COMPLEXITY, RELIABILITY, AND DESIGN: MANUFACTURING IMPLICATIONS

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FOREWORD

This paper appeared previously as an IIASA Working Paper, WP-87-94. The ideas in it have been evolving for several years. In fact some of the ideas discussed in this paper appeared in the original in-house proposal for the Computer Integrated Manufacturing (CIM) Project in 1985, and the author still contends that the growing complexity of manufacturing is one of the most powerful *drivers* of the worldwide trend towards computerization in manufacturing. The ideas were further developed while the author was at IIASA from 1986–87.

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Complexity, Reliability, and Design: Manufacturing Implications

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This paper presents some interesting and new ideas about the nature of the forces driving the worldwide trend toward flexible automation. It suggests, in brief, that the demand for computer-integrated manufacturing (CIM) arises from what Nathan Rosenberg has termed a "mismatch," that is, a problem that was created, in effect, by technological progress itself. In this case the "problem" is that defects in manufacturing have become intolerable. The reason for this is that demand for higher and higher levels of product performance, over many decades, has required orders-of-magnitude increases in mechanical complexity, on the one hand, and higher precision, on the other. To satisfy these high standards requires a level of error control that increasingly precludes the use of human workers in direct contact with workpieces as they move through the manufacturing system. This paper explores four related hypotheses, as follows:

- *That the human "error rate" is inherently large and cannot be reduced to (or nearly to) zero even under the most favorable conditions.*
- *That "high performance" in a product tends to require a high degree of precision and complexity in the design and manufacturing process. This tendency can be seen most clearly over time.*
- *That defects can be thought of as lost information (just as errors in accounts or messages) and that error-detection and error-correction techniques from communications theory may be appropriate tools for management.*
- *That defects can best be eliminated in manufacturing by adopting the "monolithic" concept that has been so successful in electronics.*

1 INTRODUCTION

According to the poet Alexander Pope "to err is human; to forgive divine." This may be a truism in the moral sphere, but it is only half true in the production context. Modern manufacturing, in particular, is unforgiving of error. Exact figures are lacking, but a surprisingly large fraction of the cost of production is directly attributable either to the prevention of avoidable defects (e.g., quality control), their detection (e.g., inspection), or their elimination after the fact (repair, rework). Informal estimates from various sources suggest that quality control in all its ramifications (design, inspection, scrap, rework, repair, and warranty) may account for 40% of total costs, or even more. The importance of this figure is doubled when one considers that roughly 50% of the sales dollar goes for purchased materials which *also* include a large quality cost component. From another perspective, the celebrated Japanese superiority over the U.S. in manufacturing may stem largely from a longer established Japanese recognition of this problem, coupled with widespread commitment to ameliorate it.[1]

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[1] Xerox Corp. offers an interesting example. Recently Xerox announced with some pride that its parts reject rate is now down to 1.3 per 1000 (from

2 THE INTRINSIC HUMAN ERROR PROBABILITY

Ergonomists and human factors engineers have traditionally approached the "error" problem by "explaining" errors by machine operators in terms of poorly designed man-machine interfaces. Their focus has been largely on redesigning this interface to increase system reliability. This is understandable and desirable, but it tends to obscure a key fact: that even with the best-designed man-machine interface, the probability of human error can not in practice be reduced to zero except, of course, by decreasing the rate of useful output to zero also. Among the fundamental reasons why humans are inherently error-prone is the inability to maintain a permanent state of concentrated attention. Subconscious, autonomous processes are necessary for the functioning of the organism. Heart and lung operation are only two examples. Limbs must move or twitch from time to time or they will cramp. Eyes must blink occasionally to maintain external lubrication, itches must be scratched, throats must be cleared, and so on. These biophysical functions occasionally interfere with conscious mental activities and cause lapses in attention.

Factors that tend to increase the error-rate above the theoretical minimum rate are known to include:

- emotional stress
- physical strain and discomfort
- interference (noise)
- poor illumination
- information load (overload)

The influence of these factors on human performance and error rate is discussed in a number of ergonomics and human factors monographs and research reports, such as Meister [1, 2] and Swain and Guttmann [3].

The general relationship between information processed (input) and information transmitted (output) has been discussed extensively in the ergonomics and psychology literature, especially in the context of estimating maximum output rates. To summarize a great deal of ergonomic data in a few words (see reference [13] for a more extensive review), the amount of information "lost"—which is equivalent to the error rate—rises extremely sharply as the input rate approaches 10 bits/s. This can be interpreted, without straining the facts, as a straightforward problem of information overload, or saturation. The overload hypothesis would seem to offer a partial explanation, at least, of the extremely high propensity of humans to make errors in emergency situations, noted by Swain and Guttmann [3]. More relevant to this paper, however, is the fact that there is apparently a minimum error rate for human workers, even under ideal conditions.

As a matter of historical interest, the major justification for automatic computation from Charles Babbage's time onward, is the fact that mathematical tables computed by humans are notoriously full of errors (mostly of transcription). According to one historian of computers, speaking of Babbage's motivation:

> None of these tables could be trusted, and many an experiment was undermined when the scientist discovered an error in a table he had relied on. One writer of the time, Dionysius Lardner, discovered that mistakes originally committed by European mathematicians in 1603 cropped up 200 years later in Chinese manuscripts. Government tables used for accurate navigation had more than 1100 errors and seven folio pages of corrections. The corrections needed corrections [4, p. 23].

The problem only got worse, as mathematical tables were needed for more and more purposes. In the 1930s the Works Progress Administration (WPA) tabulated many mathematical functions (using people with hand calculators), but these tables were full of errors—mostly mistakes in copying. The tables were later recalculated by Howard Aiken's Mark I Electromechanical computer, to eliminate these errors [5]. Recent Department of Defense studies indicate an average of 1 error per 30 manual data entries. By comparison, optical scanners reading bar codes make 1 error per 3,000,000 entries [6]. Roughly speaking, electronics technology is now five orders of magnitude less error-prone than human workers.

There is no experimental evidence, nor any theoretical reason, to suppose that the human error probability (HEP) can ever be reduced to zero (or even very close to zero) in any practical case. Indeed, Meister himself remarks that "errors are inevitable unless thare are no tolerance limits" [9]. In repetitive jobs involving simple decisions of the yes/no type the minimum (HEP) appears to be of the order of 10^{3}.In other words, the error rate generally exceeds 1 per 1000 opportunities.[2] HEP may be much greater if working conditions are not ideal. However, further exploring of the relationships between various aspects of working conditions and HEP will not be done. It is, however, worthwhile to recall that experiments show that the error rate begins to rise rapidly as information output approaches about 8 bits/s. To achieve a low HEP, other factors being favorable, the information processing load must be kept well below the workers' capacity—probably well below 2-3 bits/s.

3 PRECISION, COMPLEXITY, AND PERFORMANCE

With regard to the second hypothesis—that high performance demands precision and complexity—a few random examples will have to suffice to make the point, since no scholar (to my knowledge) has ever explored the question in depth. Indeed, the proposition becomes almost self-evident from the superficial examination of early machines. Invariably, they are quite simple and crude by comparison

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8 per 1000 a few years ago). However, its Japanese competitors have achieved reject rates less than 1 per 1000 (*New York Times,* Nov. 16, 1985). Since the early 1970's, when its exclusive patent protection expired, Xerox's market share of the plain paper copier market has fallen to about 36% while Japanese companies like Ricoh and Canon totally dominate the low-cost segment of the market. A recent study of the room air conditioner industry found even more startling differences: Japanese firms achieved assembly line defect rates almost 70 times lower than U.S. firms, on the average, while among U.S. firms there was a best-to-worst range of 7 per 100 to 165 per 100. The best Japanese producers achieved failure rates between 500 and 1000 times better than the worst U.S. producers [12].

[2] This number comes from a recent publication summarizing the literature [3]. An earlier book by Swain suggested the range 10^{4} for HEP. Evidently recent evidence tends toward the larger figure. However, to be conservative the lower figures should be considered as a remote possibility.

to their modern counterparts. One early weight-driven clock, for instance, used eight gear wheels, an escape wheel, a crank (three parts) a foliot balance (five parts), a verge (three parts), six axles, two pointer hands, a face plate, and various frame parts, pins, and so on [7]. Later versions introduced second-hands, adjustment mechanisms, self-winding mechanisms, chimes or alarms, calendars, jewel-bearings or ball-bearings, and so on. Surface tolerances for early clock parts were seldom better than 1:100, and time-keeping accuracy was correspondingly low. By contrast, modern mass-produced electronic watches achieve time-keeping precision of the order of $1{:}10^6$ or even better. This level of performance obviously requires a correspondingly high order of precision in the manufacturing process.

Tools provide another illustration. Early hand tools, such as hammers, tongs, or shears, typically involved two or three parts. A late 19th-century hand-drill (brace and bit) with a chuck accommodating various drill bit diameters involved 20 parts. A push-type reversible hand-held screwdriver with an adjustable chuck utilized 30 or more parts. The addition of an electric drive motor would, of course, add another 50 or so parts. A handsaw had 3 to 5 parts. A motor-driven chain saw of current vintage has several hundred parts, excluding the motor. Moreover, each of these parts is made with a level of precision in terms of composition and surface finish far beyond the capabilities of 19th-century manufacturers.

Vehicles provide the clearest evidence of the trend toward precision combined with complexity. Horse-drawn taxicabs of the mid-19th century consisted of a springless chassis with an enclosed body for the passengers; two doors and a simple bench for the driver, two iron axles; solid iron sleeve-type bearings; four relatively simple spoked wheels; and tiller-type of steering mechanism. The wheels were already moderately sophisticated, with 8 to 12 spokes and steel rims. The introduction of the safety bicycle in 1885 brought a quantum leap in several areas, including the lightweight wheel, gearshift, chain-sprocket drive, and ball-bearings. Each of these devices is highly complex. Thus an 1885 Rover safety bicycle required more than 500 individual parts.

The earliest motorized vehicles (the 1886 Benz) added a small one-cylinder gasoline engine with a chain and sprocket drive mechanisms to a three-wheeled carriage using bicycle wheels.[3] Benz's one-cylinder engine was a direct adaptation of Otto's successful spark-ignition gas engine (1876) for gasoline. In 1893 Maybach invented the carburetor. The steering wheel replaced the tiller after 1901 and the steering knuckle followed in 1902. Differential gears were introduced to allow the rear wheels to turn at different speeds.

Other features adding greater convenience, power or ability—at the price of added complexity—included the pneumatic tire (now a very complex product in itself); springs and shock absorbers; multicylinder engines; the electric self-starter; acetylene headlamps followed by electric headlights; batteries; dashboard instruments; more controls—such as the throttles and chokes—water cooling; forced feed lubrication; mechanically operated valves; magneto's (later generators and alternators); hydraulic brakes; synchromesh transmission (1914), later followed by automatic transmission; safety glass; power brakes; power steering; radio; air conditioning; emission controls; and so on.

In fact, the modern car is a relatively complex piece of machinery, involving as many as 30,000 component parts. Of these, only a few percent are actually manufactured by auto companies themselves.[4] As many as 30% of the total number are electrical or electronic, and this percent is rising rapidly. Most parts have at least three distinct surfaces, while many parts (including threaded connectors) have 8 to 10 surfaces. A few parts, such as gear-wheels, pistons, crankshafts, and camshafts, have a large number of surfaces. Thus a car probably has 60,000 to 80,000 distinct oriented surfaces.

Yet autos are relatively simple compared to aircraft, helicopters, diesel-electric locomotives, transfer lines, electric generating plants, computers, and other capital goods. A large steam turbine involves 350,000 parts. A Boeing 747 includes roughly 3.5 million parts. The space shuttle is probably the apogee of mechanical complexity (with unfortunate consequences); it probably involves on the order of 10 million individual parts. See Fig. 1.

Quite apart from the large number of distinct parts in a complex modern product, a manufacturer today typically offers a large number of different models of each basic item. For example, Westinghouse Electric Co. manufactures over 50,000 different steam turbine blade shapes alone. A

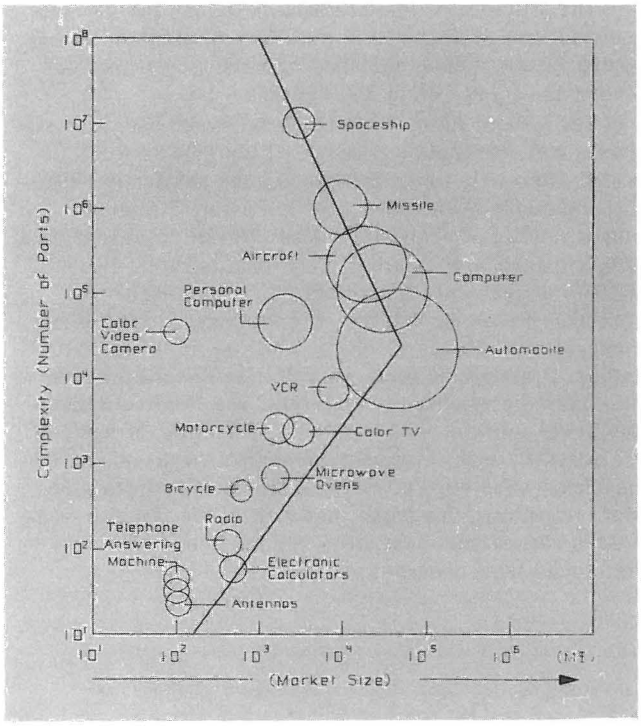

FIG. 1. Major U.S. durable goods industries (Source: Nagayama and Funk, 1985 [8])

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[3] One later simplification was the introduction of pressed solid metal wheels, in place of complex bicycle type wheels. This became possible because of the development of new metal-working processes.

[4] Virtually all of the simple parts (bearings, pistons, rings, and fasteners) are purchased, as well as most electrical parts, rubber, glass and many complex subassemblies such as brakes, transmission, hydraulics, and emission controls.

major electrical connector manufacturer (AMP) produces 80,000 different connector models. The IBM Selectric™ typewriter (with 2700 parts) could be made in 55,000 different models.

4 THE RELATIONSHIPS BETWEEN COMPLEXITY, ERRORS, AND DEFECTS

It is axiomatic among industrial engineers that

> product defects, failures, and accidents are invariably the result of human error... Since the worker is merely part of the production system, which has been consciously and deliberately designed, it stands to reason that those who designed the system are responsible for any inadequacies occurring in it. [9]

This view, of course, put enormous emphasis on human factors and on systems engineering. The role of human factors engineering is undoubtedly important and often underrated. Indeed, HEP for a given activity in a given situation can often be sharply reduced from current levels, at modest cost, by eliminating certain factors that tend to increase errors. On the other hand, the claim "that errors can always be eliminated by better systems design" [9] is not scientifically justified, except in the special case where human workers are eliminated. The basic reason is that the human worker himself is not subject to redesign. Hence any system involving human workers is inherently subject to human limitations.

Of course, many errors in manufacturing are caught by multilayer inspection systems. An average human-based system will catch and eliminate 70–80% of the defects per inspection. With a hierarchy of several inspection systems, the probability of a defect being undetected can be reduced to perhaps 2 in 100, giving a theoretically achievable final rate (for defects embodied in the product) of the order of 10^{-5}.Of course, this is very low compared with the current defect rate of 10^{-2} to 10^{-3}. Nevertheless, it is not low enough, as will be seen.

Also, it must be recognized that, because of design redundancies and other factors, most (70–80%) defects do not matter much. For instance, spot welders in auto body plants are expected to make a certain number of bad welds. To compensate for this, designers simply provide for more welds than would otherwise be necessary. (Robot welders are more reliable than human workers and plants using robots can design for about 10% fewer welds). Hence the *critical* defect rate would be somewhat lower than the basic defect rate.

All things considered, it seems possible that critical undetected defect rates might be reduced to the order of 10^{-5} (0.0001) or perhaps even 10^{-6} (0.000001). But these rates are hypothetical. They are far lower than actual current industrial performance. (A "good" reject rate today is around 0.1% or 1 per 1000). Nevertheless the costs of overdesign (or "gold-plating"),[5] multiple layers of inspection, debugging, rework, maintenance and, above all, the heavy costs associated with catastrophic parts failures that occur after a product is in service make human errors increasingly intolerable in manufacturing. The direct cost of error control (e.g. inspection) is only the tip of the iceberg. When the bureaucratic structures and accounting procedures made necessary by the tendency of humans to err are also considered, the "real" cost of error control in a modern manufacturing firm may be much higher. This problem is particularly burdensome where high levels of product performance are desired, requiring high degrees of complexity in the product design, or in mass production situations.

According to Meister [9], a single large U.S. auto manufacturer provides about 3 billion opportunities for human error per day in assembly operations alone. Even in the most optimistic case, assuming a probability of undetected serious error of 1 per million opportunities an auto manufacturer would have to expect about 3000 *serious* undetected production flaws per day, or 1 in 3 cars. The actual number of assembly defects in autos is almost surely much larger under present conditions. In fact, consumer surveys have repeatedly noted, on the average, several defects per car, although most are minor.

The dilemma faced by manufacturers of complex products can perhaps be understood more clearly from a simplified "model" of the production process. Suppose the final product involves components of N distinct part types, each of which involves a sequence of unit operations. The total number of actual operations involved is, therefore,

$$M = \sum_{i=1}^{N} n_i m_i \tag{1}$$

where n_i is the number of *components* of the i^{th} part type and m_i is the number of *unit operations* needed to produce the i^{th} part type. Each unit operation is an opportunity for error and a decision point where a hypothetical inspector makes a yes/no decision. ("Yes" means the operation was carried out correctly, while "no" means it was not.) If the result of the inspection is positive ("yes") the workpiece presumably moves on to the next operation. If the results of the inspection are negative ("no") the workpiece is presumably rejected and discarded or diverted into a "rework" line of some sort.

Suppose the a-priori probability of error in the j^{th} unit operation of the i^{th} branch (or part type) is known to be p_{ij}. We can assume p_{ij} is a small number, of the order of 10^{-8}. Assuming perfectly reliable inspectors, the a-priori probability of a "yes" at the ij^{th} inspection point is $(1 - p_{ij})$. The probability of making one flawless component of the i^{th} type, with no parts rejections or need for rework is, therefore,

$$u_i = \prod_{j=1}^{m_i} [1 - p_{ij}] \tag{2}$$

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[5] The high costs associated with overdesign are particularly evident in military procurement. So-called military specifications (or mil specs) typically lead to unit costs from 10 to 100 times greater than comparable products designed for the civilian market. Yet military hardware is notoriously unreliable. This is surely attributable, in part, to the attempt to achieve maximum possible performance which, in turn, leads to extraordinary complexity of design. On the other hand, military equipment is often made in small batches unsuited for automation, thus simultaneously maximizing opportunities for human error.

where u_i is the probability of making the i^{th} part successfully.

It follows that the probability u of manufacturing *all* the components flawlessly is

$$u = \prod_{i=1}^{N} \left(\prod_{j=1}^{m_i} (1-p_{ij}) \right)^{n_i} = \prod_{i=1}^{N} u_i^{n_i} \tag{3}$$

For purposes of argument, suppose that there is a lower limit on p_{ij}, namely

$$\eta \leq p_{ij} \qquad \text{for all } i, j \tag{4}$$

It follows immediately that

$$(1 - p_{ij}) < (1 - \eta) \tag{5}$$

for all *i, j* and, therefore, the probability of achieving "zero defects" is bounded, viz.

$$u \leq \prod_{i=1} (1-\eta)^{m_i n_i} = (1 - \eta)^M \tag{6}$$

where M is defined by equation (1).

Now equation (6) can be approximated in two different limiting cases, depending on the product $M\eta$, the number of "opportunities" for an error times the *a priori* probability of an error per opportunity.

If $M\eta >> 1$

$$\begin{aligned}(1-\eta)^M &= \exp[M \log (1-\eta)] \\ &= \exp M (-\eta - \tfrac{1}{2}\eta^2 \ldots) \cong \exp(-M\eta)\end{aligned} \tag{7}$$

But if $M\eta << 1$

$$\begin{aligned}(1-\eta)^M &= 1 - M\eta + 1/2M(M-1)\eta^2 - \ldots \\ &\cong 1 - M\eta\end{aligned} \tag{8}$$

In other terms, if opportunity multiplied by probability of error significantly exceeds unity, the probability of achieving a product with zero defects (without many layers of inspections and rejections and much rework) is essentially zero. Consequently quality control and rework must inevitably constitute a large fraction of the costs of any complex product. Since inspection itself is subject to human error, complex systems manufactured, maintained, and operated by humans are statistically certain to fail with some regularity. (The reliability problems of the U.S. space shuttle illustrate this point perfectly).

The production system can be regarded as a noisy channel of communication where the final product (or service) is, of course, the "message." Errors in manufacturing certainly constitute a kind of information loss or "noise," with humans themselves constituting the major source of noise in the system. The reduction or elimination of channel noise effectively adds useful information to the message. Since the number of inspection points (error possibilities) is defined as M (equation 1), it follows that the number of possible erroneous versions of the message is 2^M. Hence, the selection of one "correct" version requires exactly

$$H = \log_2 (2^M) = M$$

bits of information per unit of final production.

Taking a clue from communications engineering, there are two possible strategies for increasing the signal-to-noise ratio and ensuring correct transmission of the desired message through a noisy channel. One strategy is to reduce the intrinsic noise level in the channel (e.g., by cooling it). The other is to code the transmission in such a way as to increase redundancy. In fact, it is relatively easy to design codes to automatically reveal (i.e., detect) certain classes of common input/output errors, such as transpositions. With slightly more sophistication, errors once detected can also be corrected automatically with a known (and fairly high) probability of success.

Both of these strategies are applicable in manufacturing. The first (noise reduction) strategy is primarily accomplished by removing humans from tool wielding and direct operational control over machines. Computers using solid-state electronic circuitry are far more reliable than humans, in the sense that computers have an a priori probability of error per opportunity much lower than humans. The worldwide trend toward automation can be regarded as an implementation of this strategy. The second (coding) strategy must be accomplished through product design. "Design for manufacturability" is nearly a cliché. However, just as coding can make many types of transmission errors self-revealing, many types of manufacturing errors reveal themselves automatically in the assembly stage. Of course, this is not a very clever solution. It is far more clever to weed out defects as soon as they occur in the process. Monitoring and screening devices of many kinds can be devised to react automatically to flaws of predictable types. It is part of the designer's function to facilitate easy error detection, if not to eliminate errors.

6 COMPLEXITY MEASURES AND COMPUTER-AIDED PROCESS PLANNING

An attractive approach to computer-aided process planning (CAPP) is to select a discrete-part manufacturing process mainly in terms of four or five key product variables: the *complexity* of the product, the *precision* with which the product must be made, the *lot* or *batch* size, and the *diversity*, or number of models in the "family." The physical size or dimension of the item is also a relevant variable. (This assumes that design and material choices are prespecified. See, however, reference [21].) Each of these variables affects the choice of manufacturing method, since labor, capital, and energy requirements differ among them. The greater the complexity of the product, in general, the greater the degree of automation required in the manufacturing process, to reduce the chances of machine operator error. The greater the precision required, again in general, the greater the degree of automation needed to reduce operator errors. The larger the lot or batch size (and the longer the expected life cycle), the less the degree of flexibility required in the manufacturing process and the equipment used. In fact, for a large enough manufacturing run, specially designed, single-purpose manufacturing machinery can be justified. On the other hand, the greater the diversity of models, the more flexibility is needed. In particular, where a family of parts is to be produced in moderate to small batches over many years, a flexible manufacturing system (FMS) will be indicated.

Evidently, these four (or five) key product variables interact in a complex way. Experience demonstrates that the choice of manufacturing methods is not a simple one, even when the complexity of the product, the precision, the lot size, and the product diversity are known. There are important advantages to be gained from incorporating empirical knowledge of manufacturing processes into an expert system, and making the system available to manufacturing engineers and managers.

It is perfectly clear that the costs of inputs (factors of production) determine the ultimate cost of the product. It follows that the optimum choice of technology depends, in principle, on these factors. One would expect some differences, for instance, between a high-wage country and a low-wage country. However, it is also clear that among the developed countries wage and capital costs are converging and technological choice in manufacturing is less and less strongly motivated by the differences that remain.

Measures of precision (tolerances) with which the product must be made, and lot size are already familiar and easily measured parameters to the manufacturing engineer and manager. However, a useful measure of product complexity has hitherto not been available. For complete assemblies one might, perhaps, use a surrogate measure, such as the number of discrete parts. An example of this approach is illustrated in Fig. 1. However, such a measure treats simple connectors and computer chips as if they were equivalent. In the mechanical sphere, there is a vast difference between the complexity (and cost) of "main parts" with many distinct surfaces vis-à-vis simpler ones. In actuality a small number of main parts accounts for somewhere in the neighborhood of half of all the value added in manufacturing (Fig. 2). Yet this is quite understandable in view of the fact that complex parts "embody" far more information than simple ones. In effect, information embodied in shapes is the logical measure of complexity. We propose to develop such a measure, since it is an important parameter in characterizing manufacturing processes. The complexity measure will be based on information theory, and will in effect measure the minimum number of bits of information needed to describe a part.

To consider how this might be done, suppose parts are classified according to one of the standard group technology systems [14–20]. For example, in the Opitz five-digit system (Fig. 3) a plain hexagonal machine nut would have the classification 30500. In this case the first digit implies a rotational part with deviation, $L/D \leq 2$; the second digit implies hexagonal overall shape; the third digit implies a rotational internal shape with screw threads; the fourth digit implies flat (unstructured plane) surfaces; and the fifth digit implies no auxiliary holes or gear teeth. The specification of a classification of this sort obviously reduces uncertainty about possible shapes and therefore has information content. (For our purposes a five-digit system is probably ample.) Of course, not all five-digit specifications are equally probable, but if they were (recalling that information is defined as the logarithm of the inverse probability of an event "coming true"), then the information content would be

$$\begin{aligned} \log_2 (10^5) &= 5 \log_2 10 \\ &\cong 16 \text{ bits} \end{aligned}$$

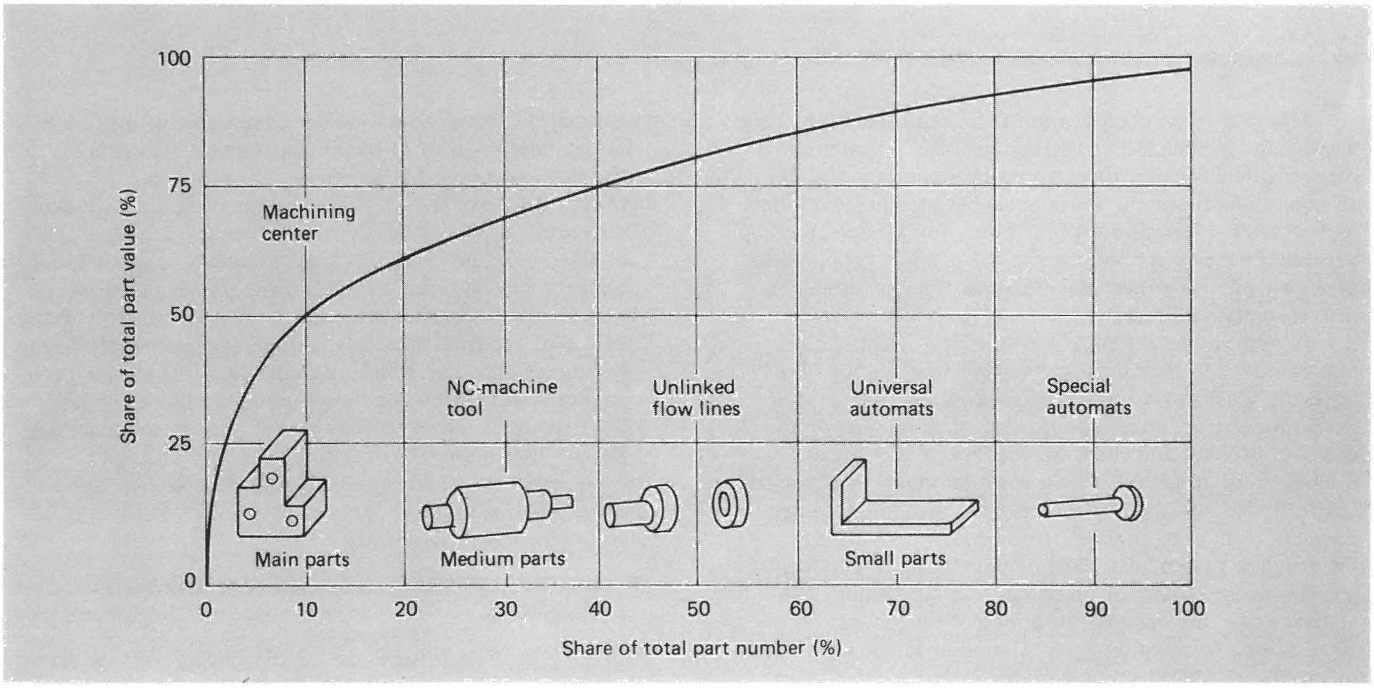

FIG. 2. Group technology and manufacturing systems

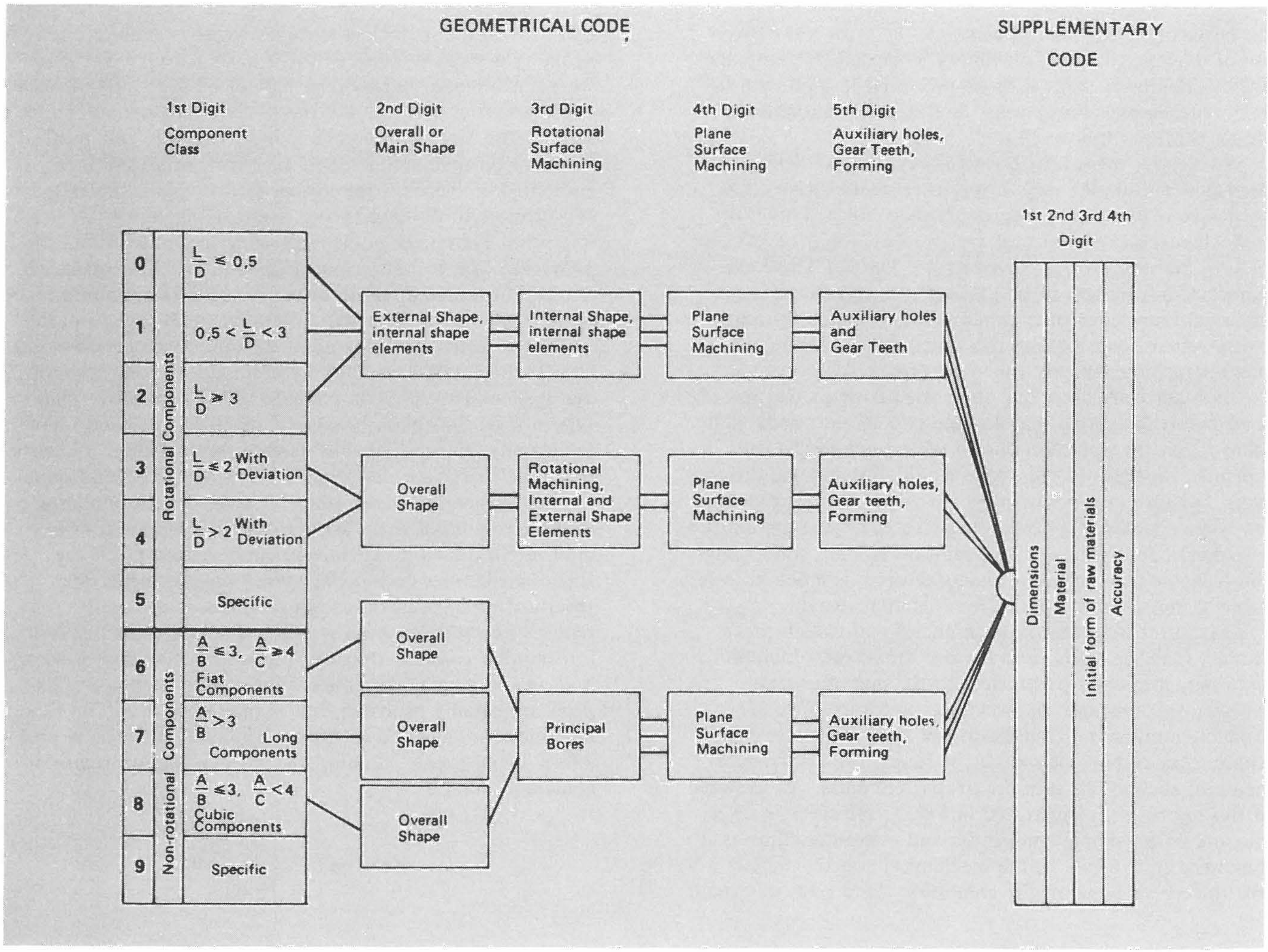

FIG. 3. Workpiece classification (Source: Opitz, 1970 [20])

Where a given classification is more probable than the average (as in the case of the hex nut) the information content of the specification would be somewhat less than 16 bits; and conversely, an improbable specification would have greater information value. Thus, for greater precision it would be necessary to estimate the a priori probabilities of each Opitz (or other) classification. This is, clearly, a task for empirical research.

In addition to the purely geometrical classification, dimensional specifications add further information. For instance, specification of the internal screw threads in the nut would require three parameters, including depth and width of groove, and pitch (or incline) of the thread. Also, the thickness of the nut L, the external diameter D, or the length of the one edge of the hexagon, and the internal diameter d must be defined. Altogether, there are 6 independent parameters, each of which can be assumed to correspond to 10 bits of information, (This assumes an accuracy of 1 part in 1000 or about 2^{10}. Note that $\log_2 1000 \cong 10$.) In addition there is another bit of information to specify whether a screw is right- or left-handed, thus making a total of 61 bits.

An important consequence of the concept of using information theory to define the complexity of a product is that *assembly is seen to be an information-destroying process.* Two parts that are to be assembled into a larger product will have two or more mating surfaces, each surface requiring several parameters to specify it. When they are assembled, however, the final assembly requires fewer parameters to describe it than did the unassembled pieces. In particular, information about the mating surfaces in the interior of the final assembly is destroyed during the assembly process. The use of information theory to define part complexity leads to a conclusion already known, namely that assembly is an expensive way of producing something. The fact that manufacturing engineers and managers choose other ways, whenever possible, encourages one to believe that information theory provides a fruitful way of defining product complexity.

7 MANUFACTURING TECHNOLOGY DECISION CRITERIA

One may suppose for purposes of discussion that the choice of manufacturing technology is made after the choice of design and materials is fixed. In reality, of course, the decision process is iterative, if not continuous. However, even an iterative decision process can be broken up conceptually into distinct steps, taken *ceteris paribus*.

With this simplification, the choice of technology will depend mainly on the following five major variables:

- complexity
- precision
- batch size/lot size/run length
- diversity
- mass or linear dimension

Complexity can be quantified, in principle, by the application of information-theoretic principles [10]. In broad terms, complexity is a measure of the geometrical two- or three-dimensional information "embodied" in a component. For multi-component systems complexity is the sum of shape information in each component individually, plus the structural information needed to assemble them. Obviously, precision, batch-size, diversity, and mass are measurable in a straightforward way.

In principle, the cost of production must depend on these variables, for a given capital and labor cost environment. With voluminous and reliable cost data for many specific products, a general cost function might be constructed econometrically.[6] However, this has not been done, because it would be enormously expensive to gather the data even if firms were willing to release them. An indirect approach is therefore desirable.

The first four variables—complexity, precision, batch size/lot size and diversity—can be considered as defining a "manufacturing hypercube" in a properly chosen parameter space. In different regions in the interior of that hypercube, different manufacturing processes will generally be optimal. These regions will be separated by "switching surfaces," such that as one crosses a surface, the optimal manufacturing method switches from one process to another. In reality, of course, these surfaces may not be sharply defined. In principle, however, one can think of such switching as dividing the regions of the hypercube from one another. Each connected region in the interior of the hypercube will be divided from all other regions by a set of switching surfaces, and within a particular region, one would expect a specific manufacturing process to be optimal. Three "cuts" of the hypercube are illustrated in Fig. 4.

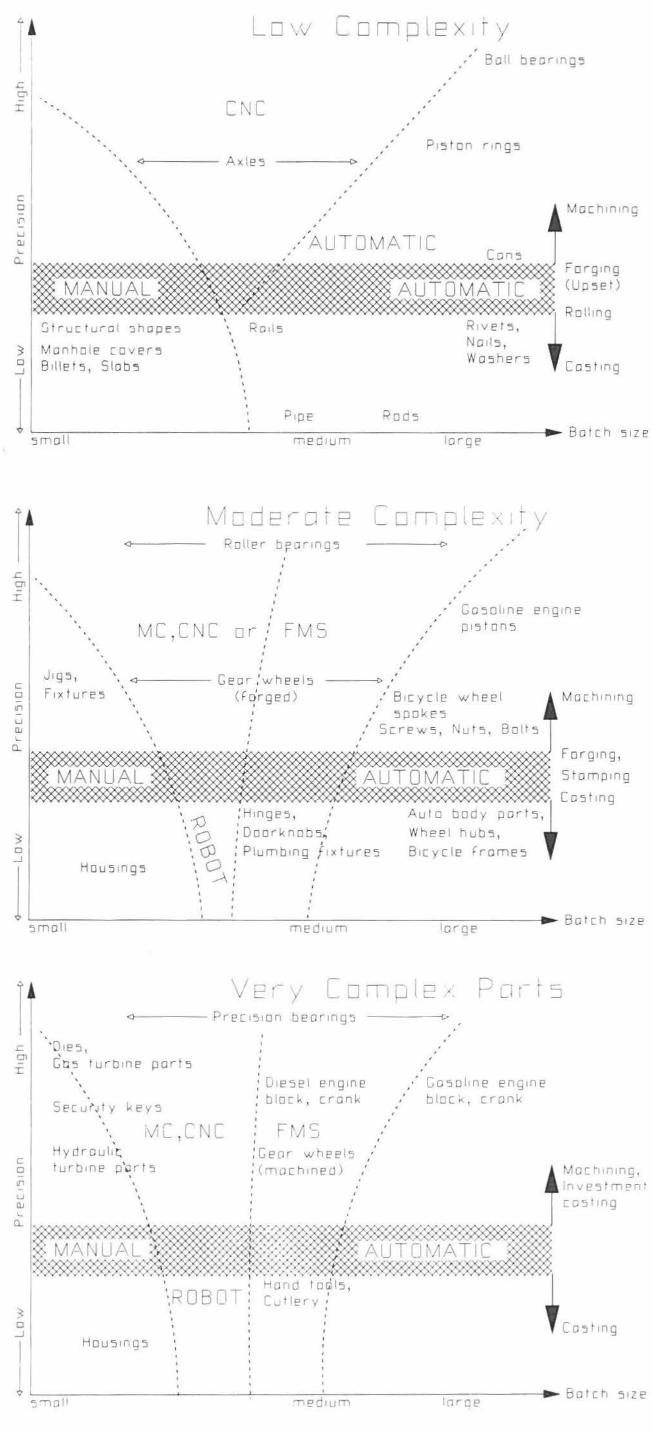

FIG. 4. Three cuts across the manufacturing hypercube

The switching surfaces which separate different regions of the manufacturing hypercube amount to isotechnology frontiers. They are the loci of points having different combinations of complexity, precision, and lot size, but that are equivalent in that they represent the boundary between two regions. In other words, they are loci of points where the performance of two different manufacturing methods is equivalent and the choice between them is arbitrary. As already noted, the switching surfaces will not be sharply defined. There will, for example, be regional differences due to wage and capital cost differentials. Moreover, they will move, as technology evolves. The choice of the proper manufacturing process becomes a multicriterion decision task, taking into account several characteristics of the product and the manufacturing processes, including such mundane considerations as the fact that in a multiproduct environment the machinery for carrying out the "optimal" process may already be committed to some other higher-priority task. Thus multicriteria decision procedures will be necessary to aid in choosing the manufacturing process which is optimal, not in some abstract sense, but in the concrete circumstances facing the plant manager.

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[6] A number of more specialized models have been proposed in the U.S., for example to minimize assembly cost (see reference [22], or to justify the use of flexible manufacturing systems (see references [23 and 24]), or to justify the use of robotic assembly (see references [25 and 26].

8 COMPLEXITY AND MANUFACTURING: THE MONOLITHIC CONCEPT

Until the 1960s, complexity of any machine could reasonably be measured in terms of its "parts count," the number of components from which it was made. The few exceptions (such as solid stamped or forged wheels replacing spoked bicycle-type wheels) essentially prove the generality of the rule. This was as true for electrical machines as for mechanical devices. In 1958, J. A. Morton, vice president of Bell Labs, wrote that scientists know in principle how to extend man's visual, tactile, and computational abilities by means of electronic circuitry, but that "such systems, because of their complex digital nature, require hundreds, thousands, and sometimes tens of thousands of electronic devices" [2]. Morton called this the "tyranny of numbers." He pointed out that each electronic circuit element (resistor, capacitor, inductor, transistor, etc.) "must be made, tested, packed, shipped, unpacked, retested, and interconnected one-at-a-time to produce a whole system." Morton said, "The tyranny of large numbers sets up a numbers barrier to future advances if we must rely on individual discrete components." Indeed, a circuit with 100,000 components could easily require 1,000,000 different soldered connections. The Control Data Corporation's CDC 1604 Computer (1959) had 25,000 transistors, 100,000 diodes, and hundreds of thousands of resistors and capacitors [27]. A navy destroyer at the time had 350,000 district electronic components, with millions of soldered connections.

This was the background for the monolithic revolution: the introduction of integrated circuits invented independently by J. Kilby of Texas Instruments Co., and Robert Noyce of Fairchild Semiconductor (1958–1959). Since then, waves of microminiaturization have compressed more and more circuit elements onto a single semiconductor chip. The latest "chips" are almost unbelievable complex devices electronically, but the complexity is embodied in compositional nonuniformities. A chip is built up of patterned layers of insulators, conductors, and semiconductors with carefully contrived properties. They are manufactured, incidentally, by a kind of controlled growth process similar to the way a natural crystal grows: from the inside out.

A similar trend in integration (to escape the "tyranny of numbers") is beginning to appear in the mechanical and electromechanical arena. For instance, early squirrel-cage induction motors (c. 1900) were assembled from a number of sheet-metal parts. Later, the number was sharply reduced by a new fabrication technique (centrifugal casting), which also cut the weight and permitted a much higher power/weight ratio. The modern stamped automobile wheel, which replaced the earlier bicycle-type wheel assembled from many individual parts, constitutes another case in point. For a third example, the 1953 Garrett turbocharger required 182 parts. The 1982 version weighs 80% less, delivers twice the speed, and requires only 53 parts [11]. More recently, the IBM dot-matrix printer introduced in 1985 involves only 60 parts, as compared to 150 parts for comparable units built only two years earlier. Much of IBM's reduction in parts number for the printer was achieved by using complex molded side frames to replace 20 other parts. Motors twist and lock into place, eliminating four bolts, four nuts, and four washers each. This greatly reduces the amount of assembly labor needed, as well as the probability of defects and need for inspection. Another recent example comes from Black & Decker Mfg. Co., the world's leading producer of electric hand tools. A comprehensive redesign and simplification of the entire product line resulted in dramatic savings in manufacturing cost.

One can scarcely escape the conclusion that the next generation of household appliances and automobiles will have many fewer mechanical parts than the present generation of such products. Just as integration of electronic circuitry involved "growing" complex chips by adding successive layers and materials with different properties, so the manufacture of integrated mechanical devices may proceed in the future. One can easily envision a monolithic chair, for instance, having rigid legs, springy seat and back, foam cushions, and a velour or leather-like surface, entirely manufactured by adding successive layers to a molded substrate in a controlled fashion without any cutting or assembly of pieces. If chairs, then why not desks, tables, sofas, and beds? Moving parts introduce difficulties, but not necessarily insuperable ones. Ultimately, the number of parts in a car might well drop into the low hundreds, as complex body and frame subassemblies are replaced by monolithic molded substitutes. Henry Ford considered his major contribution to manufacturing to be the elimination of "fitters." The next major revolution in manufacturing may be the (gradual) elimination of assembly itself.

To be sure, the manufacturing of monolithic mechanical products analogous to the chip would likely entail very complex multistage processes, just as chip-making does. But increasingly sophisticated and predictable counterpressure casting/molding techniques and isostatic powder metallurgical techniques are beginning to find wider uses. Extensive pretesting can reduce intrinsic defect rates to almost arbitrarily low levels. A flaw once detected in the manufacturing system itself is eliminated forever. Downstream inspection will largely be done by computer-assisted microscopy and thermography. A final bit of speculation: Man will not fully conquer space until monolithic construction techniques are adopted for spaceships. Until then, operational reliability will remain an elusive dream. MR

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