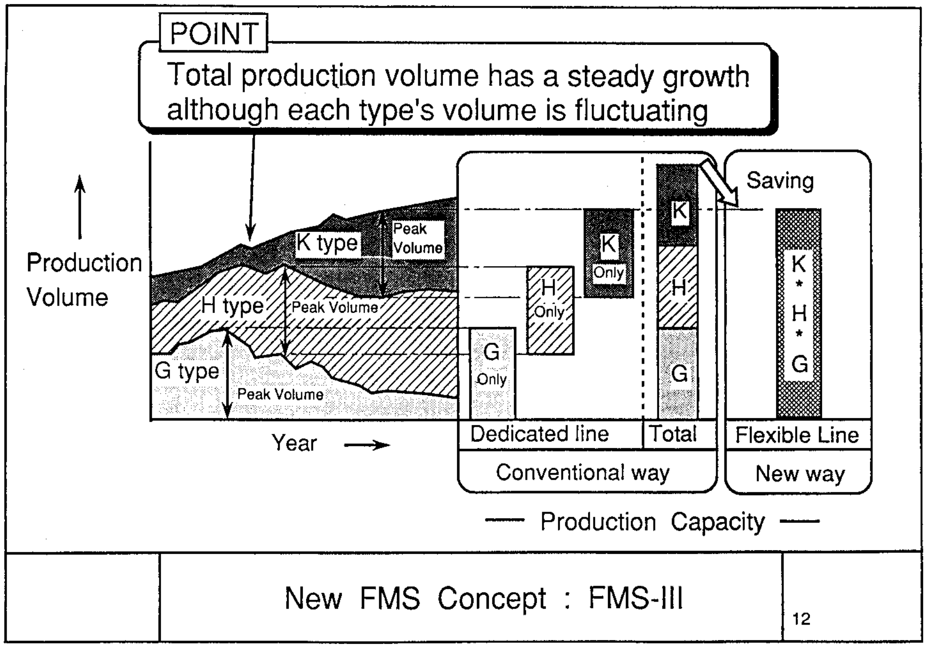


Figure 11. "Realization of both High Productivity and Flexibility" Courtesy of Nippondenso. Used by permission. This figure classifies different design challenges for multi-model alternator production: cutting different rotor diameters is easy, assembling rectifiers in different sizes is medium, while stator fabrication and winding are difficult. Most of the innovation effort was focused on the difficult parts, but all three problems were solved by methods similar to those shown here.

Figure 12 shows the capital investment problem. Not only is total volume growing (one type of flexibility shown in Figure 6) but the relative volume share of each of the three sizes is not known (another type of flexibility). To accommodate the worst case demand for each size would result in considerable over-investment. This is especially bad in Japan, where land is so expensive and earthquakes prevent multi-storey factories in many areas.



POINT

Total production volume has a steady growth although each type's volume is fluctuating

New FMS Concept : FMS-III

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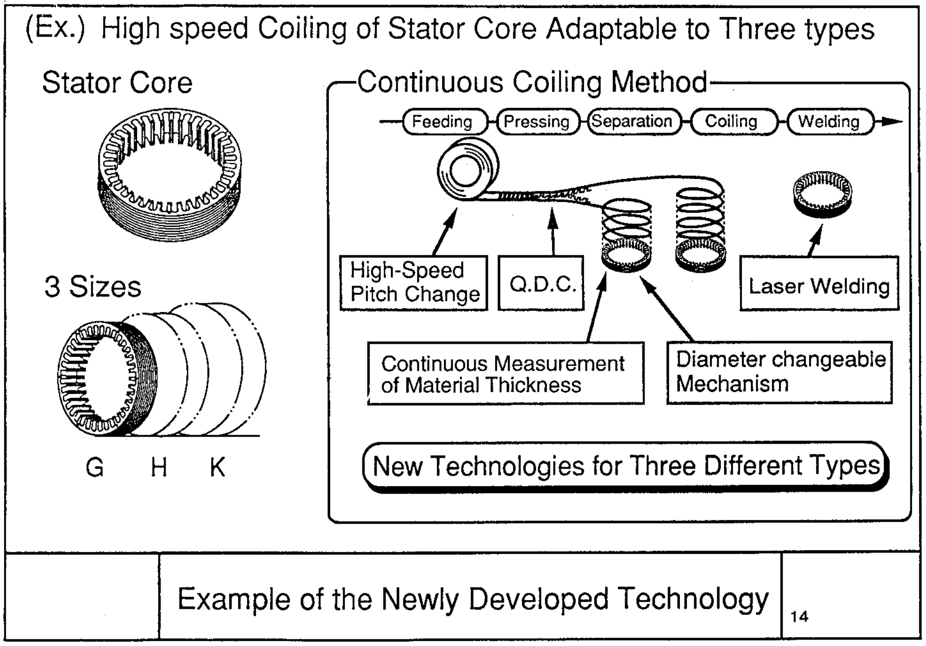
Figure 12. "New FMS Concept: FMS III" Courtesy of Nippondenso. Used by permission. FMS III is aimed at avoiding over-investment in the face of unpredictable distribution of volume demand for different models of alternators. At the left is a hypothetical time history of demand for three types of alternators (G, H, and K). Each is a different size and would normally require that a "dedicated line" be built to make it. Each such line must have enough capacity to make the largest quantity of its assigned type that might occur (indicated by "peak volume" on the time history). Inevitably this will result in each line having too much capacity, but the penalty for undercapacity is so severe that there is no alternative under the "conventional way." To save investing so wastefully, it is necessary to conceive of a line that can make all three sizes, permitting production capacity to be shifted from one size to another as demand requires. This is called FMS-III or "new way" at the right.

One aspect of dealing with different sizes is shown in Figure 13, where the typical method is shown on the left. Stator laminations are typically built by stacking up rings that have been stamped from flat sheet stock. The inside of each ring and four corners outside are scrap. When a different diameter is needed, different stamping and assembly machines are used. The new continuous coiling method, by contrast, starts with straight strip stock, cuts (almost) rectangular holes in it, slits it longitudinally, and coils it into a stator. By comparison there is much less waste. When a different diameter is needed, the size and spacing of the punched holes are changed, and the coiling diameter is also changed, each by means of quickly substituting one punch die or coiling spindle for another. One machine can thus make any size needed. Accommodations to different sizes elsewhere in the assembly process are relatively easy to make, resulting in a system that can switch on demand from one size to another.


(Ex.) High speed Coiling of Stator Core Adaptable to Three types

Example of the Newly Developed Technology 14

Figure 13. "Example of the Newly Developed Technology" Courtesy of Nippondenso. Used by permission. In this figure, QDC means quick die change. Alternator stators are built up in different diameters by forming straight strips and then coiling them into stator stacks. This wastes less material than the old method and can be switched quickly, permitting the same machines to make different size stators.

One has to respect the degree to which the method on the right in Figure 13 differs from conventional alternator or motor manufacture. This alternator, as a business concept, exists basically because of the manufacturing process. Like VLSI but totally unlike conventionally made alternators, this product is the child of its process.[15] It is unlikely that a conventional product design process, in which manufacturing skills are purchased from outside vendors, would have come up with this method.

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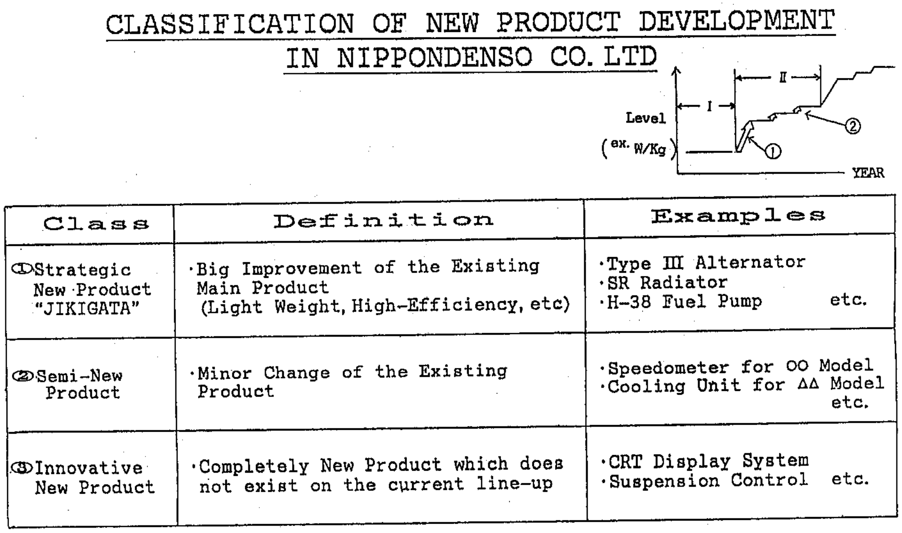
[15] Since reporting on this product in various seminars, I have heard anecdotally that the strip-coiling method of making stators originated in the US. If this is the case, it is another example of a US development being raised to a new level by a Japanese company. I have been unable to find out who the original developer was.

New Product Development Process

These interesting products emerged from a Concurrent Engineering process aimed at creating breakthroughs in an existing product line. Again, a classification has been made, this time a classification of product development methods, as shown in Figure 14. The process used on the alternator is the *Jikigata* (meaning strategic new product) type. It is aimed at creating major improvements in performance, in contrast to minor tweakings. *Jikigata* is used on products deemed to be the mainstays of a product division but which face or might face severe competition. To ensure technical, budget, and schedule success, a systematic approach is used. This approach is applied from the beginning of the design project, and involves tight integration of product planning and development along with process development and manufacturing implementation. The process is shown in outline form in Figure 15.

The process shown in Figure 15 indicates the existence of two teams, one focused on product design, the other on production system design. In fact, the agendas of these two teams are established at the beginning of the project by the Strategic New Product Development Council, which keeps the subsequent activities coordinated. While the Figure indicates two separate teams, in fact there is a great deal of coordination, and the distinction between the teams may not in fact be very strong.



CLASSIFICATION OF NEW PRODUCT DEVELOPMENT
IN NIPPONDENSO CO. LTD

Class	Definition	Examples
①Strategic New Product "JIKIGATA"	·Big Improvement of the Existing Main Product (Light Weight, High-Efficiency, etc)	·Type III Alternator ·SR Radiator ·H-38 Fuel Pump etc.
②Semi-New Product	·Minor Change of the Existing Product	·Speedometer for OO Model ·Cooling Unit for ΔΔ Model etc.
③Innovative New Product	·Completely New Product which does not exist on the current line-up	·CRT Display System ·Suspension Control etc.

Figure 14. "Classification of New Product Development in Nippondenso Co., Ltd." Courtesy of Nippondenso. Used by permission. Jikigata means "strategic new type" of product. It is not a revolutionary new technology but a great advance in cost and performance over existing designs.

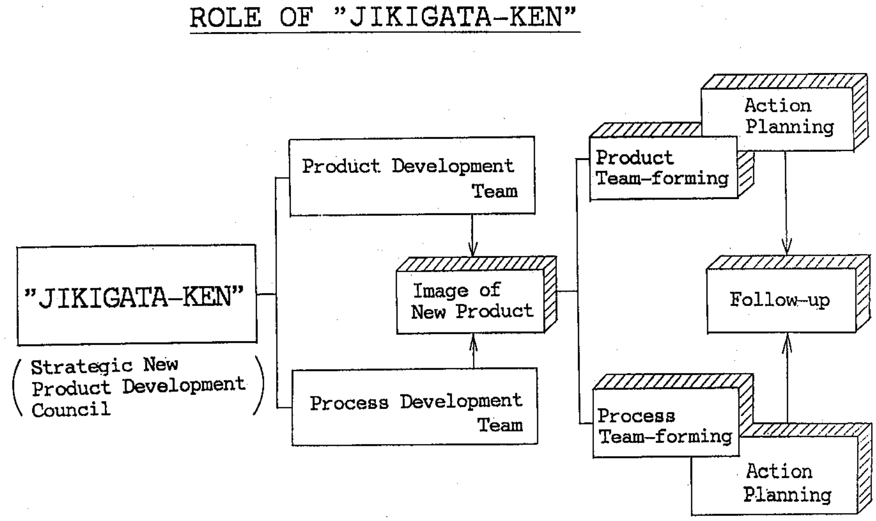
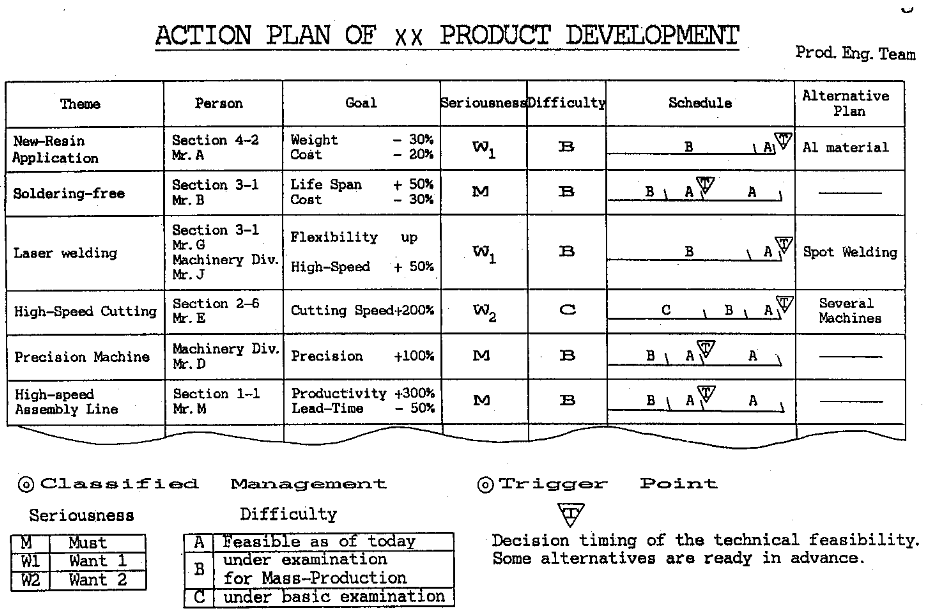


Figure 15. "Role of Jikigata-ken" Courtesy of Nippondenso. Used by permission. The development activities proceed in time sequence from left to right. The Product Development Team and the Process Development Team are chaired by the respective chiefs of Product and Production Engineering departments. Once the image of the new product (its specs for performance and production/selling strategy) have been decided, larger teams form to carry out the design. Action planning and follow-up are discussed in Figure 16.

What is more important is the degree of advanced joint planning and setting of objectives. The first step in this process is to create the "Image of the New Product." This means defining the specifications and performance of both the product and its production process. In the case of the alternator, this included requiring the production process to accommodate several sizes. Once this image is complete, the process expands to two larger teams which create action agendas for achieving this image plus other objectives for production. As indicated in Figure 16, each objective is given specifications and two classifications according to desirability and risk. The action plan specifies a schedule and identifies fallbacks in case the more risky objectives cannot be achieved by their due dates (called "trigger points"). This process, its pursuit, and the follow-up, constitute product-process design and risk management. To shorten the overall time, process development begins along with product design and, in the case of the alternator, fundamentally affected the design.



ACTION PLAN OF xx PRODUCT DEVELOPMENT

Prod. Eng. Team

Theme	Person	Goal	Seriousness	Difficulty	Schedule	Alternative Plan
New-Resin Application	Section 4-2 Mr. A	Weight - 30% Cost - 20%	W_1	B	B A ▽	Al material
Soldering-free	Section 3-1 Mr. B	Life Span + 50% Cost - 30%	M	B	B A ▽ A	———
Laser welding	Section 3-1 Mr. G Machinery Div. Mr. J	Flexibility up High-Speed + 50%	W_1	B	B A ▽	Spot Welding
High-Speed Cutting	Section 2-6 Mr. E	Cutting Speed+200%	W_2	C	C B A ▽	Several Machines
Precision Machine	Machinery Div. Mr. D	Precision +100%	M	B	B A ▽ A	———
High-speed Assembly Line	Section 1-1 Mr. M	Productivity +300% Lead-Time - 50%	M	B	B A ▽ A	———

◎ Classified Management

Seriousness

M	Must
W1	Want 1
W2	Want 2

Difficulty

A	Feasible as of today
B	under examination for Mass-Production
C	under basic examination

◎ Trigger Point

▽

Decision timing of the technical feasibility.
Some alternatives are ready in advance.

Figure 16. "Action Plan of xx Product Development" Courtesy of Nippondenso. Used by permission. This figure basically defines NDCL's risk management methods for challenging product design activities. Each problem is defined at the start, and technological goals and schedules are established, along with fallbacks. Hard jobs are not postponed and hard decisions are not avoided. In fact, they may be anticipated, making them easier to face when they arise. Note here, too, the use of classification schemes to make planning more rational.

The Vice President of Engineering at Polaroid once called the setting of trigger dates "scheduling inventions," a dangerous practice.[16] The difference here is that each invention can be abandoned without abandoning the entire product, although it will miss some of its goals. In addition, management has agreed not to let the trigger dates slip and has blessed the difficulty classifications, making it easier for everyone to give up when necessary.[17]

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[16] Hugh MacKenzie, personal communication.

[17] A young design engineer at Apple Computer recently described his company's shift in product development imperatives this way: In the quite recent past, product development took too long because the philosophy was still that of Steve Jobs, namely keep working until it's "insanely great." Now the philosophy is "Ship it!" meaning get it going and out the door. [Levy]

Comparison to How Other Companies Meet Similar Challenges

Hitachi

Hitachi makes a wide variety of products, among them automotive parts similar to NDCL's. However, it is in video camera and VCR manufacture that it uses methods similar to NDCL's. Among its innovative practices is a model mix assembly method I call "station lockout." In this method, each assembly arrives on a pallet bearing an identification tag which indicates which parts are to be assembled to it. Each assembly station contains a robot or machine capable of adding one part in one variety. If a station is equipped for a part that a model does not require, that station simply remains idle while that assembly passes through. This method is simple but probably requires more stations and floor space than NDCL's combinatoric method. Like, NDCL, Hitachi designs and makes its own robots and many of its manufacturing and assembly systems. Thus it is well-positioned to try various approaches to model-mix assembly.

Sony

Sony is a consumer electronics company with unusual ability to sense the needs and desires of its customers. An important component of its product strategy is to switch models or to expand their features at a rapid pace. Products may appear on the market and disappear in 18 months. In contrast to NDCL, Sony is its own Toyota, providing the variety stress on manufacturing from within. The pace became so hectic in the late 1970s that the production engineering department could not keep up using conventional fixed automation. Sony's response was to launch a series of robot developments which are described in [Nevins and Whitney 89]. Initially, an XYZ robot was used to assemble the first Walkman models. These units had about 30 parts, 15 on each side of a chassis. The XYZ robots soon proved too slow and expensive, and were replaced by a 4 axis jointed robot that can attach a part every 2 seconds.

Today, Sony assembles VCRs containing 100 parts using these robots with 5-gripper tools attached permanently to a turret on the robot's wrist. Each tool assembles a different part, and typically five parts are added by one robot before the VCR moves to the next robot. Parts are in pallets, and the robot gets each one and inserts it before picking up the next.

The parts and assembly actions are often more complex by far than those typically encountered by NDCL. Short term model mix is probably limited in the Sony system because the tools and insertion routines are so intricate that they are quite specialized to particular parts and take a long time to teach and debug. It is likely that Sony exploits the modularity of these robot stations (which it designs and builds in-house) to handle long term model evolution; new stations are prepared off-line and brought to the line ready to run when needed. They are all the same size and plug in physically, electrically, and electronically, making them easy to swing in and out.

Sony sells these robot modules to other manufacturers. One of these in the U.S reports that it can switch a line of 15 to 20 robots from one product design to a totally new one in about 8 weeks. Some of its Sony robots have been in the factory for 5 years and have built a different product each year.

Yamazaki Mazak

Yamazaki is a somewhat paradoxical company that uses world class unmanned flexible manufacturing methods to make otherwise fairly ordinary machine tools. Its business success is based largely on a few important design innovations plus low cost, high reliability, and attentive service. Among its manufacturing innovations is the "defined tool method" for machining parts.[18] This method requires designers to create sets of different parts that can be machined using the same fixed (and not very large) repertoire of cutting tools. Compared to typical machine design, this method has several large advantages, especially when programmable flexible machining systems (FMS) are used for production. Two of these advantages concern scheduling the FMS.

Typical FMSs are plagued by two kinds of scheduling problems: logistics of parts and logistics of tools. Since in typical designs a limited set of part features might require 10 different tools, the flow rate of tools through an

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[18] The defined tool method was explained to me by Mr. Hiroshi Awane of Yamazaki Mazak. The discussion here also draws on [Jaikumar].

FMS can exceed the flow rate of parts by a factor of 10. The number of tool storage sockets on each machine is therefore often insufficient. One remedy is to provide ever larger tool storage magazines. Another is to limit the range of parts the FMS can handle to that small set whose required tools can be stored on the machines in any given epoch of system operation. Another is to route the part through several machines which among them hold all the required tools. Scheduling such a system is a constant battle to find a consistent set of parts and routings that will reasonably utilize the system and not overflow the tool storage. One company even sells quick change tool magazines.

The defined tool method so restricts the number of tools that the storage magazines do not overflow. A part can therefore get most of the necessary machining operations for one set of features by visiting one machine. Yamazaki's FMSs are therefore small, consisting typically of four machines, each equipped with identical tools. Parts visit these FMSs in series in order to obtain all the required machining. Scheduling each of these FMSs is a breeze: "the next available part goes to the next available machine." One of the Yamazaki brothers, while guiding some visiting American dignitaries around the shop, pointed out two sets of machines waiting for shipment. "The ones with 60 tool storage sockets are for Japanese customers. Those with 120 are for the USA. Americans always want more tool storage." [Kelly]

Telemechanique

Telemechanique makes a wide variety of electrical, hydraulic, and pneumatic control devices, among a large range of industrial products. It faces many of the same problems NDCL faces except that it receives small orders world wide from thousands of customers rather than from one or two dominant customers. As Telemechanique strives to improve its order response and approach true JIT, it has begun to systematize product design in ways similar to NDCL's.[19] A typical problem is that of designing and producing a family of products, where family members usually differ by size and other measures of "capacity," such as electrical power. Larger members of

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[19] This description is based on discussions with Dr. Albert Morelli, Director of Research at Telemechanique.

the family are not simple scale-ups of smaller ones, but may differ qualitatively or quantitatively. Efforts are under way to gain control over part proliferation, part naming conventions, consistency of approach to design and redesign of different members of the same family, systematic ways of propagating design changes from one member to others, and so on.

One fascinating challenge is to design modular products. A "module" is an element chosen by the customer; buyers can design their own item by choosing base modules and adding feature modules to suit their requirements. "Buying" amounts to searching a catalog for the needed modules. A successful product line is likely to be one that is "easy to buy" in some sense. To design such a product requires placing oneself in the customer's shoes and emulating his thought process as he considers his needs and modular ways of meeting them. One must visualize how the customer might decompose his problem, and then prepare module options that fit into the decomposition's classes. One next designs a "buying process" around that decomposition and implements it in a design for the *catalog*, exploiting the process by creating modules that perform easily identifiable options and fit into recognizable classes. Only then does one design the modules, making use of parts commonality where possible, taking care that tolerances do not build up too much as modules are stuck together to make systems, deciding how to divide the product into subassemblies (NOT the same as modules), and so on.

Like NDCL's products, Telemechanique's modules are good examples of products whose engineering is driven by the conditions under which the items will be sold, or, equivalently, by the customer's behavior while buying.

Remarks

While each of the above companies has responded creatively to the challenge of high variety manufacturing, only NDCL has adopted all of the techniques identified in this paper. For example, both Hitachi and Yamazaki Mazak appear to focus on fabrication and assembly methods rather than overall design strategy. Only Telemechanique among these companies appears to be thinking about design and assembly in ways that are similar to NDCL's methods. Telemechanique also makes some of its manufacturing equipment, but nothing as sophisticated as either NDCL's robots or the coiling method of making alternator stators.

Summary and Conclusions

NDCL has spent the last 30 years or so becoming smart about developing products for the high volume JIT model mix business environment. The trend has not been so much increasing the *quantitative* variety or reducing the *quantitative* batch size as much as increasing the *qualitative* degree of variety that can be accommodated while reducing short term (changeover, tool change) or long term (reinvestment) waste. It has done this mainly by exploiting the design process and the assembly process of each of the products discussed. In this way it has succeeded in largely decoupling flexibility from efficiency, increasing the former without sacrificing the latter.

In general, NDCL's approach has depended on creating new product design methodologies, developing in-house capabilities for realizing these designs and making them, and pursuing an intellectual framework of classification of problems and solutions, plus identifying a sequence of harder and harder problems to pursue.

If we look at the individual examples, we can see a number of specific principles, only some of which are applicable to each situation or product:

- use the least complex approach available (for example, try to get the customer to reduce the variety in its orders or to accept more standard items; use conventional automation where possible, or with minor enhancements)

- increase the standardization of its own designs (for example, by finding ways to accomplish more functions with the same parts or by eliminating variations in design that the customer does not want)

- build the capability for variety into the product rather than depending on the manufacturing system to be flexible or reconfigurable (for example, by using different combinations of the same parts, assembled by simple automation, rather than assemblies of different parts created by programmable robots that access different part supplies)

- express the variety during the assembly process rather than during the fabrication process (each model is made of several different but simple parts rather than one complex part that is unique to each model; assembly is more complex this way but fabrication is less complex; also, JIT is better supported because the lead time for assembly is seconds to minutes whereas the lead time for fabrication can be minutes to hours or more)

- identify the sources of model/variety changeover time or cost and seek ways to eliminate them through product design if possible; otherwise, identify places where fixed tooling with long changeover time and high first cost can be replaced by reconfigurable tooling, and design the product to utilize that tooling

Each of these ideas alone can be found at many companies. What sets NDCL apart is the fact that these ideas are not only used together but are part of a larger intellectualizing of product/process design. This intellectualizing sees product/process design and automation as an organically growing set of capabilities divided into distinct problem and solution classes, and maturing into more and more difficult solutions. NDCL recognizes the importance of this organic process and supports it from the top by means of organization, corporate support for generic activities, and intervention to solve problems.

The circumstances in which such approaches can be successful are not available in every industry. NDCL has products which are technologically rather stable. Redesigns occur every three to five years, providing temporal stability as well. Under this stable umbrella, NDCL has conquered a number of demands that shift more rapidly, such as the pattern of types or sizes needed within a defined set. The same methods that NDCL uses to respond to pattern shifts that occur every few seconds are applicable, without modification, for responding to shifts that occur over hours, days, or weeks. Only a totally new design (a shift that occurs once in three years or so) currently requires a new approach. And NDCL has targeted <u>that</u> challenge, too.

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Figure Captions

Table 1. Classification and Properties of Several Products Whose Model Mix Assembly Was Totally or Mostly Automated at NDCL. (The radiator does not appear in Figure 6. It is shown schematically in Figure 8.)

Figure 1. "Mission of Auto. Component Manufacturers." Courtesy Nippondenso Co. Ltd. Used by permission.

Figure 2. "Organizational Structure in Nippondenso" Courtesy NDCL. Used by permission. Shaded regions indicate which divisions, inside or outside the company, participate in which of the functions listed at the left. This structure illustrates the partnership between corporate and divisional levels in NDCL that provides production knowledge, technology development, and factory systems.

Figure 3. "Assembly Technology Development" Courtesy Nippondenso. Used by permission. This figure shows that NDCL has partitioned development of assembly automation into two classes: dexterous/intricate assembly and large variation assembly. The former involves difficult physics which may be easy to identify, while the latter mainly involves part logistics and changing conditions that may not be obvious. NDCL notes in this figure that one can attack the dexterous/intricate problems by making robots that have the intelligence and dexterity of people, by assuming that robots cannot do such tasks, or by redesigning the product slightly but meaningfully so that it will be easier to assemble by robot. The last approach has been taken, resulting in products that, despite their difficulties, can be handled effectively by relatively ordinary robots. NDCL finds the targets among the large variation problems by direct economic analyses, focusing attention on the cost-drivers. These may or may not pose technological challenges, in contrast to the dexterous/intricate cases. The solutions may require only better organization or communication; or they may require new part feeding methods or cleverly designed robot grippers.

Figure 4. Comparison of Fabrication-driven Manufacturing and Assembly-driven Manufacturing. In fabrication-driven manufacturing, the order stream enters prior to fabrication, which makes a few complex parts to differentiate models of the process. In assembly-driven manufacturing, the order stream enters prior to assembly, which assembles a larger number of simpler parts to create different models. Parts are fabricated according to statistical trends in the order stream instead of the actual order stream. Fabrication-driven manufacturing is a low-bandwidth process compared to assembly-driven manufacturing since fabrication takes relatively longer than assembly, and changeover also takes longer.

Figure 5. NDCL's Methods for Streamlining the Product Design Process, with Comparison to Toyota's. Both companies overlap successive design tasks, using strong communication between the end of an upstream task and the start of its successor. NDCL employs "early sourcing" to warn downstream tasks of impending design information, and employs "front loading" to provide feedback to the upstream task. At Toyota, "early sourcing" is called "flying start." However, Toyota also identifies an element called "continuing responsibility," in which each upstream task keeps an eye on those downstream and fixes errors it was responsible for. This element was not described explicitly by NDCL. On the other hand, "front loading" is an integral part of "flying start" at Toyota and is not called out as a separate element.

Figure 6. "Three Characteristics of Flexibility." Courtesy of Nippondenso. Used by permission. Three classes of flexibility have been identified, each concerning a different time scale, source, and class of technological challenge. Volume change is often end-user market driven, can occur over weeks to years, and can comprise overall change or redistribution of demand within a product line. Design changes are often in the hands of NDCL and can be frequent and minor or be a switch to a new generation that occurs every half decade. Product variation is usually driven by the OEM customer and comprises the kinds of variants wanted, which depend on each kind of product.

Figure 7. "Development of the Automated Manufacturing System." This chart shows that NDCL has tried to conquer a series of increasingly difficult automation problems, each of which presents a more difficult variety or changeover problem than the one before. Starting with islands of automation in the 1950s, the progression has also been toward more integration. For the 1990s, the goal is to be able to bring a new design of the product into an existing factory. Courtesy Nippondenso. Used by permission.

Figure 8. "History of FMS in Nippondenso" Courtesy Nippondenso. Used by permission. Over the time span of the 1960s to 80s NDCL has automated more difficult production situations. The relays have minor variations and comprise mass production. The meters have arbitrary variation within a fixed part count and function suite. The air conditioners are large and differ considerably in features from one model to the next. The alternators vary in size as well as features and present the most challenging problem so far.

Figure 9. A Panel Meter (left) and the Combinatoric Strategy (right). Each zig-zag line on the right represents a valid type of meter, which is assembled by following the path from top to bottom. "SD" stands for standardized design, an effort that reduced the number of variants of each part as shown. The production rate is 32000 per shift. A "catalog" of only 16 parts is sufficient

to support production of 288 different kinds of meter. If all the 288 possible paths at the right were drawn, one would see that each part is a member of many possible types of meters. Thus to first order most parts will be used regardless of the pattern of the order stream, so there is little inventory risk in making the 16 kinds of parts. If each different meter type were created by a few parts that were special to that type, a shift in the order pattern would require a large and awkward shift in part fabrication schedules, which could not be accomplished as quickly as the assembly machine can be switched. Also, feeding the hundreds of different kinds of parts needed to support so many varieties of meter would be very awkward. These are some of the reasons why expressing variety during assembly is easier than doing so during fabrication. Courtesy of Nippondenso. Used by permission.

Figure 10. The Radiator, Showing its Main Parts and General Sequence of Construction. The radiator is made by cutting and folding arbitrary lengths of flat brass stock, snapping them together to make a core, and oven-soldering it into a rigid structure. Top and bottom tanks are added by a self-configuring crimping press. The use of arbitrary stock lengths, the snap-together core design, and the self-configuring press together permit one of a kind production at mass production unit costs. There are no fixtures, so there is no changeover time, hence no EOQ.

Figure 11. "Realization of both High Productivity and Flexibility" Courtesy of Nippondenso. Used by permission. This figure classifies different design challenges for multi-model alternator production: cutting different rotor diameters is easy, assembling rectifiers in different sizes is medium, while stator fabrication and winding are difficult. Most of the innovation effort was focused on the difficult parts, but all three problems were solved by methods similar to those shown here.

Figure 12. "New FMS Concept: FMS III" Courtesy of Nippondenso. Used by permission. FMS III is aimed at avoiding over-investment in the face of unpredictable distribution of volume demand for different models of alternators. At the left is a hypothetical time history of demand for three types of alternators (G, H, and K). Each is a different size and would normally require that a "dedicated line" be built to make it. Each such line must have enough capacity to make the largest quantity of its assigned type that might occur (indicated by "peak volume" on the time history). Inevitably this will result in each line having too much capacity, but the penalty for undercapacity is so severe that there is no alternative under the "conventional way." To save investing so wastefully, it is necessary to conceive of a line that can make all three sizes, permitting production capacity to be shifted from one size to another as demand requires. This is called FMS-III or "new way" at the right.

Figure 13. "Example of the Newly Developed Technology" Courtesy of Nippondenso. Used by permission. In this figure, QDC means quick die change. Alternator stators are built up in different diameters by forming straight strips and then coiling them into stator stacks. This wastes less material than the old method and can be switched quickly, permitting the same machines to make different size stators.

Figure 14. "Classification of New Product Development in Nippondenso Co., Ltd." Courtesy of Nippondenso. Used by permission. Jikigata means "strategic new type" of product. It is not a revolutionary new technology but a great advance in cost and performance over existing designs.

Figure 15. "Role of Jikigata-ken" Courtesy of Nippondenso. Used by permission. The development activities proceed in time sequence from left to right. The Product Development Team and the Process Development Team are chaired by the respective chiefs of Product and Production Engineering departments. Once the image of the new product (its specs for performance and production/selling strategy) have been decided, larger teams form to carry out the design. Action planning and follow-up are discussed in Figure 16.

Figure 16. "Action Plan of xx Product Development" Courtesy of Nippondenso. Used by permission. This figure basically defines NDCL's risk management methods for challenging product design activities. Each problem is defined at the start, and technological goals and schedules are established, along with fallbacks. Hard jobs are not postponed and hard decisions are not avoided. In fact, they may be anticipated, making them easier to face when they arise. Note here, too, the use of classification schemes to make planning more rational.