Working Paper

COMPLEXITY, RELIABILITY AND DESIGN: MANUFACTURING IMPLICATIONS
(Revised Version)

Robert U. Ayres

September 1987
WP-87-94

International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria

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FOREWORD

A major component of IIASA's Technology-Economy-Society (TES) Program is a project to assess "Computer Integrated Manufacturing" (CIM), by which is meant the whole range of application of computers to discrete parts manufacturing and assembly. The various familiar acronyms and buzzwords, such as NC, CNC, DNC, CAD/CAM robotics, FMS, "group technology" and MRP all fit under the broad CIM umbrella. The present paper is the first to be generated, at least in part, under the project. (In fact, an earlier draft was written while the author was at Carnegie-Mellon University). The 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 CIM arises from what Nathan Rosenberg has termed as "mismatch", i.e. 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 that 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 working paper is being made available more widely to stimulate discussion and comment. We hope that it will succeed in that regard.

Robert H. Pry
Director

COMPLEXITY, RELIABILITY AND DESIGN: MANUFACTURING IMPLICATIONS

Robert U. Ayres

1. Background

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). A survey carried out by Quality (June 1977, p. 20) over 10 U.S. manufacturing industries found that total quality costs (inspection, scrap, rework and warranty) averaged 5.8% of sales. 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 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]. In this paper I will explore five 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

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[1] Xerox corporation offers an interesting example. Recently Xerox announced with some pride that its parts reject rate is now down to 1.3 per thousand (from 8 per thousand a few years ago). However, its Japanese competitors have achieved reject rates less than 1 per thousand (N.Y. Times, November 16, 1985). Since the early 70'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 airconditioner 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 [Garvin 1983]. The best Japanese producers achieved failure rates between 500 and 1000 times better than the worst U.S. producers (ibid).

favorable conditions -- although clever human factors engineering can often achieve substantial improvements over existing rates in given cases. Nevertheless, human workers are not improving rapidly (if at all) in terms of their prospensity to make mistakes on the job;

- 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 as precision increases and the production system becomes more complex and more interrelated the cost of information required for controlling the manufacturing process as a whole has been growing geometrically. The cost of discovering and/or eliminating defects, in particular, seems to increase as a non-linear function of product complexity and diversity;
- 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.

2. The Intrinsic Human Error Probability

Ergonomists and human factors engineers have traditionally approached the "error" problem in terms of "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 tends to obscure a key fact: that even with the best designed man-machine interface, the probability of human error cannot in practice be reduced to zero except, possibly, 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, etc., etc. 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 71], [Meister 76], and [Swain & Guttmann 83].

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,[2] the amount of information "lost" -- which is equivalent to the error rate -- rises extremely sharply as the input rate approaches 10 bits/sec. 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 & Guttmann [op cit]. 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

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[2] For a more extensive review of the background of this statement, see Ayres [1987c].

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". [Shurkin 85, p. 23].

The problem only got worse, as mathematical tables were needed for more and more purposes. In the 1930's the 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 [Brooks 86]. Recent Department of Defense studies indicate an average of one error per 30 manual data entries. By comparison, optical scanners reading bar codes make one error per 3,000,000 entries [McKenney & McFarlan 82, p. 109]. Roughly speaking, electronics technology is now on the order of 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 there are no tolerance limits" (op. cit.). In repetitive jobs involving simple decisions of the yes/no type the minimum human error probability (HEP) appears to be of the order of 10^{-3}. In other words, the error rate generally exceeds 1 per 1000 opportunities.[3] HEP may be much greater if working conditions are not ideal. However, I will not further explore the relationships between various aspects of working conditions and HEP, except to recall that experiments show that the error

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[3] This number comes from a recent publication summarizing the literature [Swain 83]. An earlier book by Swain suggested the range 10^{-3} - 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.

rate begins to rise rapidly as information output approaches about 8 bits/sec. 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/sec.

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 to their modern counterparts. One early weight-driven clock, for instance, utilized 8 gear wheels, an escape wheel, a crank (3 parts) a foliot balance (5 parts), a verge (3 parts), 6 axles, 2 pointer hands, a face plate, and various frame parts, pins, etc. [Strandh 79]. 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 2 or 3 parts. A late 19th century hand-drill (brace and bit) with a chuck accommodating various drill bit diameters involves 20 parts. A push-type reversible hand-held screw-driver with an adjustable chuck utilizes 30 or more parts. The addition of an electric drive motor would, of course, add another 50 or so. A hand-saw had 3-5 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, 2 doors and a simple bench for the driver, two iron axles, solid iron sleave-type bearings, four relatively simple spoked wheels, and tiller-type of steering mechanisms. The wheels were already moderately sophisticated, with 8-12 spokes and steel rims. The introduction of the safety bicycle in 1885 was 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 (Benz, 1886) added a small 1-cylinder gasoline engine with a chain and sprocket drive mechanisms to a 3-wheeled carriage using bicycle wheels[4]. Benz's 1-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 very complex product in itself), springs and shock absorbers, multi-cylinder 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.

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

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.* As many as 30% of the total number are electrical or electronic, and this percent is rising rapidly. Most parts have at least 3 distinct surfaces, while many parts (including threaded connectors) have 8-10 surfaces. A few parts like gear-wheels, pistons, crankshaft, and camshaft 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 1 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 Figure 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 Company manufactures over 50,000 different steam turbine blade shapes alone. A major electrical connector manufacturer (AMP) produces 80,000 different connector models. The IBM Selectric™ typewriter (with 2,700 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." [Meister 82].

This view, of course, puts enormous emphasis on human factors and systems engineering. The role of human factors engineering is

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*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 like brakes, transmission, hydraulics and emission controls.

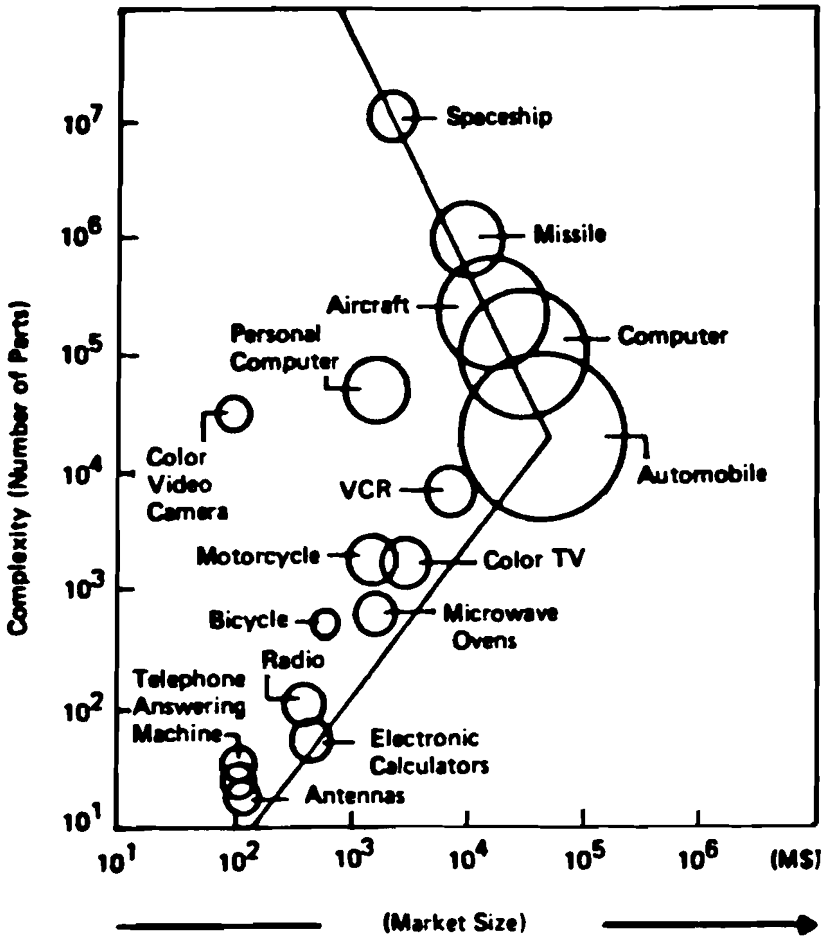

Figure 1. Major U.S. durable goods industries.

Source: [Nagayama & Funk 85] (Revised).

undoubtedly important and often underrated. Indeed, human error probability (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 (ibid) "that errors can always be eliminated by better systems design" 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 multi-layer 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 as compared with defect rate of 10^{-2} - 10^{-3} currently. 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 don't 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} (.0001) or perhaps even 10^{-6} (.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 thousand). Nevertheless the costs of overdesign (or "gold-plating"),[6] multiple layers of inspection, debugging, rework,

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[6] 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

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. A 5.8% direct cost percentage was cited earlier, but this is only the tip of the iceberg. When the burocratic 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 (op. cit.), 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 autom 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.

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 which involves a sequence of unit operations. The total number of actual operations involved is, therefore,

$$M = \sum_{i=1}^{N} n_i m_i \qquad (1)$$

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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 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}. Asssuming perfectly reliable inspectors,[7] 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,

$$u_i = \prod_{j=1}^{m_i} [1-P_{ij}] \qquad (2)$$

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

$$u = \prod_{i=1}^{N} \Big(\prod_{j=1}^{m_i} (1-P_{ij})\Big)^{n_i} = \prod_{i=1}^{N} u_i^{n_i} \qquad (3)$$

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

$$n \le p_{ij} \quad \text{for all } i,j \qquad (4)$$

It follows immediately that

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[7] Obviously, the real situation is much less favorable!

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

for all i,j and, therefore, the probability achieving "zero defects" is bounded

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

where M is defined by equation (1).

Now (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 $M\eta >> 1$

$$(1 - \eta)^M = \exp[M \log(1-\eta)] = \exp M(-\eta-1/2\eta^2, \ldots)$$

$$\doteq \exp(-M\eta) \qquad (7)$$

But if $M\eta << 1$

$$(1-\eta)^M = 1 - M\eta + 1/2M(M-1)\eta^2 - \ldots$$

$$\doteq 1 - M\eta \qquad (8)$$

In words, if opportunity -times- 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 nil. 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". Humans are obviously 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 of having an a priori probability of error per opportunity much lower than humans. The worldwide trend towards 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 cliche. 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 cleverer to find and 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 system designer's function to design for easy error detection.

5. Management Implications and Complexity & Diversity

The evident trend toward product complexity on the one hand, and model diversity on the other hand, also puts great stress on management. Just keeping track of parts inventories and suppliers is becoming an enormous task for large manufacturers. For example, Caterpillar Tractor Company does business with 25,000 different suppliers, worldwide. This number could well be dwarfed by comparable figures for General Electric, IBM or General Motors.[e] The problem on the product distribution side is equally formidable (and less well understood), because demand patterns can change very quickly. Manufacturers are in a position as difficult as that of banks, which have to obtain their funds from short-term depositors while making risky long-term commitments. Manufacturers of consumer products today must make comparatively long-term commitments to their own suppliers, while responding to short-term changes in their own markets. This puts increasing emphasis on managerial and manufacturing flexibility.

Generalities aside, it is arguable that the information processing requirements associated with efficient manufacturing increase much faster than complexity/diversity per se. The evidence supporting this conclusion will be reviewed hereafter. The implications are worth stating clearly now: <u>unaided human intelligence is increasingly inadequate for purposes of selecting optimal or near optimal manufacturing strategies, given the enormous range of choices to be made</u>. These include: long-term business strategy, (what business are we in?) marketing strategy (e.g. mass v. custom); product design strategy (performance, reliability, finish price); materials choice; make v. buy decisions for each component; supplier selection; supplier relationship (long-term v. short term) mfg. strategy (location, scale, process choice); assembly strategy; distribution strategy; maintenance and customer support strategy. The choices to be

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[e] It was reported recently, however, that Xerox Corp. has cut the number of its suppliers from 5,000 to 300, in order to work more closely with each of them (New York Times, November, 1985).

made are interdependent, as well as being functions of the state of technology, financial constraints (interest rates, debt v. equity, liquidity, current profitability, etc.). Many managers believe that the inherent complexity of these higher level decisions is such that only human judgment can ultimately be relied on. It is arguable, however, that the complexity is so great that (unaided) human judgement is almost inevitably inadequate. I mean that obvious or traditional choices are likely to turn out to be <u>significantly</u> inferior to optimal choices that might (in principle) be found with enough help from computers and artificial intelligence (A.I.).

It is not possible to examine each of the above-mentioned sub-optimization problems in any detail. In keeping with the primary focus of this paper, I will consider only the physical aspects of parts manufacturing and assembly. Figure 2 outlines schematically the processes of design, manufacturing and assembly as it might conceivably be organized in the future [DeFazio & Whitney 83]. The two boxes marked by asterisks represent tasks of considerable difficulty that are currently carried out manually, and probably will be for some time to come. Until now relatively little research has been done on devising systematic methodologies or "algorithms" for determining assembly order, and parts transport and feeding technologies.

The corresponding problem for parts manufacturing strategy is to select parts forming processes and sequences, and to layout the machines on the plant floor for efficient scheduling. This problem has been approached more or less systematically by classification of parts by shape and creating a geometrical parts code (Figure 3). This code permits rapid computerized sorting of parts by shape, size, material and other characteristics and matching to approximate machines. It also permits grouping of parts based on geometrical similarities. In some cases existing parts can be found that preclude the need to design new ones. More commonly, new parts can be developed by identifying similar existing ones and modifying them appropriately. For manufacturing purposes, groups of geometrically similar parts correspond to machine groupings.

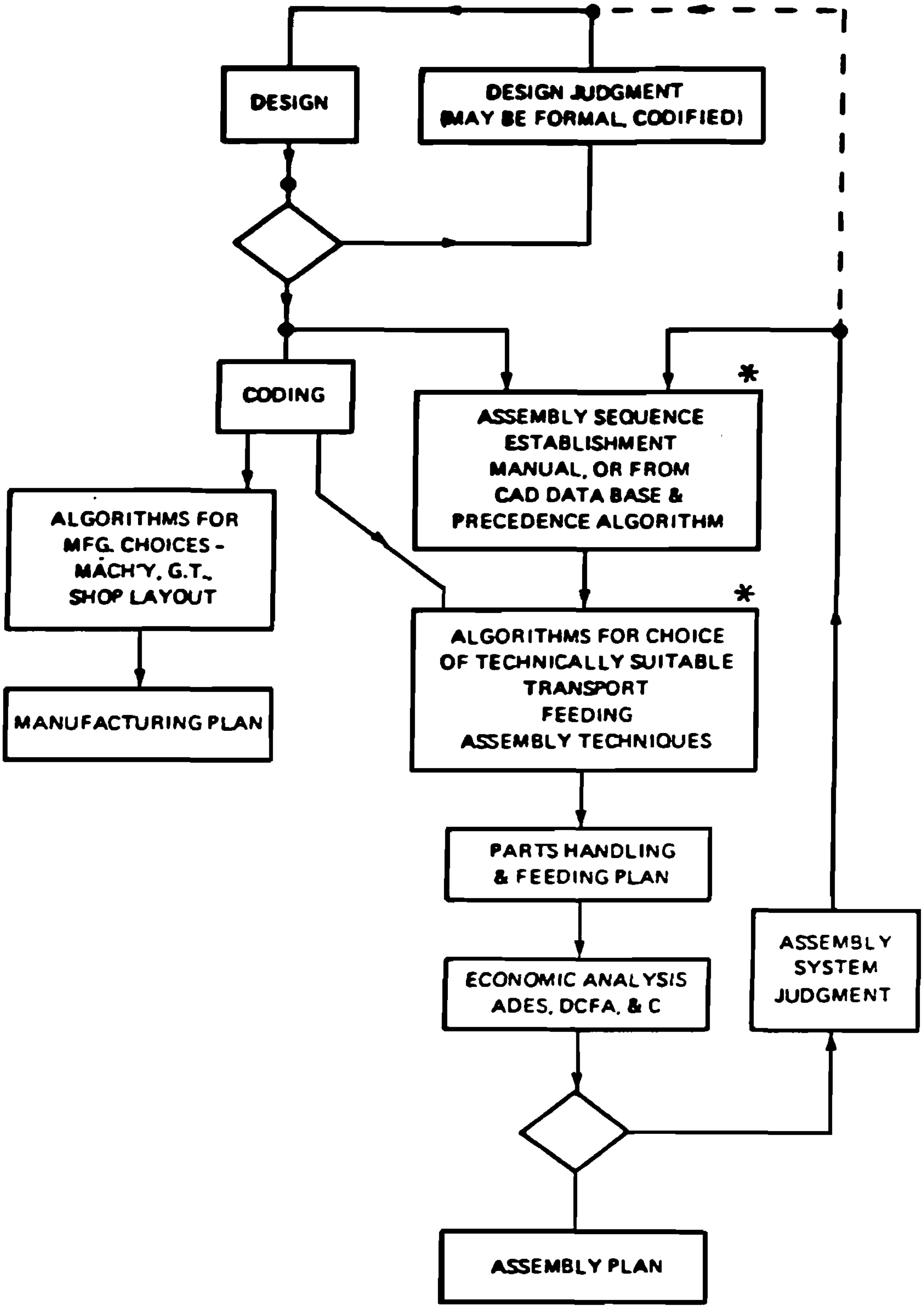

Figure 2. Interrelationships between design manufacturing and assembly plans.

Source: [DeFazio & Whitney 83].

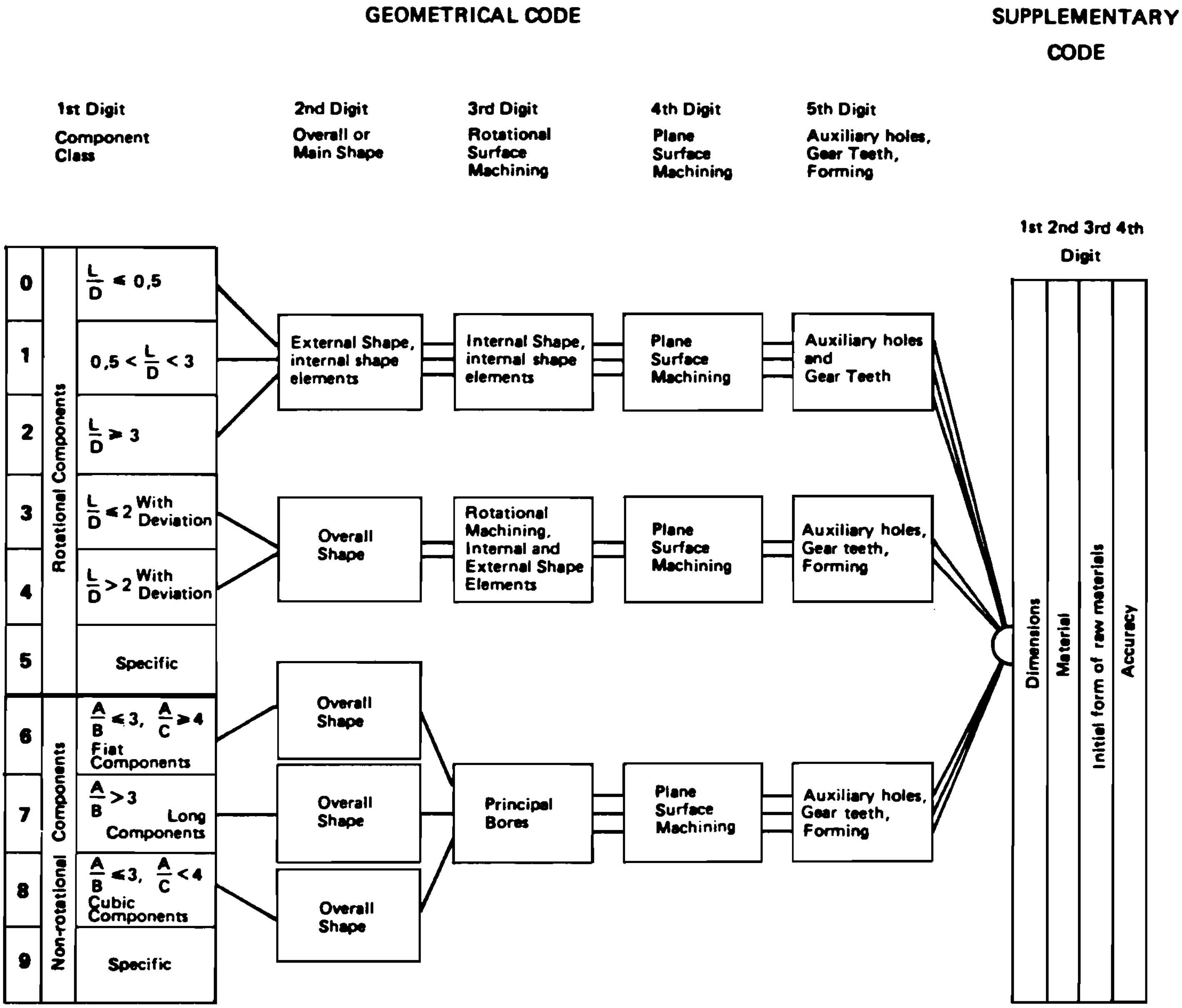

Figure 3. Workpiece classification.

Source: [Opitz 67, 70].

"Group technology" (or GT), as it has come to be known,[9] is essentially an information processing system for systematizing design and manufacturing choices. General benefits are claimed in terms of both planning and implementations. With regard to the choice of process sequence the two aspects converge and interfere since the matching parts to machines (planning) is constrainted by machine availability (implementation). Machine availability is, of course, determined by scheduling. The production schedule, in turn, governs raw materials requirements.

The nature and difficulty of the optimization problem emerges more clearly from the consideration that two management objectives are clearly in conflict. On the one hand it is desirable to maximize the effective utilization of all capital equipment, especially the most expensive machines such as CNC milling centers.[10] On the other hand, it is desirable to minimize the number and value of parts in the "work in progress" inventory. It is fairly obvious that machine utilization can be increased in general by using idle machines to build parts inventory. On the other hand, work-in-progress can be reduced essentially to zero, but only by having a large enough inventory of machines such that no part ever has to wait for a machine to become available. Since both machines and work-in-progress represent real capital, the true optimum (disregarding other constraints) is obviously some compromise between these extremes. Assuming the machines inventory is fixed (in the short term) the variable factor is the length of the queue of work-in-progress. A pure optimum solution would be characterized by at least one machine being 100% utilized--a "bottleneck"--while the rest are idle to variable degrees.

The above problem can be solved in principle by integer-programming techniques, for a given machine inventory and product mix. The problem is far more difficult to solve if parts mix demand is variable and uncertain and machines can break down at random intervals. Nevertheless, existing mathematical

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[9] See, for example Burbridge [1975]; Devries et al. [1976]; Edwards [1971]; Gallagher & Knight [1973]; Ham & Ross [1977]; Mitrafanov, S.P. (in English [1966]); Opitz [1970].

[10] But not by using an expensive machine for an operation that a cheaper one can perform just as well!

programming and simulation techniques for planning, packaged as Manufacturing Resource Planning (MRP) systems are now commercially available yielding significant improvements in overall capital utilization. Even so, the optimum capital utilization rate will tend to be fairly low in batch production situations where product diversity is high and production rates are comparatively low.

With regard to the "amount" of information processing needed as a function of the complexity of products (i.e. the number of different parts in the filing system), it is difficult to state a general theorem. Experience suggests, however, that the number of distinct operations involved in sorting and matching items on a list (even by the most efficient method) increases as something like the square of the number of items on the list. From a purely combinatorial perspective, the number f(n) of number of possible scheduling schemes for n different parts, each of which can be made on m_i different machines, at (i = 1, ...n) different rates subject to various constraints, is almost beyond calculation when these numbers are large. At any rate, it is safe to assert that

$$f(n) \gg n \tag{9}$$

Selection of the optimum schedule from among these f(n) possibilities by any known mathematical programming technique involves a number of mathematical operations g(n) of the order of

$$g(n) = 0(f^2(n)) \tag{10}$$

That is, the number of mathematical operations required to compare and select the most efficient schedule option is of the order of the square of the number of such options. This number, in turn, is much larger than the number of different parts to be made.

Another illustration of the complexity-related combinatorial explosion (and its implications) comes from the problem of assembly optimization. It has been shown [DeFazio & Whitney 83] that, as the number of parts in the assembly increases, the number of possible ways of assembling them -- "parts trees" --

increases much faster than n, as shown in Table 1 and Figure 4. To be sure, many parts trees are physically unrealizable, but the only known method of optimization (to date) is to construct all possible parts trees and test them individually, for physical realizability by applying constraints such as contact and precedence conditions.

6. Complexity Measures and Computer-Aided Process Planning (CAPP)

An attractive approach to computer-aided process planning 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.[11] Each of these variables affects the choice of manufactyuring 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, an 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

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[11] This assumes that design and material choices are prespecified. See, however, Ayres [1987b].

Table 1. Numbers of trees as a function of number of branches $n_t(n)$ and number of parts trees possible with all parts different $n_{pt}(n)$.

n No. of parts	n_t No. of trees	Max, min no. of nodes to get to tip	Max, Min No. of Distinct Locations	No. of Distinct Locations for Parts							n_{pt}
				1	2	3	4	5	6	7	
2	①	1, 1	1, 1	1							1
3	①	2, 2	2, 2		1						3
4	②	3, 2	3, 2		1	1					18
5	③	4, 3	4, 3			2	1				120
6	⑥	5, 3	5, 3			1	4	1			1,140
7	⑪	6, 3	6, 4				4	6	1		12,120
8	㉓	7, 3	7, 4				2	11	9	1	149,520
n		$(n-1), \log_2(n)$ ROUND TO HIGHER INTEGER	$n-1, (n/2)$ ROUND TO HIGHER INTEGER	NUMBER OF CASES							

Source: [De Fazio & Whitney 83].

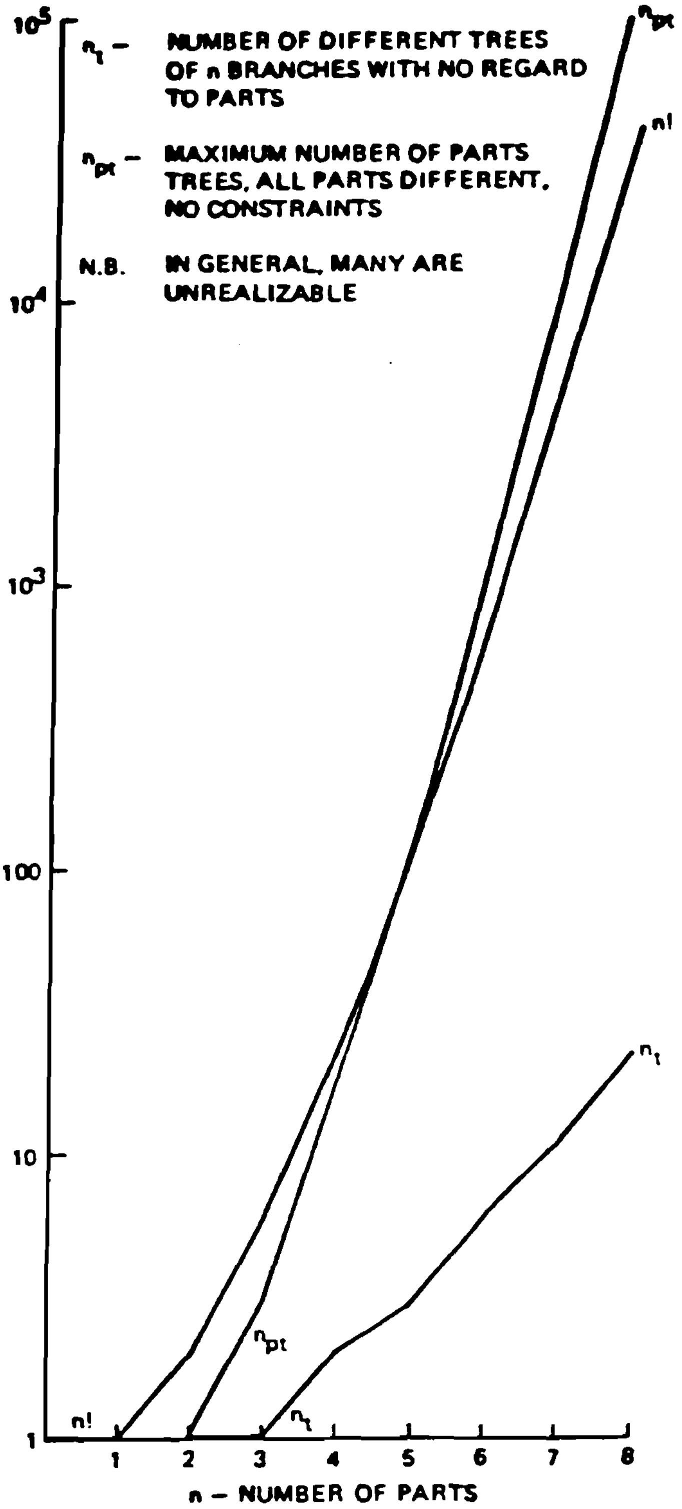

Figure 4. The number of parts-trees vs. number of parts.
Source: [DeFazio & Whitney 83].

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 differnces that remain.

Measures of precisions (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 Figure 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 a vis simpler ones. In actuality a small number of "main parts" account for half of all the value added in Manufacturing (Figure 5). 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 GT systems. For example, in the Opitz 5-digit system 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

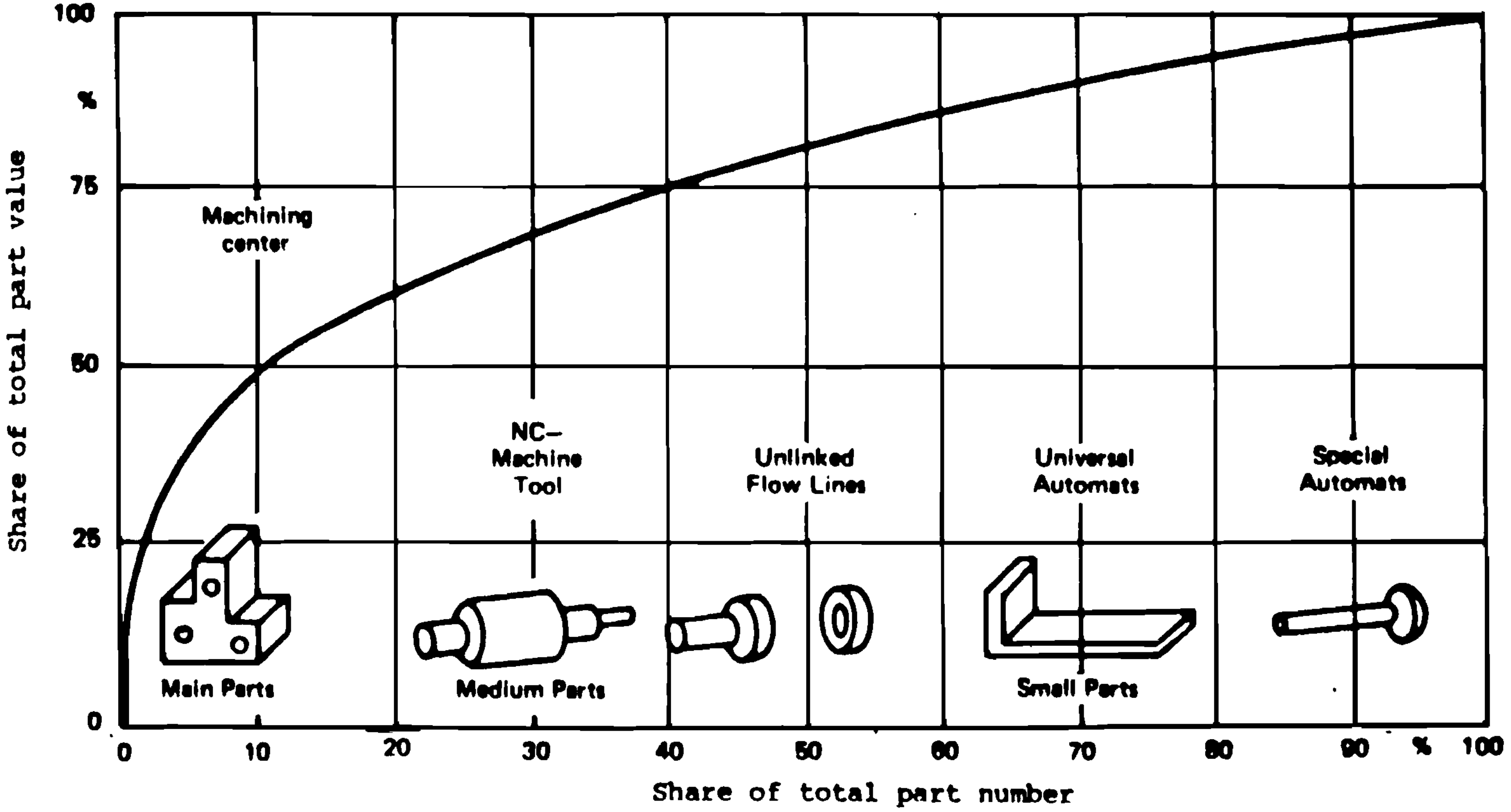

Figure 5. Group technology and manufacturing systems.

Source: unknown.

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 5-digit system is probably ample.) Of course, not all 5-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

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

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 improbably specificiation 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 net 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,[12] plus an additional bit of information to specify whether a screw is right or left-handed, or 61 bits total.

An important consequence of the concept of using information theory to define the complexity of a product is that assembly is

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[12] This assumes an accuracy of 1 part in 1000 or about 2^{10}. Note that $\log_2 1000 \cong 10$.

seen to be an information-destroying process. Two parts which 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 four major variables previously identified:

- complexity
- precision
- batch size/lot size/run length
- diversity

(A fifth variable, mass or linear dimension, may be added for completeness).

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.[13] However this has not been done, because it would be enormously

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[13] A number of more specialized models have been proposed in the U.S., for example to minimize assembly cost [Boothroyd, 1983], or to justify the use of flexible manufacturing systems [Gustavson, 1983], [Hutchinson, 1984] or to justify the use of robotic assembly [Funk, 1984, 1986].

expensive to gather the data even if firms were willing to release it. An indirect approach is therefore desirable.

The four variables -- complexity, precision, 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 surfaces 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 whithin a particular region, one would expect a specific manufacturing process to be optimal. Three "cuts" of the hypercube are illustrated in Figures 6(a,b,c).

The switching surfaces which separate different regions of the manufacturing hypercube amount to iso-technology frontiers. They are the loci of points having different combinations of complexity, precision and lot size, but which 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 technolgoy evolves. The choice of the proper manufacturing process becomes a multicriterion decision task, taking into account several chatacteristics of the product and the manufacturing processes, including such mundane considerations as the fact that in a multi-product 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.

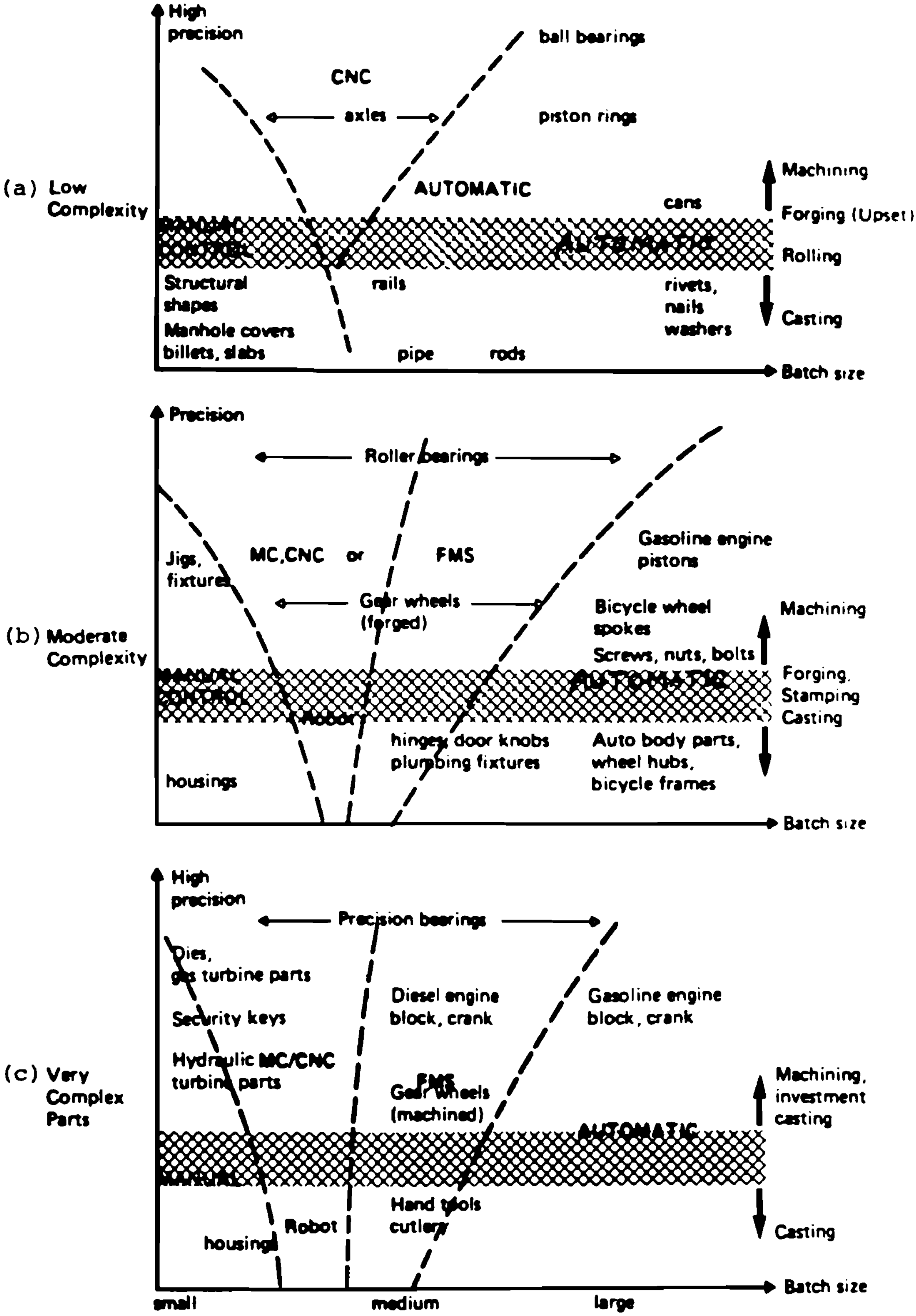

Figure 6. Three cuts across the manufacturing hypercube.
Source: R.U. Ayres, IIASA.

8. Complexity and Manufacturing: The Monolithic Concept

Until the 1960's, 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 Laboratories, 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 electron devices."[14] 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 Corporations CDC 1604 Computer (1959) had 25,000 transistors 100,000 diodes, and hundreds of thousands of resistors and capacitors (ibid). 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 Company, 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 non-uninformities. A `chip' is built up of patterned layers of insulators, conductors

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[14] Quotes cited by T.R. Reid in "The Chip" <u>Science</u> 85, February 1985, page 35.

and semiconductors with carefully contrived properties. They are manufactured, incidently, 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 avoid 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 turbo-charger required 182 parts. The 1982 version weighs 80% less, delivers twice the speed and requires only 53 parts [Aerospace 85]. 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.[15] 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

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[15] Wall St. Journal, April 13, 1986.

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 multi-stage processes -- just as chip-making does. But increasingly sophisticated and predictable counter-pressure 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 once-for-all. 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 space-ships. Until then, operational reliability will remain an elusive dream.

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