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FINAL REPORT
PARTS-ON-DEMAND: MANUFACTURING TECHNOLOGY AND TECHNOLOGY TRANSFER ASSESSMENT

by

James L. Nevins, Daniel E. Whitney
Cline W. Frasier, Stephen E. Deutsch

December 1983

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The objective of Parts on Demand (POD) is to reduce the Navy's spare parts supply, stocking, and procurement problems by creating new methods for manufacturing parts when needed. This study surveys the state of the art in programmable batch manufacturing and recommends strategies for bringing POD into being.

Major study findings are:

1. The most critical problem in applying POD to the current parts inventory is the lack of technical data on the parts.
2. There are hundreds of thousands of potential POD parts, and → (Cont.)

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3. Existing and emerging manufacturing technology has much to offer this problem, but significant gaps were identified.

Major recommendations are:

1. For future parts, a POD system should consist of:
   - "POD PARTS" which are procured complete with manufacturing data packages;
   - "POD FACTORIES" of different sizes and characteristics, each capable of making a class of POD parts, and
   - "POD DECISION LOGIC" that handles make-buy and factory assignment decisions when orders are received.
2. For parts in the current inventory, the need is for "REVERSE ENGINEERING CENTERS" that can recreate parts for which complete data are not available.
3. For parts whose manufacture involves luck or art, research is needed to create quantitative and reproducible manufacturing methods.

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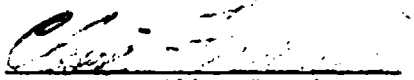
Approved: 
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Publication of this report does not constitute approval by the U.S. Navy Office of Naval Research of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

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BACKGROUND

The objective of Parts-On-Demand (POD) is to reduce the Navy's spare parts supply, stocking, and procurement problems by fabricating parts when needed, in small quantities, in a short time, and for reasonable cost. The need stems from the difficulty of predicting the future demand for that half of the parts for which demand is low. When timing and size of demand are incorrectly predicted, supply and demand are out of balance. Unnecessary costs are borne for uncalled-for parts, whereas procurement delays of a year or more can occur if parts are out of stock when ordered. Delays arise from difficulty identifying the part accurately, assembling the data needed to reproduce it, and finding a suitable and willing source.

The POD approach is based on the existence or emergence of new technology in manufacturing and data processing. Applicable techniques are found in computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM), as well as programmable manufacturing, assembly, and test systems

This study surveyed the state of the art in advanced manufacturing in order to determine the extent of its suitability, and to recommend strategies for bringing POD into being. The analysis covered the Navy's problem, the status of current and emerging technology, and the fit or gaps between the technology and the Navy's problem. Plans of action are offered for parts in the current inventory, future parts, parts with incomplete manufacturing information, and parts whose manufacture is still an art.

STATE OF THE ART

It was assumed for study purposes that functioning POD would be a system comprising order processing, scheduling and allocation procedures, as well as facilities for rapid design, fabrication, assembly, and test. All these arts were therefore included in the study, which focused on four generic kinds of parts: metal, nonmetal, electronic, and optical. The Navy's current supply system was visited to obtain knowledge of the quantity and types of parts involved.

The study found isolated examples of portions of applicable technology in all the required functions, applied to all of the generic part types. For example, one can buy a computer numerically-controlled lathe with a built-in CAD system. While one part is being cut, the machinist

can program the next part.

A few partly integrated systems containing some of the required functions also exist. These are listed in Table 1 on page 7. These systems have been designed to meet the needs of industry and would have to be modified to meet POD requirements. Many types of fabrication are excluded, such as molding, forging, and bending. In addition, the systems are configured for, and function efficiently with, a steady flow of parts or assemblies of a limited class.

GAPS BETWEEN THE ART AND THE NAVY'S PROBLEM

Let us specifically characterize the Navy's problem so that we can compare it to the state of the art in manufacturing. The Naval Aviation Supply Office (ASO) and Naval Ship Parts Control Center (SPCC) between them manage about 775,000 stock-numbered parts, of which perhaps half are low-volume, low original cost, and currently hard to get. In any year, perhaps 25% of these items[1] will be ordered. In addition, to the stock-numbered parts, there are perhaps ten times as many unnumbered parts. In a year, we estimate that orders for perhaps 300,000 are received[1]. These items fall into two classes: consumables (the great majority) and repairables. The latter are likely to be assemblies, which mean that they contain many parts made by many vendors. Repairables also require assembly and test as well as part fabrication.

The current art does not mesh completely with this situation. The key gaps, listed in Table 2 on page 8, lie in the areas of technical data about the part, design standards and design for automation, and fabrication/assembly/test.

RECOMMENDATIONS

To bridge these gaps requires a four-prong attack which divides current parts from future parts, and divides all parts into two groups depending on whether or not their manufacturing is inherently well enough understood to be automated.

1. For future parts that can be automated, we must define and implement a POD System of Procurement with the following components:

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1 These estimates count numbers of orders, not numbers of parts ordered, since the former is data kept by the Navy.

Table 1. Examples of State of the Art in Integrated Programmable Assembly Systems Capable of Economic and Rapid Low-Volume Production

Product	Functions Performed	Typical Production Quantity	Status
Electronic Circuit Boards	Orders, part retrieval, testing, guided manual assembly (automatic assembly in the research laboratory).	Batches of 50	Almost ready for production
Prototype Integrated Circuit Fabrication	Design, simulation, fabrication, test(?).	One or a few	In use for a year or two?
Metal Shafts	Design, process planning, N/C control of machining.	Small batches	In use for a few years
Gears 3" to 6" Diameter	Design, process planning, hierarchical control of fabrication system.	Ten	In use for 10 years
Eyeglass Lenses	Orders, grinding, test.	One	In use for many years
Sheet Metal Boxes	Design, process plan, cutting, bending.	One	In use for 10 years

Table 2. Gaps Between State of the Art in Integrated Manufacturing and the Navy's Supply Problem

Topic	Best Conditions for the Art to Function Well (Speed, Cost, Performance)	Navy's Situation in Many Cases
Technical Data on Parts and Assemblies	Resident in computer; coded for design, fabrication, assembly, test.	Data lacking, incorrect, incomplete, dispersed, or not in machine-readable form.
Design Standardization	Standardized designs, parts, fasteners, data storage conventions.	Many unique designs.
Design for Automation	Simplifies parts & products so that manufacturing system is faster and cheaper.	This art is new and not widely practiced. The Navy's parts are not new.
Fabrication, Assembly, Etc.	Steady flow, in small or large quantities, of a few batches of similar parts requiring the same kinds of processes.	A few of something will be ordered and probably never ordered again.

- "POD Parts", which are originally purchased complete with the necessary data package, economically and efficiently coded and machine-readable.

- "POD Factories", of different sizes, each of which can make to order a class of POD parts, including process planning, adapting existing designs, fabrication, assembly, and test. The smallest configurations could probably be put on a tender or carrier.

- "POD Decision Logic" to identify potential POD part candidates as early as possible, and to decide how best to fill a need when it arises: stock, buy, adapt, POD (which factory to use).

- "Data-Driven Automation", the integration of the above into a complete system.

2. For current parts that could be automated given the data, we must provide "Reverse Engineering Systems" capable of determining the manufacturing requirements for parts with incomplete data. Perhaps only a sample, damaged part will be available[2]. Information gaps will have to be filled using knowledge about how the part is used, plus shape measurements and materials tests. Knowledge bases of design rules and typical uses will have to be developed for common classes of parts.

3. For current and future parts whose automation is not now possible due to lack of a reproducible process, or because production involves chance, research priorities must be set.

Bridging these gaps will require that industry and the Navy change some long-standing procedures in order to take advantage of the opportunities that new technology offers for Parts-On-Demand.

Many specific needed technological advances have been identified. For example[3]:

1. Rapid creation of molds, tools, dies, and fixtures.

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2 Eyeglasses can often be replaced if part of a broken lens is available.

3 A more complete list appears in "Part 7. Conclusions and Recommendations" on page 44.

2. A theory of substitutability so that an existing part could be found and used with a ittle modification to fill a POD order for a different part.

3. New types of FMS architecture and machine tool design suitable to the Navy's low volumes and wide part diversity.

4. Goal-oriented programming languages for automated fabrication, assembly, and inspection systems.

5. Expert systems to recreate missing data on parts so that they can be made.

PART 2. INTRODUCTION

Between March 1, 1983 and December 31, 1983, The Charles Stark Draper Laboratory, Inc. (CSDL) conducted a study of Parts-On-Demand under contract to ONR (Contract Number N00014-83-C-0313). This is the final report on that study.

The objective of Parts-On-Demand (POD) is to reduce spare parts supply and procurement problems by fabricating parts to order in small quantities in a short time. This capability would reduce stored parts inventories and the time required to provide a needed part. It would also reduce the number of parts stored for which a need never arises. Finally, it would provide a source for parts that, for one of several reasons, can no longer be obtained. All of these benefits would save money, time, and human effort, and would increase the readiness of forces in the field.

The Navy does not need POD for those parts that are in continual high demand. Consistent and predictable demand makes it relatively easy to keep a balanced supply on hand and to maintain suppliers. The problem occurs with parts whose demand is low, or has suddenly risen unexpectedly, or which were last made regularly many years ago, or whose demand was incorrectly predicted.

In these and similar circumstances, the former sources of the parts may be reluctant to start up production again for a small quantity. Worse, they may have discarded their records and tooling or lost knowledgeable personnel, and thus cannot supply the part. It may represent out-dated technology they have discarded. Or they may have gone out of business altogether.

Obtaining the parts, therefore, can entail long delays, either to locate a new supplier or to reinstate an old one. Many steps are involved in this process, which often exceeds a year.

The Navy's parts are extremely diverse. Excluding liquids, we can distinguish metal, nonmetal, electronic, and optical parts categories. Furthermore, many things called "parts" are in fact assemblies of several or even hundreds of parts from one or more of these categories. When one part breaks, the entire assembly is out of service. Under the current procurement system, records may exist only at the assembly level, or it may have been predetermined that the assembly, rather than the part, must be replaced.

Making a part requires data. These data cover the item's size, shape, materials, cutting, forming, heat treating, finishing, inspection, and possibly assembly. Data are usually in the form of drawings, lists, build books, and unwritten anecdotal information. Typically, data to make a part are scattered over different vendors and Navy supply offices. Also, data may be incomplete, irrelevant, unavailable, or missing due to the

passage of time, evolution of technology, or disappearance of sources.

Implementing POD must take two paths: one suitable for parts in the current inventory, the other for future parts which are declared "POD parts" at the time they are procured. For current parts, we must assume that lack of data about them will be the major difficulty. Thus, POD will require considerable skill in reverse engineering, which poses challenging intellectual problems. Inevitably, some parts will lack so much data or be so complex that POD should not be asked to cope with them. Instead, they should be targeted for research. Standards for acceptability of a current part for POD will have to be developed.

For future parts, we must learn enough about design, fabrication, and assembly that we can define the minimum data requirements that enable POD. Second, we should define "POD factories" suitable for handling a well defined class of part efficiently. This will allow correct allocation of part orders to facilities and will keep a continual flow of work moving in each facility. Third, we must define a procurement process that can identify POD-potentials when systems are initially procured. An important step would be to increase part standardization. This would reduce the variety of similar but non-substitutable items and would reduce the variety of parts that POD must process. Creating or expanding existing cross-referenced data files of substitutable parts would be very useful.

We thus may identify the following elements of POD:

1. A "POD Part" which which is born with the necessary data.

2. A "POD Factory" that can make and assemble POD parts.

3. A "POD Reverse Engineering Center" that can handle parts with missing data.

4. A "POD Decision Logic" that allocates parts to the appropriate facility, identifies substitutions or near-substitution possibilities, and does long-term scheduling and materials purchasing.

5. The "POD System" comprising all of the above with enough facilities and sufficient production capacity to meet the Navy's needs.

While any one POD facility will probably have a limited range capability, the entire POD system must be able to deal with individual parts as well as assemblies of parts. This means that some facilities must be able to design parts, make and inspect them, assemble them, and test the final assembly. Since the range of required parts is so broad, and the required processes and range of applications are so different, the facilities will need to have different technologies at hand.

Presuming that the technical issues were solved and a POD system existed, how would it interact with ships, NARFs, and the existing supply system? The basic steps are shown in Figure 1 on page 14. A fundamental

step is the "Allocation Decision" which determines how the order is to be filled. The required data include part order histories and allocation decisions, as well as minimal identification and technical data. If the order is assigned to the POD system, then more detailed data are required on materials, fabrication processes, and test or inspection requirements.

This diagram shows two things. First, data files are crucial for proper operation of the whole process. Missing or incorrect data can cause an unwise allocation or an incorrect part to be made. Time and money will be lost, voiding the original goals of POD. Second, the diagram shows that POD is a part of the entire supply system and cannot function successfully by itself. The decisions made regarding allocation and fabrication methods exactly parallel the kinds of decisions made now by the current supply system.

Several possible implementations for POD can be imagined, differing in the degree of centralization of the Allocation Decision and of the actual POD production facilities. In one implementation, the Allocation Decision is made by a central authority. Fabrication of the part could be accomplished at a centralized POD facility or at a local, decentralized one on a ship or at a NARF or NSY. In another implementation, the Allocation Decision is made closer to the point of need, say at a NARF or NSY, or directly aboard ship. Fabrication would take place at the nearest capable facility. Each implementation combination has its pluses and minuses. Key ones are listed in Table 3 on page 15.

The above discussion points to the importance of data in making POD a success. Successful POD will embody a new idea, Data-Driven Automation. Successful POD will constitute a new method, Data-Driven Procurement. This will mesh perfectly with the current rise in information technology: office automation, CAD, CAM, CAE, numerical control, robotics, and integrated manufacturing.

Because POD will be the partner of the current procurement system and will share its problems, it is important to understand those problems and how they are coped with now. These issues include:

1. How are orders classified and allocated? What criteria are used?

2. What data and decisions are made, and what pressures determine how they are made?

3. What is the structure of the current inventory? How many "POD parts" might a POD system have to deal with in a typical year?

4. What is the structure of orders? Are they orders for single parts or entire subassemblies? Are they in singles, or are several parts ordered at once? What percent are for consumables, and would POD be relevant for them?

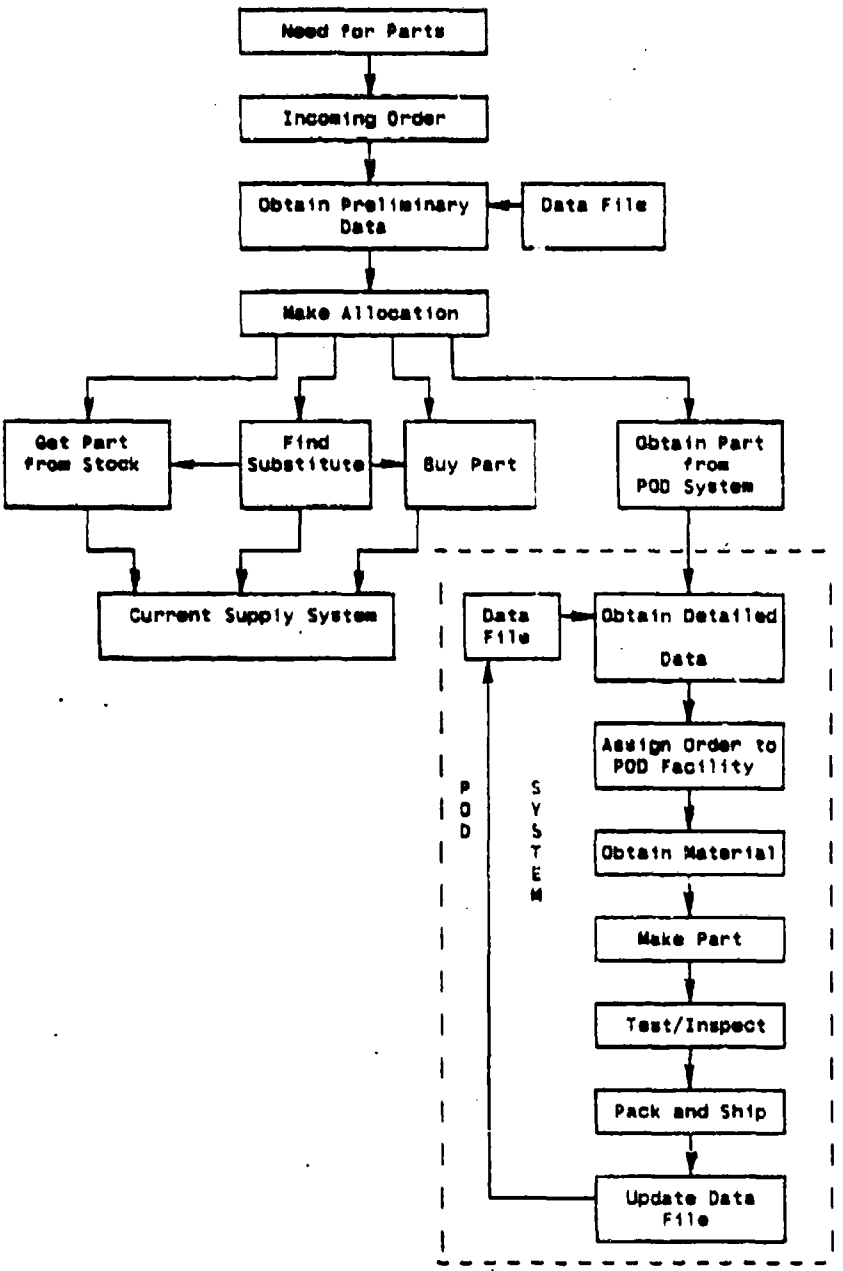


Figure 1. POD System in Action

Table 3. Various Advantages to Centralized or Decentralized Allocation Decisions and Centralized or Decentralized POD Production Facilities

	Centralized	Decentralized
Allocation Decisions	Better integration with current supply system. Allocation Decision based on more complete data about procurement options.	Less delay obtaining Allocation Decision. Better appreciation of degree of need for part. Less shock to existing system when POD is introduced.
POD Production Facilities	Higher production volume and more specialized parts requirements make system more efficient. Better access to data. Better access to expensive or specialized equipment.	Less delay in obtaining part if local facility can make it at all.

The answers to these questions will deeply affect the design of the POD system, including data requirements, decision algorithms, facility location, processing methods, communication links, and so on.

The technology for meeting the requirements of POD is developing rapidly, although some key gaps have been identified. An important fact is that this technology has developed up to now in response to the needs of civilian industry, which tends to shun automation of true low-volume production and true production-to-order. The needs of POD will, therefore, require adaptation of existing technology, as well as development of new technology more suitable for low volumes.

Technology is not uniformly advanced in all areas. In all four part categories defined above, we can find examples of automated design, fabrication, assembly, and test. But automated design and test are probably most advanced in integrated circuits, while automated assembly is probably more advanced in metal parts than in optical parts. Furthermore, there appear to be no facilities in existence where all production activities from order processing through final packaging are automated or even integrated. Only disconnected islands exist now.

POD can be made a reality. To do so will require that a step-by-step realistic plan be developed. The system must be sized first for a small number of the Navy's millions of parts and, at first, for a limited variety. There should be strong emphasis on integration of technologies into factory systems that can provide all the needed operations from order processing to final packing. Last, creating POD will require basic and applied research in data representation and retrieval, part design, reverse engineering, rapid creation of process plans and process tooling (dies and molds), and automation of process and assembly steps.

PART 3. THE NEED FOR POD

POD is needed for three basic reasons. First, there may be a defect in original estimates of the future demand for a part. Second, there may be difficulty locating a source. Third, the part may be inherently difficult to produce. The overall results are delays in obtaining parts, high costs when they can be obtained, and large stocking costs for holding parts that never get ordered. Simply put, the goal of POD is to bypass these problems by making the parts as the need arises. The directness of this approach makes it appealing, but implementing it is not a straightforward process. The difficulties will be discussed in later sections of this report.

The Navy supply system manages millions of items with stock numbers. These are classified, as shown schematically in Figure 2 on page 18, into several "mark" levels depending on how much an item costs and how many are ordered each year. Those designated Mark 0 are the ones most likely to be candidates for POD. Demand for them is low. Their unit cost is also low, making them tend to "disappear" from close scrutiny by the supply system until a crisis need arises. Many Mark 0 items are called "insurance items", meaning that they are held in stock in nominal quantity regardless of predicted need, because having none on hand would have a large negative impact on readiness.

Beyond the supply-demand mismatches that are tolerated with insurance items are those mismatches due to incorrectly predicting the need for an item. It is not clear how many prediction errors are inevitable. Further study is needed. Prediction errors can be due to new technology in a weapon system for which field performance data do not exist. Or funding limits can cause a system to remain operational longer than originally planned. Original spare part procurements may not be followed up by major restocking when the original stock is depleted. Special conditions in an operational theater can cause temporary surges in the need for an item.

When a part is found to be out of stock, or when, more often, it is discovered that a part is needed that never was stocked, the delays in procurement can be as long as a year or more. Many avenues are pursued, such as seeking the part in salvage or borrowing it from a temporarily inoperative unit. As succeeding attempts fail, time passes while the likelihood of finding the item decreases. Finally, the last resort is a vendor nicknamed a "bicycle shop", who, for a price, will make one of anything.

A successful POD system must have operating protocols that quickly identify such situations and short-circuit them to the POD technical facility without a year passing. That is, POD will not succeed if it is merely a technical substitute for the bicycle shop at the end of the existing chain.

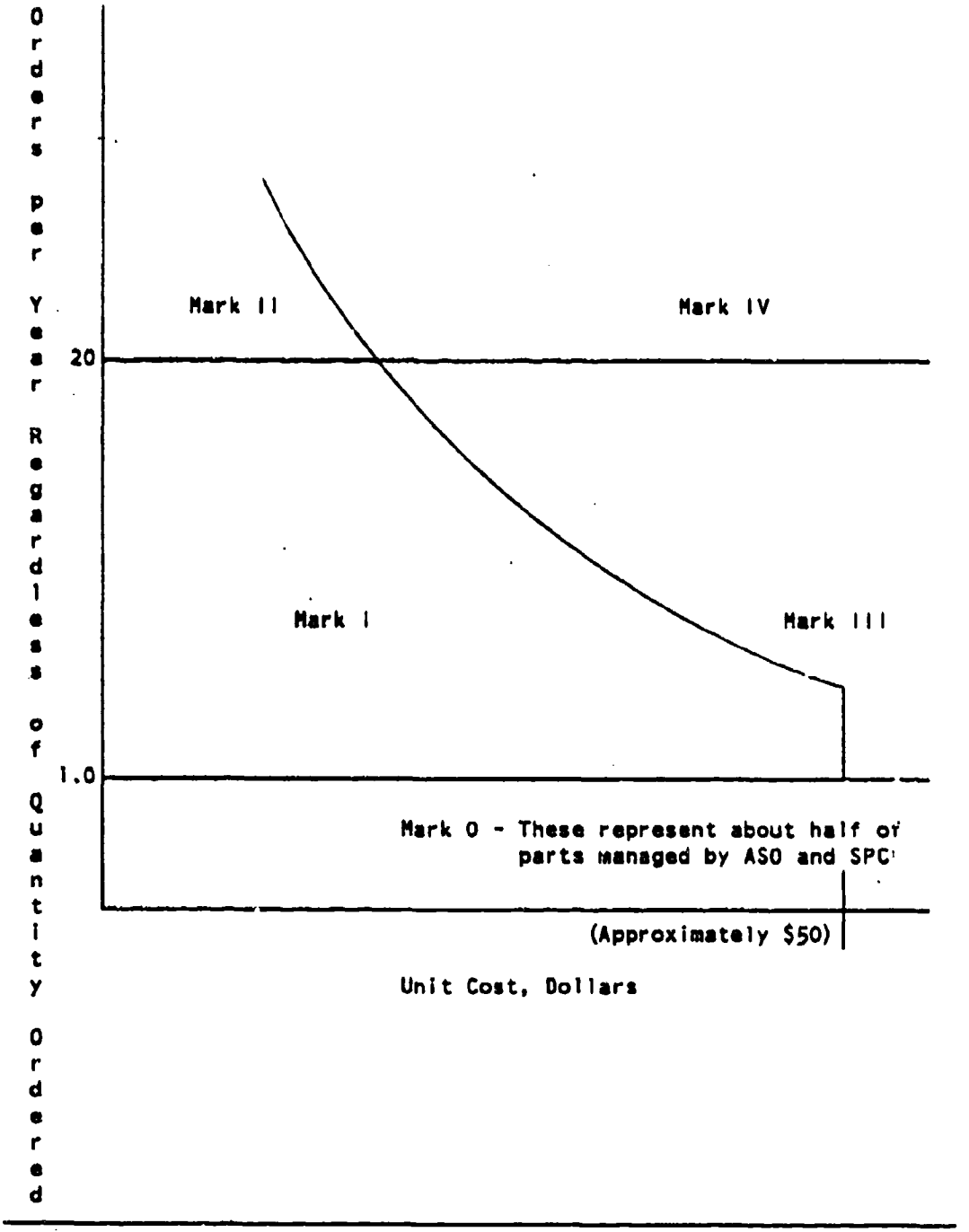


Figure 2. Mark Levels of Navy Parts System

Recourse to a bicycle shop is needed when the original vendor is unavailable. This often occurs. Typically, supply problems occur after the original system procurement, often long after. Given the fluidness of the U.S. economy, it is not surprising that vendors go out of business or shift to new lines of work. Procurement policies often encourage the subcontracting of work to many small companies whose survival is less than certain.

Various incentives have been tried to keep vendors. These are mainly procurement policies, payment plans, shared ownership of tooling, life of type purchase plans, warrantees, and so on. None of these has succeeded completely, probably because of the difficulty of devising incentives that simultaneously benefit both the Navy and the vendors.

If parts are bought in advance and never needed, large amounts of money are apparently wasted. Valuable space is taken up, and it costs money for the paperwork, personnel, and preservation requirements to keep these parts. Some of this cost must be swallowed as the cost of "being in business", but reducing it is an important goal.

Altogether, the dilemma can be depicted in Table 4. The upper left and lower right corners of the diagram indicate supply-demand consistency, while the other two indicate inconsistency. All four conditions exist. Complicating the picture is the fact that an item may switch from one corner to another during its supply life. Most frustrating is the case where a stocked part appears unneeded and is purged, whereupon orders arrive for it.

Table 4. The Supply Dilemma

	The Item is in Stock	The Item is Not in Stock
There is or has been a need for the item.	Good	Delays High procurement costs
There has not been and is not now a need for the item.	Waste of purchase price. Waste of space. Waste of holding costs.	Good

POD represents application of technology rather than new procurement policies, to solve these problems. With POD in effect, the unpredictability of demand would cease to be a problem. The search for sources would end because the POD system would become the source. Stocking parts needlessly could be reduced because there would be confidence that items could be made as needed. Delays could be reduced because POD facilities could be located close to users, and would be designed to respond quickly to orders.

It must be kept in mind, however, that the POD system will be a procurement system and not just a factory or collection of factories. Thus, it will need its own procurement policies, including how to identify a "POD part" and take it into the system, and how to decide which POD facility and technical method should make it. Schedule, military need, relative costs and time, and availability of technical data will be important factors. The POD system also must be large enough and have enough throughput to meet the possible demand.

The current supply system must make similar decisions. To make POD a success, it will be necessary to understand how the current system responds to these challenges, what demand patterns it faces, and what performance achievements it presents which POD must match or can exceed. The POD problem is not wholly technical.

PART 4. TECHNOLOGICAL ISSUES THAT MAKE THE CURRENT SUPPLY SITUATION DIFFICULT

This section and the next expand on the causes of the problems discussed in "Part 3. The Need for POD" on page 17. In "Part 4. Technological Issues That Make the Current Supply Situation Difficult," technological issues are presented while the non-technological ones are discussed in "Part 5. Non-Technological Issues That Make the Current Supply Situation Difficult" on page 26.

TECHNOLOGICAL ADVANCES MAKE PARTS DIFFICULT TO REPRODUCE BY THE ORIGINAL METHODS

A part may originally have been procured many years ago. It was made by methods that were suitable for the technical specifications and quantity ordered, using materials, machines, and methods in current use at the time. When the original order was filled, production ceased. Personnel turned to other tasks. Special tooling was set aside (or discarded: see below). Generic equipment was used on other work. As time passed, this equipment wore out and was replaced by better equipment. Personnel may have left the company or retired. Materials may have been replaced by new with presumably better properties.

Now the Navy needs more of these parts. The existing data and specifications for the part, if they exist, are relevant to the old methods and materials. A combination bicycle shop and museum might be needed if the parts are to be made the original way. Otherwise, a vendor must be found who can translate the original specification into methods he can apply.

This problem can occur in mechanical parts in the form of materials substitutions. New metal alloys and plastics are developed, and old ones go out of production. A materials expert is then needed to determine a suitable substitute, based on such factors as strength, corrosion resistance, dimensional tolerances or surface finishes, heat resistance, availability, or cost, to name a few.

The problem is acute in electronics, where the item may have been a custom-made packaged circuit, built with machines, materials, and methods that simply do not exist any more.

Technical and non-technical issues combine here when there exists a method of making large numbers of something but no method, at reasonable cost, of making one or two. This, too, is especially acute in integrated electronic circuits, where preparing a design and creating a successful process can be costly and time-consuming. Much of industry in mechanical

and electronic parts is set up to produce in large quantity. A goal of POD is thus to create cost-effective ways of making small quantities.

SOME ITEMS ARE INHERENTLY HARD TO MAKE

Items can be so hard to make that only one vendor can supply them. What this really means is that there does not exist sufficient understanding of the required processes to create the item repeatably and to the required quality every time. Examples include transistors and ultra-quiet ball bearings.

In some cases, luck plays a role. The vendor knows he can make a certain percentage of his output meet the specification, so he makes many and searches through the output for those that are good enough. For this method to be worth his while, he needs a market for the other parts, for example, the civil sector. Even in this case, the Navy can be in difficulty if it orders a small quantity since the vendor may refuse to go to the trouble of conducting the search, or his yield of good items may be too low in absolute terms if the overall production quantity is too low. (If 1000 are made, perhaps 10 will meet the Navy's specification, while if only 100 are made, perhaps none will.)

THE ORIGINAL EQUIPMENT LASTED LONGER THAN ANTICIPATED

Lack of funds or design success can keep a system operational long beyond its intended life. Many of the parts survive, but procuring those that do not can be difficult. Navy design specifications are usually strict so that extended life programs have a good base to build upon.

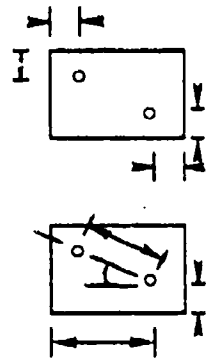
Examples of this occur often in jet engines where the initial procurement may have occurred 20 or 30 years ago. A decision to take the system out of service may be delayed year by year, so that quantity purchases of the parts are not made, whereas in hindsight they would have been justified.

THE TECHNICAL DATA NEEDED TO MAKE THE PART NO LONGER EXISTS

When the part was originally made, there were blueprints, process plans, inspection requirements, acceptance tests, material descriptions, and sources. Now the data are gone or the vendor is gone, and all we have is the part, perhaps damaged or broken. Indeed, some of the data may never have been committed to writing, or the actual process found to be nec-

essary did not agree with the written record, which was never updated. Finally, the data may not include subsequent redesigns or improvements to the item. This problem is different from that of the process requiring luck. Here, we are dealing merely with loss or irrelevance of information. Table 5 on page 24 gives examples of the kind of information involved.

Table 5. What is the Information Suite about a Part?

Information Covers	Factors Described Are:	Examples
Concept Design & Engineering	Functional Description: Concept and Specifications on performance and composition: size, weight, balance, strength, magnetism, etc.	Resistor Material Ohms Watts Tolerance on Ohms
Detailed Design and Drafting	Geometric Shape: Main dimensions Tolerances on dimensions Mutual tolerances between features: parallelism, concentricity, perpendicularity Reference Surfaces Surface and Edge Finishes Non-geometric issues Alloy, heat treatment, surface treatment	Two totally different parts with identical nominal dimensions:
Manufacturing or Process Engineering & Craftsmanship	Processing steps, in correct sequence to preserve dimensions and tolerances Rough cuts, welds, finish cuts, heat treat, grind	

Of all the technical difficulties identified, this one is the most severe. It occurs the most often and involves the most basic information: what is, in fact, the item described by the stock number? Central to the success of POD, permitting it to take over as the vendor, is the successful solution of this problem.

Two basic strategies exist. One is to alter future procurement policies so that the necessary data are acquired by the Navy when the parts are bought[4]. Gradually, this will create a new generation of candidate "POD parts" that the POD system can provide replacements for. The other is to find ways tc recreate thc necessary information from available clues.

Both of these approaches appear necessary, and both will require research to implement them, such as a theory to code and search for similarities between parts, or expert systems that can fill gaps in existing data about a part. Research needs are discussed in "Part 7. Conclusions and Recommendations" on page 44.

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4 The data must be coded and condensed because it is not practical to purchase and store the entire data package. Research is needed to determine the minimum data necessary from which the entire manufacturing file (drawings, tapes, materials lists, process plans, assembly and inspection steps) can be reconstructed.

PART 5. NON-TECHNOLOGICAL ISSUES THAT MAKE THE CURRENT SUPPLY SITUATION DIFFICULT

In addition to technical problems, such as advances in materials or obsolescence of manufacturing methods, there are many non-technical reasons why supplying low demand parts is difficult.

THE SOURCE MAY BE UNIQUE

Perhaps only one source has the know-how to make an item. This is especially likely if, as with quiet bearings, there is an element of luck in successful manufacture. This source has accumulated the skilled personnel or cultivated the alternate markets for extra parts that do not meet the Navy's specifications.

Second, perhaps only one or a few sources are willing to make the item, due to its difficult process or low-volume requirements. The source does not need such small orders and has plenty of other business. He is unwilling, in other words, to become a bicycle shop. Third, due to patents or other sole rights, only one source is permitted to make the item. The Navy must deal with the source on his terms, having no alternative. Whether POD would be legally able to make such a part would have to be studied separately.

Each of these circumstances currently leaves the Navy with few alternatives when faced with the delay or high prices for parts.

THE SOURCE NO LONGER EXISTS

Either the source has vanished altogether or no longer produces the kinds of parts it used to. The U.S. economy is dynamic, and producers shift their businesses toward dependable, sizeable and growing markets. Since the Navy often needs replacements for parts last made years or decades ago, it is often found that the original source is gone.

While the source may be present in name, it may have meanwhile been bought by another firm that changed its line of business. Or it may be in a similar business, but the trained personnel who used to make the item have retired or left. Finally, it may have found other, more attractive markets and does not want the low quantity, specialized business of the Navy -- the electronics business would rather make products for the toy industry, for example.

The Navy has little control over these circumstances. The best remedy is to capture the data on the part from the original source because survival of the data is the basic requirement. This leaves unresolved the question of parts whose creation involves luck, where the "data" are not enough. Such parts are targets for producibility research.

THE DEMAND FOR THE PART IS QUALITATIVELY DIFFERENT NOW

In most cases, it is relatively easy to get a vendor's attention when large quantities are ordered, but not when orders are small. The vendor cannot use efficient, high-volume manufacturing methods because their fixed cost and startup costs are too large. Less efficient, manual methods end up being less costly for the quantity ordered. This paradox can be better understood when all the costs of production are taken into account. Only the original vendor has a chance to use the original higher volume equipment and tooling. These, however, may be busy now with other work, or may be in storage. Getting them out, set up, and verified also takes time and money.

As long as a "buy as needed" policy is in effect, it translates into a need to reduce these overhead costs so that efficient production can occur on small quantity orders. This means reducing costs of paperwork, purchasing, contracting, and design, as well as costs of fabrication. Commercial industry has come to realize that these "white collar productivity" issues are as important as traditional "blue-collar" productivity issues.

IT CAN BE DIFFICULT TO IDENTIFY A PART CORRECTLY OR ISOLATE IT FROM AN ASSEMBLY

Many of the things called "parts" are really assemblies of many parts. Assemblies are purchased whole and often have stock numbers. The constituent parts often do not have stock numbers and are not stocked separately. The vendor of the assembly has given each part a part number that sometimes can be used to identify it, but not always.

Even when a part can be correctly identified by part number or stock number, it may not have been made by the vendor who furnished the assembly. This other vendor may not exist or may be reluctant to make a replacement. A consequence of multiple tiers of vendors is that technical data about an assembly is likely to be dispersed widely rather than being concentrated in one place. The adequacy of the data is thus not known until the need for a part arises.

The result of all these problems is that the data to make an item, the

only thing really needed, is not always available. If the Navy does not have control of the data and control over the cost of producing the quantity it needs, then it is unable to establish favorable terms in price or delivery times when parts are needed.

PART 6. FINDINGS

The findings of this study are divided into two categories: those relating to problems facing the current procurement system, and those relating to the ability of new technology to meet those problems.

PROCUREMENT

The current procurement system is discussed here to gain perspective on problems the POD system will have to face and solve if it is to be successful. These center on what data and decisions are needed in order to determine the best method for procuring a part. As indicated in Figure 1 on page 14, the basic choices are: get the part from stock, buy it, find a substitute that can be taken from stock or bought, or obtain the part via POD. Naturally, we would like the best decision made for each part.

What Data and Decisions Are Needed?

The most fundamental data are those that correctly identify the item. Misidentification occurs frequently, usually on items that have part numbers rather than stock numbers. The likelihood of correct identification increases as personnel closer to the center of the procurement system become involved.

Once the item has been identified, the stock-buy-make decision must be made. This is no problem when the item has a stock number and is in stock. The problem arises when the item is in low demand, is not kept in stock, or does not have a stock number because sufficient demand was not anticipated.

The quantity to be obtained is an essential question here since efficiency of production and cost per unit are generally lower when larger quantities are ordered. Figure 3 on page 30 shows the relation between most appropriate type of machining method, production volume, and system flexibility for making large machined metal parts. (This will be true of POD, too, though to a lesser degree. There will always be fixed costs that do not depend on how many of an item are made.) Knowledge of previous order history for the item is necessary. On this point, the currently kept data are cloudy, since they comprise the number of orders, rather than the number of items ordered. The procurement system sometimes receives contrived orders from knowledgeable personnel who know that they can manipulate the system with proper quantity and timing of their orders. To function efficiently, the POD system will have to be assured that the quantity ordered is the quantity needed.

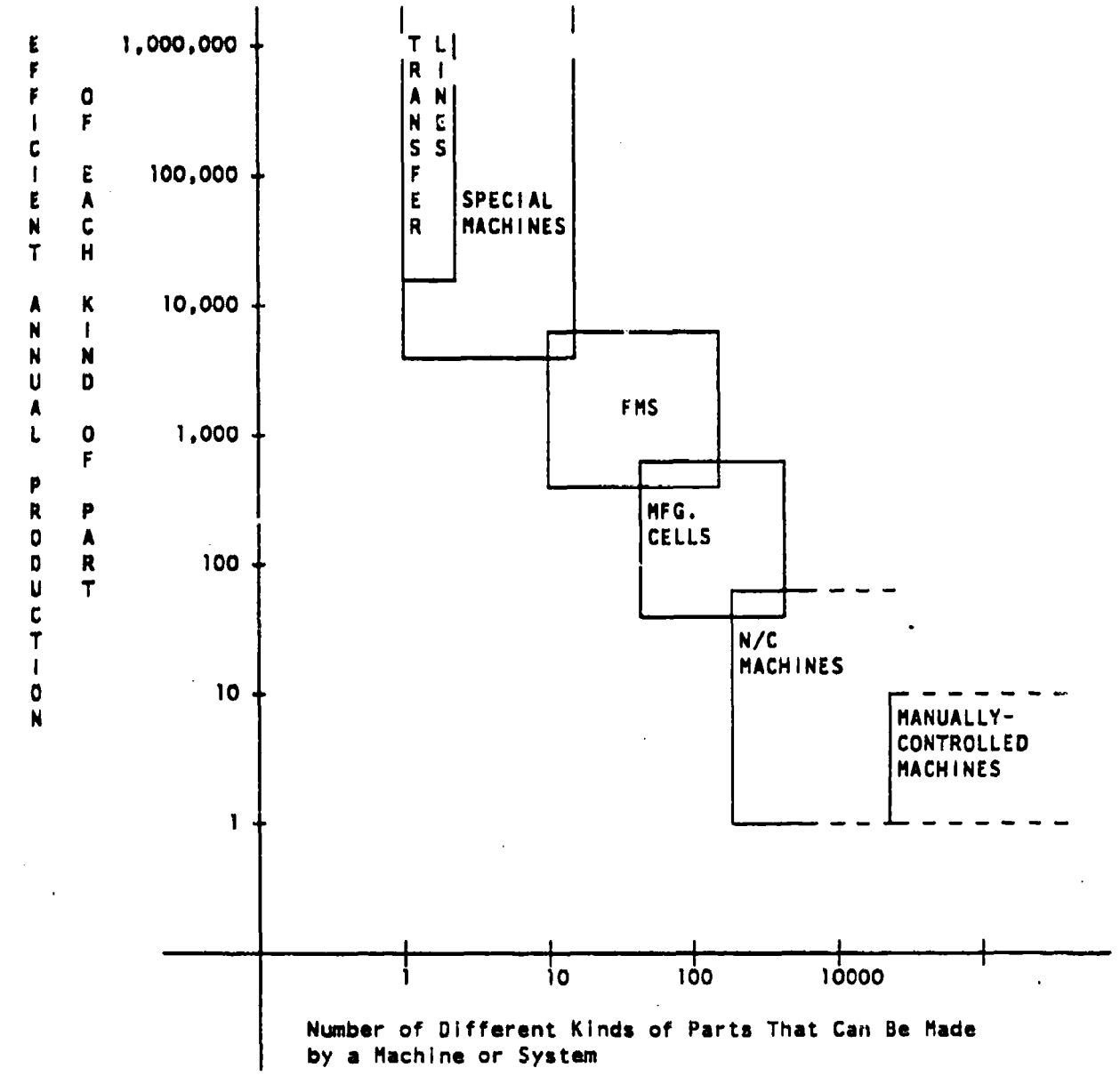

Figure 3. Comparision of Efficient Production Ranges for Current Machining Methods for Prismatic Parts About One Meter Cube: Note that FMS's are mid-volume systems, not low-volumes systems, at present.

It is also important to know if a substitute item is available. Compiling a cross-reference file would be a huge job, made more difficult by the large number of vendors and lack of standardization on low quantity parts. An important contribution potentially available from POD is the use of data processing technology to search data bases for similar parts, using Group Technology, Artificial Intelligence, or other techniques. If an exact match cannot be found, a near match may be, with the result that a minor design change will yield an acceptable substitute. The size of such a data base and the research problems that must be solved are both large, however.

To put these data problems in perspective, it is worth considering some specifics. ASO manages 240,000 parts, of which about half are in the Mark 0 category most likely to be POD candidates. While this is already a large number, it may be that there are 10 times this many items in an airplane that do not have stock numbers and do not get counted in the 240,000. One indication is that ASO receives about 100,000 inquiries per year for non-stock number items. Most of these items cost less than $6000 each, which means that they cost too little to receive regular reviews as to whether thay should be given stock numbers.

Reviews for a stock decision will be made if there are enough orders in one quarter, but apparently only a tiny fraction of the part number items qualify this way for review and only a fraction of those reviewed receive stock numbers. (Of about 24,000 orders received in the first quarter of CY1983, only 168 were offered for review, and, of these, only 9 got Navy stock numbers.) Order histories must be analyzed and future order patterns predicted. The techniques currently being used in these tasks could be improved.

Reviews for purging an item from stock occur if too few orders arrive, unless the part is classified as an insurance item. In a recent year, ASO purged only 180 of its 240,000 parts.

If these sample statistics are representative, they suggest a largely stagnant inventory. Figure 4 on page 32 expresses the situation schematically.

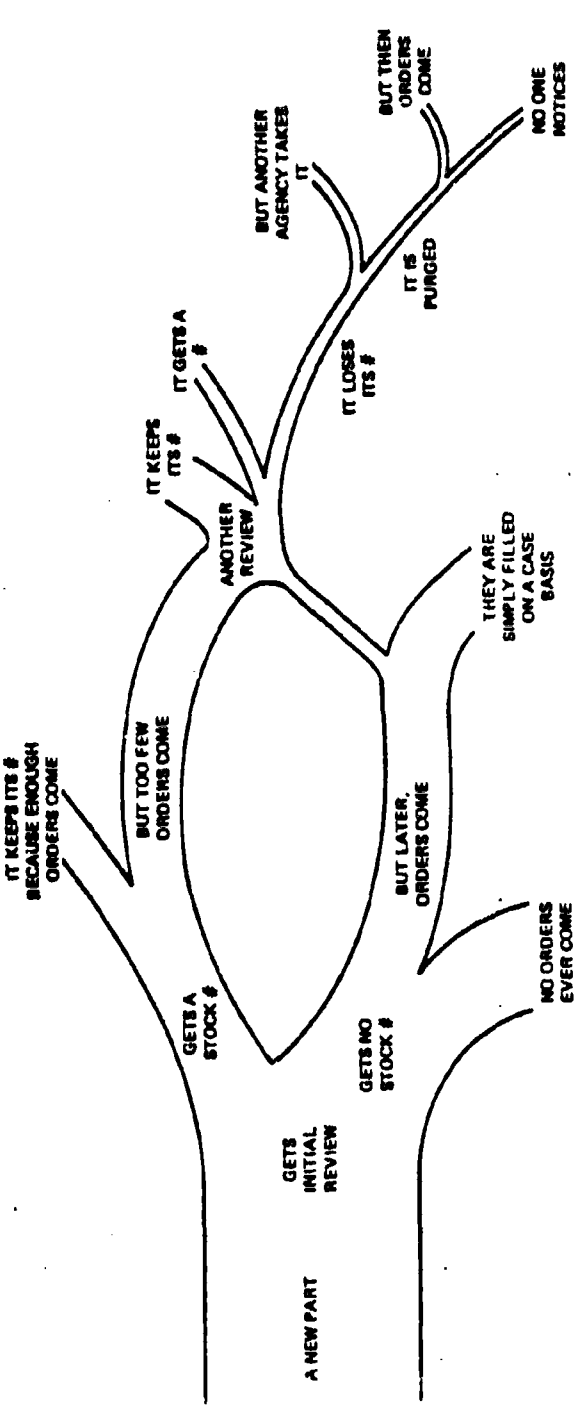

Figure 4. Schematic History of a Part: Path widths indicate qualitatively only the relative amounts of parts that follow each path.

Consequences for POD

The above findings indicate that data storage and handling, and decision making will be important functions for POD. First, there are a lot of potential POD parts. Second, POD should participate with the current system by aiding the decisions on whether a part should be a POD part or a stocked part. The POD system not only could search a technical data base, but could also do the necessary statistical analyses of order histories to determine appropriate production quantities and delivery schedules. It also could determine the most appropriate manufacturing methods and POD facility for providing the part. These capabilities could also be used to aid the current procurement system make its decisions. Therefore, a data base on fabrication methods and costs, plus the availab lity of facilities for scheduling purposes, will also be necessary.

While definitive data are not available at this time, it is clear that Mark 0 parts fall into three main categories: single parts, assemblies of parts, and commodity items (called consumables) like lubricating oil or packing compounds that are called "parts" but are made by totally different methods from rigid parts. To supply single parts, POD need only make them, while to supply assemblies requires providing many parts and assembling them. If only one part from an assembly is needed, then the POD system needs more component part data on stocked assemblies than is currently available. If POD is also expected to provide consumables as well, this requires additional types of production facilities.

The actual need for whole assemblies may not be known at this time since, with current technology and procurement policies, many items must be bought as part of an assembly. As single items, they are deemed unavailable. This policy could be changed if the ability to make parts improves. This will reduce the need for assembly.

TECHNOLOGY

At least two ways exist by which to divide manufacturing technology for discussion purposes. One is by function, starting with design and ending with final packaging (see Table 6 on page 34). The other is according to type of part, which can be roughly broken out as metal, nonmetal, electronic, and optical (see Table 7 on page 34). Naturally, there are overlaps in these categories, but they help focus the discussion. We will organize this subsection according to function, using materials to give examples along the way. The objective of the discussion is to give the state of the art in technologies applicable to creation of small quantities of parts at reasonable costs.

Table 6. Steps in Manufacture

Design Shape, materials, process method
Fabrication Materials processing, shape creation
Inspection Shape and material property verification
Assembly Mating, joining, fasteners, lubrication, cleaning
Test Appearance, function, reliability

Table 7. Types of Parts

		Metal	Non-Metal	Electronic	Optical
Single	Parts	Machined Cast Injection molded Forged Extruded Powder Pressed	Injection Molded Layed-up Fibers & textiles Liquids & greases	Discrete parts Integrated circuits	Lenses Light sources
Example	Assemblies	Mechanical Assemblies	Uniforms, parachutes	Circuit assemblies	Optical trains

Design

Automation of design of all the listed types of parts is well advanced in some places. When automation is carried to high levels, there is good potential for standardization, either enforced by an automated design library or encouraged by availability of existing designs. Design libraries are common in some integrated circuit and mechanical shaft design programs.

Essentially all integrated circuit (IC) design is now computer-aided or semi-automated. The reason is that otherwise reliable complex designs would simply be impossible. Thus, progress in IC CAD is driven by the need to design complex new circuits quickly with very high densities while minimizing the the interference of one circuit to another. Design libraries and prior designs are often available. While the pressure does not come from the need for one part, the tools support that need too. In addition, types of standard IC's, called Standard Cells, Gate-Arrays, or the more restrictive Programmable Logic Arrays, now exist. These are uniform in structure and are made the same, to be programmed later for their final function. To better aid POD, more recourse to design libraries and existing designs would be needed, along with intelligent software to help search data bases for "similar" designs.

Research is progressing on a CAD system that will create IC's of modern technology that reproduce the function of a previous electronic device made from older technology. This technique is called emulation. It directly addresses the technological obsolescence problem in electronic assemblies (Boeing).

For mechanical design of machined parts or machined molds for molded parts, there is similar but less widely used equipment. It is most often capable of making a computer drawing, but less often able to link that drawing to a functional simulation, a frequent feature of IC design systems. Also lacking in most mechanical systems, though present in IC systems, is the link to the fabrication process. Where these gaps have been bridged, the type of part is limited, usually being circular shafts (Technical University of Berlin, West Germany).

Many stand-alone mechanical design aids exist, some proprietary, for designing particular items like four-bar linkages, gears, cams, electric motors, and so on. Gears and motors are good success stories because a wide family of items in one shape class can be covered. (In the case of gears, there is an East German factory in Zerbst called ROTA 250 that can make small quantities to order under computer control.)

In textiles, there are proprietary design programs that create cutout patterns in a range of sizes, or that create weaving machine instructions to generate designs.

In optics, there are programs that analyze (and possibly synthesize) optical trains and single lenses.

Major gaps exist in automated creation of process plans for designed parts. Again, access to a plan library would be helpful, but the search problem would be difficult. Process plans contain many steps like rough cutting, finish cutting, heat treatment and intermediate measurements. The required tools and fixtures must also be identified and designed. Many alternate process plans can be created for the same part, with the major factors being available process equipment and the number of parts needed in one batch.

This gap is a serious one because a major source of delay and cost in part design is process planning. It is usually absorbed easily when many parts are made from one plan, but not when one part is needed.

It is important that parts and assemblies be designed at the outset so that they can be easily fabricated and assembled by automated systems. This has been called "design for manufacture" and "design for assembly". These disciplines are most advanced in Japan, where attention to shifting market demands and "just in time" production strategies require the ability to make small quantities and batches economically in arbitrary mixes. Design for assembly results in products that have fewer parts, fewer screws, more parts in common over different models, and assembly from one direction (no need to turn the item around or upside down during assembly). Products are often built up from carefully designed subassemblies that can be made in advance of actual need, or which are the common elements in a variety of product styles. A good example is panel meters made for Toyota by Nippon Denso: from a suite of 40 models, batches of one to 40,000 can be made on one day's notice.

"Design for POD manufacture and POD assembly" do not exist as organized disciplines. They would share some of the features of existing methods, but would have to be modified to meet the fabrication methods and low production quantities of the POD environment.

Fabrication

Automated techniques exist or are being developed for economical low quantity production of machined, textile, and optical parts. But, in most cases, the "low volume" really means a steady flow of individual parts in a restricted class, rather than one's and two's of widely differing designs.

The best known examples are flexible manufacturing systems (FMS's) capable of creating a variety of machined parts within certain size and shape limits. Typical commercial systems, such as those at Caterpillar, Hughes, or Ingersoll-Rand, have repertories of 50 to 200 different part numbers. They have been designed to be efficient producers when the demand is for sustained batches comprising 10 or 20 part numbers at any one time. Their efficiency falls in the POD type of environment, where small numbers of many part numbers are needed one after the other. This falloff is due to limitations on fixtures, tool inventories, and tool sto-

rage capacities. Pressure to meet the POD type of need could correct these weaknesses.

Simpler than FMS's are single numerically-controlled machines with built-in graphics CAD capabilities. An experienced machinist can be designing the cutter instructions for the next part while the current one is being made (West Germany).

There has been research on computer-aided sheet metal bending. Complete commercial CAD/CAM sheet metal-cutting and forming systems exist for making families of items like boxes and electronic chassis (GenRad in the U.S. and N.E.C. in Japan). The bends are limited to being straight lines. No system for making arbitrary bent surfaces to order by CAM techniques has been found during this study.

In the commercial optical market, eyeglass lenses are ground to order for each customer, usually in a few days. As with other successful FMS's, these are limited to a size and type range, but quantity one is obviously achieved at reasonable cost. Plastic lenses for Polaroid's cameras are successfully molded; here the problem for POD would be to rapidly create the mold.

Rapid mold creation is also the roadblock in applying plastic forming and rapid solidification (powder metallurgy) to POD. In both cases, complex net shapes can be created. In the case of rapid solidification, new alloys and superior mechanical behavior are possible.

In IC manufacture, there exists at least one proprietary automated system capable of creating a prototype IC directly from the CAD system without the use of optical masks. Quantity one production is possible, although the process takes longer than mass production with masks (U.S.).

Flexible automation is also being applied to non-metal fabrication like composite layup and textile products assembly. Here, robots and other programmable equipment can handle a variety of patterns, shapes, or layup sequences within a restricted range of products like military uniform sleeves or flat aircraft panels (Grumman, among others).

Assembly

Mechanical, optical, electronic, composite and textile products are all capable of being assembled automatically under mass production and, to a limited degree, under batch production. The batch environment is much less well developed and is the subject of considerable research.

Many applications of automated batch assembly are not implemented for economic reasons even though they are technically feasible. One reason is that robots and other programmable assembly systems components cost too much, and their integration into a system requires too much engineering and not enough standard modules. The result is that, apparently, it is

less expensive to assemble things manually.

There are two important environments where this cost disadvantage should not exist. One is an area of labor shortage, such as in Japan. Another is a shortage of trained, capable people who can remember all the assembly process steps when, as in a small batch environment, they do not get much practice with any one type of item. Both of these environments are characteristic of POD assembly.

In any manual assembly process, there is a learning curve: the percentage of correct assemblies and the speed of assembly rise approximately in proportion to the total number of assemblies produced. Many examples exist of military products that went out of production and whose production lines had to be started up again some years later. At this point, much of the production had to be thrown away because the people had forgotten how to do the assembly operations properly. This is usually exaggerated at lower batch sizes, where one person is responsible for many, if not all, of the assembly steps.

Automated assembly would thus contribute economically not by replacing people, but by producing less scrap and rework costs. This will be an added dividend for POD since time, as well as cost, can be saved if the assembly of one needed item can be done correctly the first time. The advantage will be most keenly felt in complex items like fire control or navigation equipment. Both mechanical and electronic assemblies are excellent candidates. In both environments, reject and rework rates of 50% to 75% occur frequently.

Automated batch assembly with programmable machines is most well developed in Japan. The products are usually small, mechanical items like tape recorders. Although the batches may be small, the overall production volume is large. Products have been specifically designed to be assembled by machines. In addition, the machines are equipped with a great deal of special tools and fixtures for performing the actual assembly operations. These include presses, lubricating guns, screwdrivers, and grippers. Instead of a "universal hand", these machines have universal tool sockets, like computer-controlled machine tools. These allow rapid tool changing. (Sony, Hitachi)

To make this technology more suitable for POD will require reducing the dependence on special tools and fixtures. As with FMS's, there seem to be two main strategic choices: (1) to make the machine systems much more general, or (2) to design things for automated manufacture and group similar items on carefully designed automated systems. It remains to be seen, for example, whether assembly machines should have a universal hand or whether products should be designed so that a limited set of tools can assemble them. The latter effectively increases the generality of the tools. It should be noted that while people have universal hands, they are used very often to pick up and operate tools that do the actual assembly operations.

Current programmable assembly systems are programmable only in a limited sense. That is, they carry parts along programmable paths to or from tools that do the actual work. (Alternatively, they carry the tools to and from the parts.) If the generality of the system is to be increased, then, in addition to effectively more general tools, more general and involved programs will be needed. These will include not only simple moves, but also test and inspection steps. If all of these have to be programmed by any of today's methods, it will take too long and cost too much, especially for assembly of one or two items. Current programming languages are procedure-oriented, rather than goal-oriented, and are focused on motions. They lack the ability to respond in real time to continuous vector feedback, although they can respond to discrete inputs that act as punctuation for a program.

A larger gap is associated with knowledge of assembly processes themselves. Assembly consists of insertions, press fits, snap fits, threaded fits, plus finishing operations like grinding and fastening operations like staking. Not only do current robot programming languages lack any ability to express these actions, but solid knowledge of their proper execution is lacking except in the case of insertion. Limited knowledge exists in press fits, snap fits, threaded fits, grinding, and staking. Since a major objective and justification for POD assembly is the ability to do the job right the first time, this gap must be addressed.

To do so requires these steps:

1. The process knowledge must be developed through research.

2. The actual requirements for assembly of a particular item must be determined and written down in terms that reflect concrete process knowledge (avoiding vague words like "tight", "smooth", "warm", and so on).

3. These requirements must be put into a data base so that an assembly machine can program itself, just as we hope that design data can one day be used to program fabrication systems like FMS's.

Test and inspection steps must be included along with assembly steps.

Test, Inspection, Acceptance and Qualification

Testing and accepting parts and assemblies are crucial activities in production of high quality items, especially military components. In many cases, however, these operations depend on human senses and judgement. Proper training and careful definition of acceptance criteria are essential. It is not often appreciated how differently different people will do the same judgement operation even though they describe it with identical words. If an operation can be understood well enough to be described concretely to a reliable and repeatable machine, then the judgement factor can be eliminated, and better production will result.

Inspection and test can cover individual parts or entire assemblies. Factors inspected range from size and shape to overall function. Surface and hidden defects must be found. Automated programmable techniques exist for some of these operations. In some cases, reprogramming is relatively easy, while in others it is very time-consuming.

Overall shape, especially if tolerances are not severe, can be measured readily by computer vision systems in many cases. These include flat objects viewed in two-dimensional silhouette and solid objects viewed by three-dimensional ranging systems. Semi-automatic programming is commercially available in the two-dimensional case (Machine Intelligence), and it seems straightforward to program either type of system from CAD data. Optical systems and components are also susceptible to automatic inspection, but this study did not encounter any automated batch methods.

Vision and electric probe testing are both being used on microcircuits and full-size circuit boards. These check for the presence of leads and components, sometimes being able to read labels (Westinghouse, Hitachi). Current techniques tend to be slow, but their combined speed and effectiveness make them attractive alternatives where quality is essential.

Automatic inspection of welded joints is currently done by merely mechanizing current manual methods. The customary magniflux or ultrasonic probe is machine-carried along the seam to be inspected.

Novel uses of sound spectral analysis to inspect assemblies include testing for proper gear noise levels, bearing operation, or the presence of foreign objects within assemblies (General Electric). These tests tend to be rather specialized, so their rapid programmability for one-time use on a small batch is unclear.

Automatic programmable inspection of solder joints on circuit boards is the focus of much current research. Methods under study include reflected light, structured light (Hitachi), heat dissipation (Vanzetti Systems, Inc.), and laser analysis of joint shape.

Automatic functional testing of complex assemblies is limited to carefully prepared test cells and preprogrammed apparatus (GenRad). Good examples are jet engines and avionics equipment. In both cases, engineers must prepare the test protocols and program them into the test equipment. In the case of avionics, the classic problem of missing technical data occurs. The test equipment is created after the avionics items are delivered, when functional data are meager or absent. Much reverse engineering, taking several months, is necessary before a useful test program can be written.

To make automatic testing of parts and assemblies feasible for POD will require that (1) original part or product data include test data and criteria in machine-readable form, and (2) a programming language or languages be created for test equipment that will survive the technological evolution of such equipment.

System Architecture and System Control

Manufacturing systems are integrated arrangements of manufacturing equipment such as metal-cutting or assembly machines. The layout of these machines, their transport equipment, and their control equipment, constitute the architecture of the system. For mass production, the accepted architecture is the line with work moving regularly and successively from one station to the next.

The main feature of batch and POD production is that this regularity and repeated sequence is inappropriate. Different items require different operations and different sequences. This means that transport and scheduling of jobs are vital activities in operating batch systems efficiently.

The current approaches in system architectures range from general systems with little regard for the product's characteristics to specialized systems with major coupling to the characteristics of the product. Some systems are built from collections of commercial stand-alone machines linked with a conveyor, while others are unique proprietary configurations of tools, motion devices, and conveyors.

Current FMS's are in the category of linked-together, stand-alone machines. Appropriate machines are carefully selected by computer analysis to meet the production and schedule requirements of a known set of workpieces. The systems are thus general and efficient within that class of workpieces, but may not accept a new piece without loss of efficiency. Their applicability to POD at present, therefore, depends on careful selection of workpieces.

In Japan, new types of machine tools are being designed that can work on a wider range of part types. This is accomplished by making the machines modular and reconfiguring them as the need arises. Repairs can also be made by switching modules. No commercial use of these has occurred, but tests are expected in the next year or so.

Modular assembly machines, capable of rapid reprogramming, are being built in Japan. They are most applicable to products designed in advance for automated assembly. Reprogramming involves attaching new tools to a frame (Sony). The bottleneck for POD would thus be rapid creation of the tools, unless design for assembly included interfacing to a predefined and limited set of tools.

The correct architecture for POD cannot be determined at this time, both for strategic and technical reasons. The strategic issue is how specialized POD facilities should be, because existing architectures favor specialization of product size, process methods, product materials, and so on. Thus, near-term strategies require finding similar types of POD parts and directing them toward an appropriate centralized facility. The facility would benefit from a steady flow of similar parts and could produce efficiently at reasonable cost. The order would have to travel and

wait its turn when it arrived, however, and the finished part would have to travel back, adding to the delay.

To make POD facilities more local and close to the point of need requires architectures geared to more diversity, even novelty, of the parts. Up to now, there has been little pressure on industry to create such systems. Existing architectures and machines would have poor efficiency in the face of a diverse incoming parts stream.

Summary of Findings

Procurement

The current procurement system must deal with literally hundreds of thousands of items that are potential POD parts. These range from simple single pieces to complex assemblies. The data that describe these items are often scant, scattered, or missing. Determining the correct identity, order history, and true need for an ordered part can be difficult. A POD system, like the current procurement system, must make basic decisions on buying, substituting, or making a needed item, and allocating a make decision to the most appropriate POD facility. These findings indicate that data storage, data handling, and decision making will be important POD functions. The data, however they may be obtained, must cover design, materials, fabrication, assembly, and test operations.

Technology

POD requires efficient production facilities that can make an item never ordered before that may never be ordered again. This degree of programmability exceeds what current technology offers, but usually in degree rather than in kind. By sacrificing efficiency or generality to some extent, the Navy can have limited near-term POD demonstrations in areas like metal-cutting, lens making, electronic assembly, precision instrument assembly, and electronic inspection. To extend the range of diversity will require:

1. Procuring parts with complete data packages.
2. Creating design rules for "dasign for POD automation".
3. Establishing substitutability data bases for parts to save design or fabrication time.
4. Improving the speed of creating molds, tools, jigs and fixtures.
5. Creating automatic process planning systems.
6. Establishing integrated facilities comprising design, fabrication, assembly and test with a common data base.

7. Making systems whose machine types and architecture are better suited to diverse parts streams.

8. Improving process knowledge in assembly, finishing, and inspection so more steps can be automated.

9. Creating programming languages for all phases of manufacturing that can combine process knowledge and workpiece design requirements into programs for the machines.

The next section turns these findings into recommendations for demonstrations, implementation strategies, and research programs.

PART 7. CONCLUSIONS AND RECOMMENDATIONS

STATE OF THE ART VERSUS THE NAVY'S NEEDS

Implementation of POD will require a four-prong attack based on dividing parts into current and future parts, and dividing again according to whether or not the parts' manufacturing processes are well enough understood to be automated. This strategy is based on comparing the state of the art in automated programmable manufacturing ("Part 6. Findings" on page 29) to the Navy's supply situation ("Part 3. The Need for POD" on page 17 through "Part 5. Non-Technological Issues That Make the Current Supply Situation Difficult" on page 26).

Current programmable manufacturing systems (design, fabrication, assembly, test) function best when presented with machine-readable and complete data packages that describe standardized designs. The standards cover sizes, dimensions, tolerances, fasteners and materials, and other things. These tend to limit the variety of items presented to the systems. More sophisticated companies have also designed their products for automation. All the process steps are well understood and described quantitatively. Unnecessary parts, part shape features, and fasteners have been eliminated. Assembly takes place by stacking the parts. All of these features help make fabrication and assembly faster and cheaper, using simpler machines.

Current programmable manufacturing systems function most efficiently when presented with batches of only a few kinds of parts that do not differ from each other very much. Overall production volume of these part classes is then high enough that the system sees practically a continuous flow of similar or gradually changing parts.

Compare the suitability of this art to the Navy's supply situation, and several contrasts appear. The typical Navy part is not backed up by complete machine-readable data, but by incomplete or incorrect paper-based data. Parts were designed well before Design for Automation began to be used. Standardization, even on traditional equipment like compressors and valves, is inadequate. Finally, in the POD environment, manufacturing systems might be presented with one unique part after another, rather than the relatively narrow range they are used to.

These are the gaps that must be addressed in order to make POD a reality.

IMPLEMENTING POD FOR FUTURE PARTS

Let us first consider the parts of tomorrow and see how they might be defined to mesh with a coordinated POD system to provide them. We must define a "POD part" when it is initially procured so that when replacements are needed, the POD system will be ready. A POD part must be provided with its own machine-readable data base describing how it is made and used. This cannot be a complete data package because experience has shown that this will be too bulky and costly to maintain. (Even irreplaceable data brought back from the Moon is now unsupported.) Data bulk and cost can be reduced by:

- Standardizing designs and referring to the standard rather than reproducing it.
- Stating that the design is merely a modification of another design and providing just the modifications.
- Coding the data compactly.
- Standardizing process steps and again referring only to the standard.
- Employing a knowledge base so that some design or process features can be included "by implication" based on other steps or intended use for the part.

Second, following a thorough survey of current and future types of parts and processes, we must define "POD factories" for generic classes of parts, within the main types -- metal, nonmetal, electronic, and optical. These factories should be sized to meet estimated needs for part classes, which hopefully will be easier than estimating needs for individual parts. Near-term factories should be planned to operate on the limited part range and flow line basis of today's successful commercial plants. This means locating them centrally and concentrating Navy-wide needs on them.

For longer-term implementations, the range of applicability of factories must be broadened while their dependence on a steady flow must be decreased. This will require especially great efforts in design standardization and design for automation, plus advances in rapid process planning and fabrication of jigs and fixtures. The resulting simplifications and overhead reductions will enable the added variety of parts to be absorbed efficiently. Lower break-even production volume will allow POD factories to be smaller and located closer to forces afloat.

Third, a "POD decision logic" is needed to help identify parts as POD parts early in system procurement and to deal with incoming orders for parts. A major role for this logic is to quickly recognize when the POD system should be mobilized to meet the need for a part. Just as is done in the supply system today, the order history of the part must be reviewed.

the best quantity to order must be determined, and the best factory, based on suitability and availability, must be designated. Since using or modifying a substitute is usually faster, these avenues must also be explored. The system will grow over time in its ability to make these decisions if the data packages on individual parts are designed to allow rapid comparisons.

These three components -- POD parts, POD factories, and POD decision logic -- are all needed to implement the POD system. The result will be a new kind of technology called Data-Driven Automation, in which everything required from order processing to final packaging can be described by machine-readable data.

IMPLEMENTING POD FOR CURRENT PARTS

The main characteristic of current parts is the lack of complete data, meaning that POD for such parts will require creation of "Reverse Engineering Centers". The amount of reverse engineering needed will vary from one part to the next. We can distinguish several levels of available information, arranged from the least to the most complete:

1. A functional description as vague as "a two-inch diameter by two-inch long bronze bearing".

2. A sketch of the part with approximate dimensions, possibly including a functional description.

3. A damaged example part.

4. A statistically unrepresentative or representative sample of used of unused parts.

5. Blueprints, which customarily include materials lists, and possibly include reference to MIL standards.

6. Machine-readable instructions for numerically-controlled machines and processes.

Naturally, as the information suite becomes more complete, current technology has more to offer. At the moment, there is nothing except human intervention at levels 1 through 4 and, with a few exceptions, nothing in level 5. Progress in this area, therefore, requires research or, in some cases at level 5, development. The issues and state of the art may be summarized in Table 8 on page 47.

The intellectual issues in reverse engineering are formidable. As indicated in Table 8 on page 47, they are the same as for the original engineering that created the part, although less is now known about the

Table 8. Technological Options When There is Missing Information (Part 1 of 2)

If We Have Only:	Then the Main Things We Do Not Have Are:	What We Do About It	State of the Art in Automation	Ease of Making Part, Irrespecitve of Automation
Functional Descripton	Concept & technical specification.	Make / buy decision. Conceptual design Human experts	Zero	As difficult as for original part, but less information available.
Sketch	• Dimensions • Tolerances • Finishes • Materials/ properties • Reference surfaces	Detail dsgn engineering drawing	Some aids for mechanical drawing	Same as above
Statistically representative sample of unused parts	Some tolerances especially relating two or more features. Reference surfaces.	"Shoot for the middle"	Some aids for automatic gauging and statistical analysis	A "simliar" part is fairly easy to make
Statistically unrepresentative sample of unused parts including 1 part.	Tolerances	Make several rather than one. Engineering Similar to Sketch	Similar to Sketch	"Similar" part fairly easy to make, but it may fail right away

context of the part's use and the tradeoffs that went into determining its specifications. A part generated by reverse engineering could resemble the original in every determinable way, given the state of incomplete information, and yet fail right away when installed.

It seems reasonable, therefore, to establish the research priorities in the order 5, 4, 3, 2, 1 in the above list. If this is done carefully, each level can build on the accumulating results. The aim, simply stated,

Table 8. Technological Options When There is Missing Information (Part 2 of 2)

If We Have Only:	Then the Main Things We Do Not Have Are:	What We Do About It	State of the Art in Automation	Ease of Making Part, Irrespecitve of Automation
Damaged Part	Some dimensions Tolerances Reference surfaces	Same as for Sketch	Same as Sketch	Same as above
Print	Process plan for cuts that yield the tolerances	Manufacturing Engineering Group Technology	Some automa- process planning for really simple parts.	Done every day. The easiest.
N/C Tapes	Process information other than cuts, e.g. heat treat, materials	Engineering and Mfg. engineering	Use of the tape itself is automated, but that is all.	

is to codify and rationalize the basic steps in designing and manufacturing certain classes of items. At levels 3 through 5, this means codifying potentially routine steps, whereas at levels 1 and 2, it means capturing knowledge, especially knowledge about topics that do not refer to the part itself, but rather to its function and surroundings. In other words, we are trying to capture engineering. The results of this research would be widely used and extremely valuable because little of it depends on the fact that the goal is reverse engineering. As noted in the previous section, commercial needs are the source of current progress in these problems in such as parts as IC's and shafts.

Along with these research results will come, at each level, quantitative understanding of what qualifies a part at that level. That is, we will be able to classify a part accurately as "having an information suite of level x". This will establish a useful standard and will allow the correct level of reverse engineering resources to be applied to its recreation.

Several consequences of this classification can be identified. First, it may be a way of reducing the amount of data that needs to be procured with future "POD parts". That is, if there is enough design stand-

ardization and cross referenced data bases, one could describe a part rather well at level 2 with adequate reference to standards and to similar designs that are represented at level 5 or 6. Over time, we can expect the abilities of the Reverse Engineering System to strengthen the POD System for Future Parts.

Second, it allows a careful definition of just what technology is needed to recreate a particular part.

Third, it brings into focus and creates better overall understanding of what engineering is and what knowledge and intellectual steps are really needed to describe a part.

OTHER RESEARCH PROBLEMS

Codifying and standardizing engineering, though extremely difficult, will be sufficient only for parts where there exist quantified and reproducible design and manufacturing methods. Where these are lacking, the parts themselves must be the subject of research. Such parts' manufacture currently requires luck or "art". Ultra-quiet bearings and some types of semiconductors and precision instruments are examples.

SUMMARY OF IDENTIFIED RESEARCH NEEDS

The research needs are categorized by general issues and specific needs. The general issues are of equal concern whether the parts are "parts" or assemblies and whether they be metal, non-metal, electronic, optical, or whatever. Special needs are cross-indexed here to the page that defines both the problem and the research need.

1. Data processing:

    a. Search methods for finding similar designs, materials, and processes.

    b. Compact data coding.

2. Design:

    a. Representing design essentials in coded form to allow comparison with other designs.

    b. Design for automation, including alternate processes and part morphologies suitable for different production quantities.

c. Capturing part function knowledge and engineering knowledge.

d. Creating a theory of substitutability for materials, processes, and parts.

e. Creation of rapid, automatic process planning.

3. Fabrication:

a. Rapid creation of tools, dies, molds, and fixtures.

b. Extension of programmable manufacturing into more part variety.

c. Creation of programmable processes in molding, forging, and bending.

d. Programming languages that reflect process knowledge and part design specifications.

4. Assembly:

a. Improvement of fundamental process understanding.

b. Creation of a theory of "assembly to meet a specification".

c. Programming languages that reflect process knowledge and assembly specifications.

5. System Architecture:

a. Architectures with better flexibility and design techniques to create them.

6. Inspection and Test:

a. Programming languages and techniques that reflect product function and systematic testing methods.

CROSS-INDEXED LIST OF IDENTIFIED NEEDS IN TECHNOLOGY TO SUPPORT POD

The list briefly names specific technological items identified in this study that would support POD, and indicates the page on which the items is discussed.

Page	Item
25	Theory of minimum data that need be stored about a part from which the completed data package can be created.
25	Expert systems to recreate data packages from available clues or from optimally configured minimum datasets.
27	Producibility research on difficult parts like quiet bearings.
31	Group technology, AI, or Expert Systems to search data bases for similar parts.
33	Data base of fabrication methods, costs and appropriate production volumes.
35	Coding methods for storing the essentials of a design so that its substitutability can be assessed.
35	Methods of designing new technology electronics to substitute functionally for old technology parts.
36	Automatic, rapid creation of process plans.
36	Improved theory of des for manufacture and design for assembly, especially for the low-volume POD environment.
36	Extension of FMS technology to POD production volumes.
37	Rapid creation of dies and molds.
37	Rapid creation of molds for advanced powder metal fabrication.
37	Systems for creating integrated circuits in quantity one directly from design data without masks.
37	Economical automatic batch assembly in low volumes.
38	Clean, accurate assembly systems for precision products.
38	More flexible tools and fixtures for assembly.
39	Goal-oriented programming languages for flexible fabrication, assembly, and test systems.