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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.

Thomas H. Lee
Project Leader,
Technology, Economy, Society

COMPLEXITY, RELIABILITY AND DESIGN: THE COMING MONOLITHIC REVOLUTION IN MANUFACTURING

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 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

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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).

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 Probablilty

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 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. From Figures 1 and 2, especially, it can be seen that as the input rate[a] increases, 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 overload, or saturation. This 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].

A representative table of nominal human error probabilities for or HEP's for operating manual controls is shown in Table 1. These figures are to be interpreted as the medians of log normal distributions of experimental subjects. (50% of subjects would have a higher HEP, 50% would have a lower HEP.) The range of uncertainty of the distribution is called the error factor (EF). It is significant that the lowest HEP shown is .0005 corresponding to 5 errors per 10,000 decisions. Modifiers for HEP's are shown in Table 2. Note that modifiers are always greater than unity. Thus the nominal HEP's can be interpreted as practical minimum median error rates for represenative populations. It is unlikely that the figures would vary significantly from one country to another, for instance. Implications of these data for manufacturing management and automation are discussed in subsequent sections.

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

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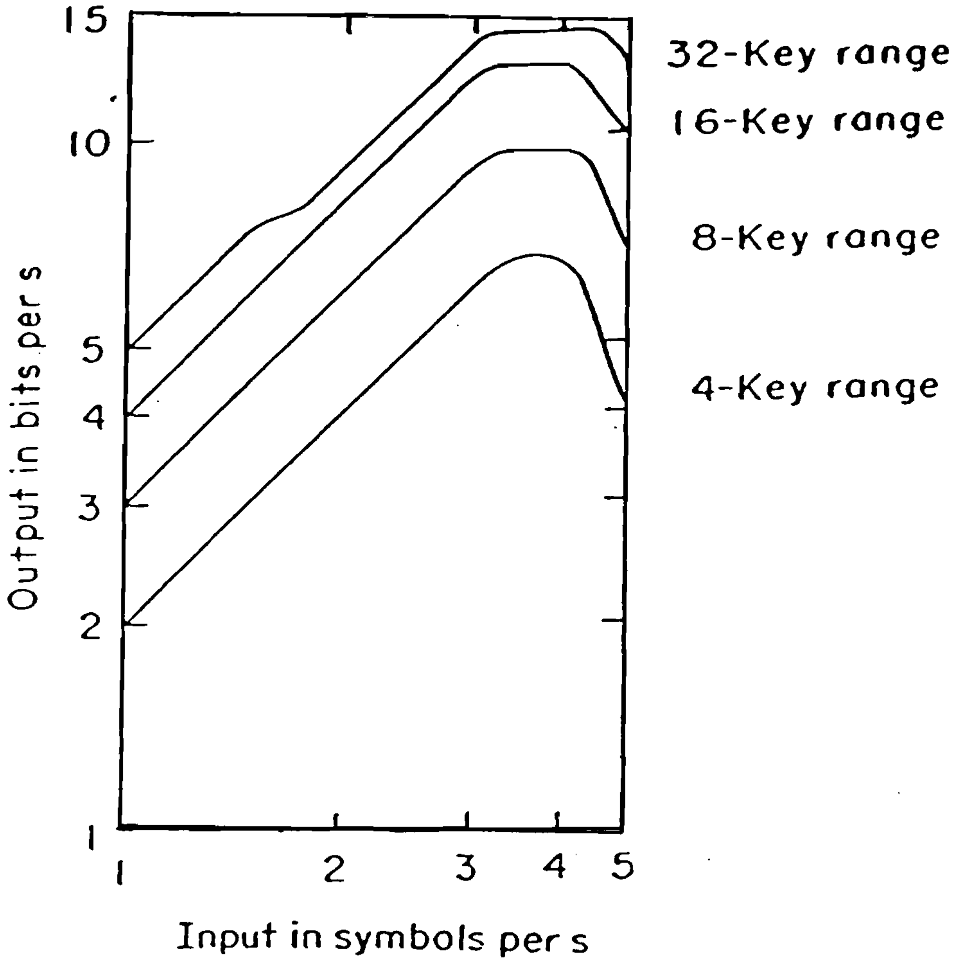
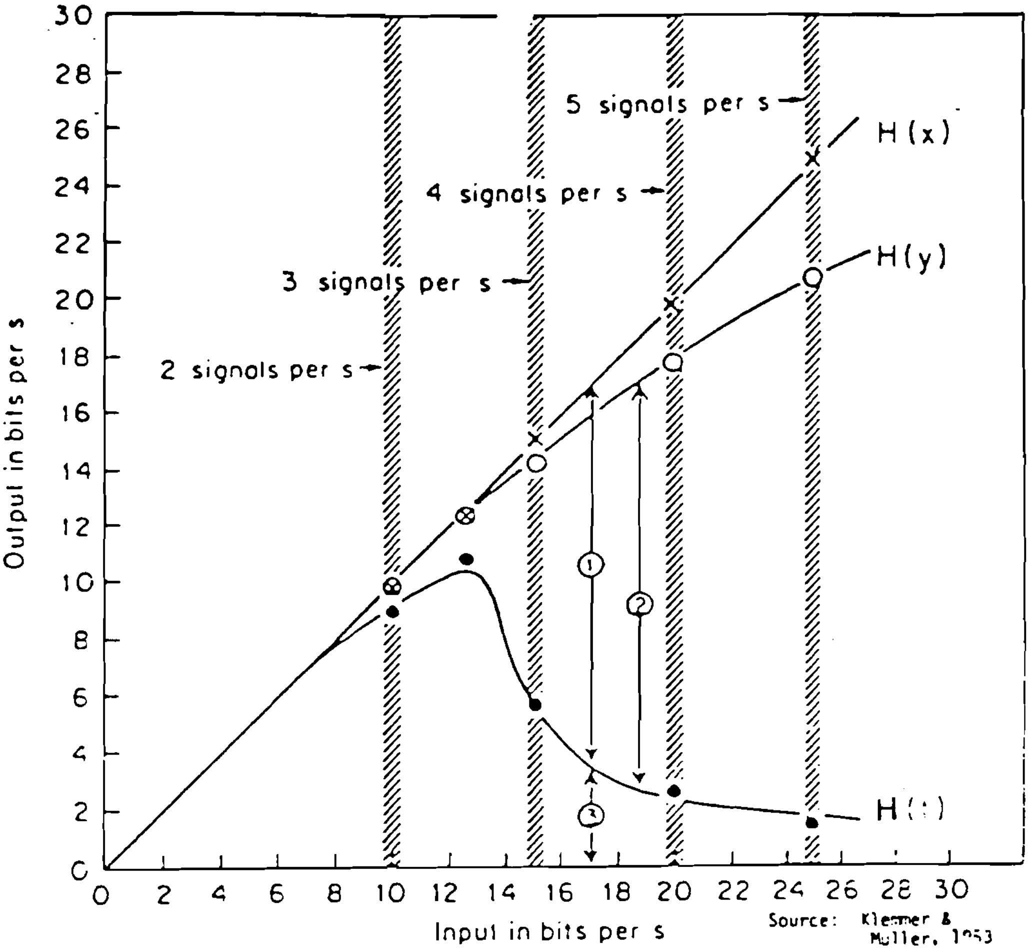
[a] The input rate in Figure 1 is shown in alphabetical symbols per second, where each symbol is equivalent to roughly 3 bits of information.



Typing Performance Curves (From H. Quastler & V. J. Wulff)
Human Performance in Information
Technical Report R-62
Urbana, Illinois: Control Systems Laboratory, University of Illinois, 1955, Pages 62-47.

Cited by Miller 78.

Figure 1. Information Troughput vs. Speed for Typing.



Averages for four subjects in five-light test, showing total informational output and transmitted information as functions of the input rate. H(x) represents information input; H(y) represents subjects' total information output; H(t) represents subjects' correct information transmitted. (1) indicates information lost (presented but not transmitted); (2) indicates noise or information in output not correlated with input; and (3) indicates transmitted information. (Adapted from E. T. Klemmer & P. F. Muller, Jr. The rate of handling information: key pressing responses to light patterns. HFORL Memo Report No. 34. USAF, ARDC. March 1953, 9)

Cited by Miller 78.

Figure 2. Information Processing by Humans.

Table 1. Estimated Probabilities of Errors of Commission in Operating Manual Controls*

Item	Potential Errors	Human Error Probability HEP	Error Factor (Range)
(1)	Inadvertent activation of a control		
	Select wrong control on a panel from an array of similar-appearing controls:		
(2)	identified by labels only	.003	3
(3)	arranged in well-delineated functional groups	.001	3
(4)	which are part of a well-defined mimic layout	.0005	10
	Turn rotary control in wrong direction (for two-position switches, see Item 8):		
(5)	when there is no violation of populational stereotypes	.0005	10
(6)	when design violates a strong populational stereotype and operating conditions are normal	.05	5
(7)	when design violates a strong populational stereotype and operation is under high stress	.5	5
(8)	Turn a two-position switch in wrong direction or leave it in the wrong setting	**	
(9)	Set a rotary control to an incorrect setting (for two-position switches, see Item 8)	.001	10***

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*The HEPs are for errors of commission only and do not include any errors of decision as to which controls to activate.

**Divide HEPs for rotary controls (Items 5-7) by 5 (use same EFs).

***This error is a function of the clarity with which indicator position can be determined: designs of control knobs and their position indications vary greatly. For plant-specific analyses, an EF of 3 may be used.

Table 1. (continued)

Item	Potential Errors	Human Factor Probability HEP	Error Factor (Range)
(10)	Failure to complete change of state of a component if switch must be held until change is completed	.003	3
	Select wrong circuit breaker in a group of circuit breakers:		
(11)	densely grouped and identified by labels only	.005	3
(12)	in which the PSFs are more favorable	.003	3
(13)	Improperly mate a connector (this includes failures to seat connectors completely and failure to test locking features of connectors for engagement)	.003	3

Table 2. Modifiers for HEP's*

	Stress Level	Skilled**	Novice**
Item		(a)	(b)
(1)	Very low (Very low task load)	x2	x2
	Optimum (Optimum task load):		
(2)	Step-by-step†	x1	x1
(3)	Dynamic†	x1	x2
	Moderately high (Heavy task load):		
(4)	Step-by-step†	x2	x4
(5)	Dynamic†	x5	x10
	Extremely High (Threat stress)		
(6)	Step-by-step†	x5	x10
(7)	Dynamic† Diagnosis††	.25 (EF = 5) These are the actual HEPs to use with dynamic tasks or diagnosis - they are NOT modifiers.	.50 (EF = 5)

**A skilled person is one with 6 months or more experience in the tasks being assessed. A novice is one with less than 6 months or more experience.

†Step-by-step tasks are routine, procedurally guided tasks, such as carrying out written calibration procedures. Dynamic tasks require a higher degree of man-machine interaction, such as decision-making, keeping track of several functions, controlling several functions, or any combination of these. These requirements are the basis of the distinction between step-by-step tasks and dynamic tasks, which are often involved in responding to an abnormal event.

††Diagnosis may be carried out under varying degrees of stress, ranging from low (optimum) to extremely high (threat stress). For threat stress, the HEP of .25 is used to estimate performance of an individual.

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 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. Moreover, each of those is made with a level of precision in terms of composition and surface finish far beyond capabilities of even 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[3]. 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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[3] 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 an extraordinarily complex piece of machinery, involving roughly 20,000 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. The space shuttle is probably the apogee of mechanical complexity (with unfortunate consequences, as will be seen). 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 large turbine involves 350,000 parts. A major electrical connector manufacturer (AMP) produces 80,000 different connector models. The IBM Selectric™ typewriter had 2,700 parts, and could be made in 55,000 different models.

4. 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 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.

It was pointed out previously that human workers are intrinsically prone to errors. 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

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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.

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 1985, 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, 1986]. Recent Department of Defense studies indicate an average of one error per 300 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 (inconsistently) 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.[5] 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 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.

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

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[5] 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.

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, 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.), the Ford Motor Company alone 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 -- Ford would have to expect about 3000 undetected serious production flaws per day. The actual number of defects in autos is surely much larger under present (far from ideal) conditions.

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,

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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 civilian market. Yet military hardware is notoriously unreliable. This is surely attributable to the attempt to achieve maximum possible performance which, in turn, leads to extraordinary complexity of design.

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

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^{-3}. 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,

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

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

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

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

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

It follows immediately that

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

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

---

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

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

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 $M\eta >> 1$

$$(1-\eta)^{M} = exp[M\ log(1-\eta)] = expM(-\eta-1/2\eta^{2}...)$$
$$\cong exp(-M\eta) \qquad (7)$$

But if $M\eta << 1$

$$(1-\eta)^{M} = 1 - M\eta + 1/2M(M-1)\eta^{2} - ...$$
$$\cong 1 - M\eta \qquad (8)$$

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. Complexity and Optimization

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.[a] 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.

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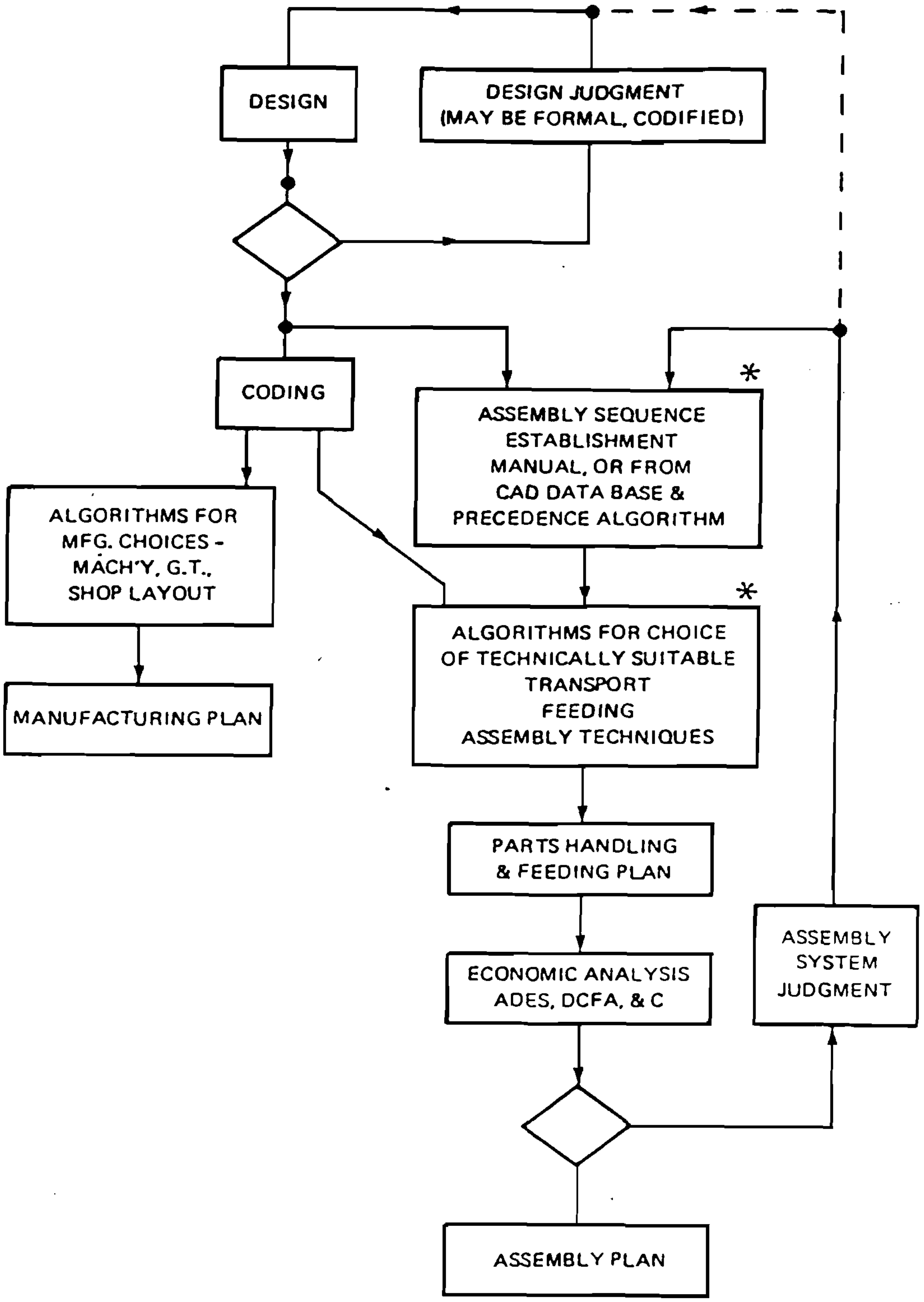
[a] It was reported recently, however, that Xerox Corp. has cut the number of its suppliers from 5,000 to 300, in order to work more closely with each of them (New York Times, November, 1985).

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: 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. 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 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 significantly 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 3 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.

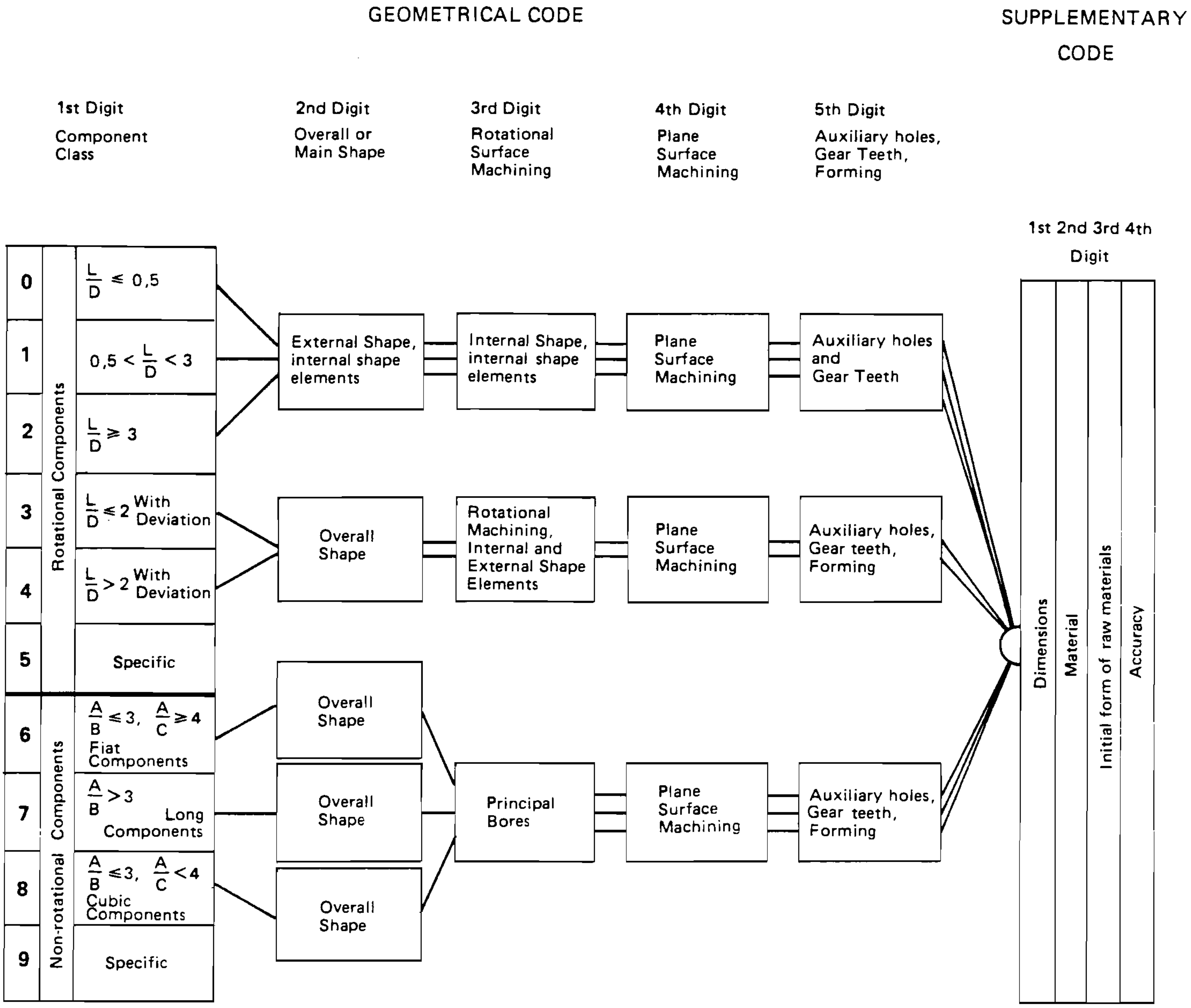
The corresponding problem for parts manufacturing strategy is to select parts forming processes and sequences, and to layout the machines on the plant floor for efficient scheduling. This problem has been approached more or less systematically since 1967 when Opitz [Opitz 67] introduced a geometrical parts code (Figure 4). 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.

"Group technology", as it has come to be known, is essentially an information processing system for systematizing



Source: DeFazio & Whitney

Figure 3. Interrelationships Between Design Manufacturing and Assembly Plans.



Schematic of the Opitz Code for Piece-Parts, ca. 1967, from "A Classification System to Describe Workpieces" Compiled by H. Opitz, Pergamon Press, Oxford.

Source: DeFazio and Whitney.

Figure 4. Flourey Workpiece Classification (Opitz).

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.[9] 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 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

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

safe to assert that

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

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

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

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 3 and Figure 5. 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 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."[10] 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

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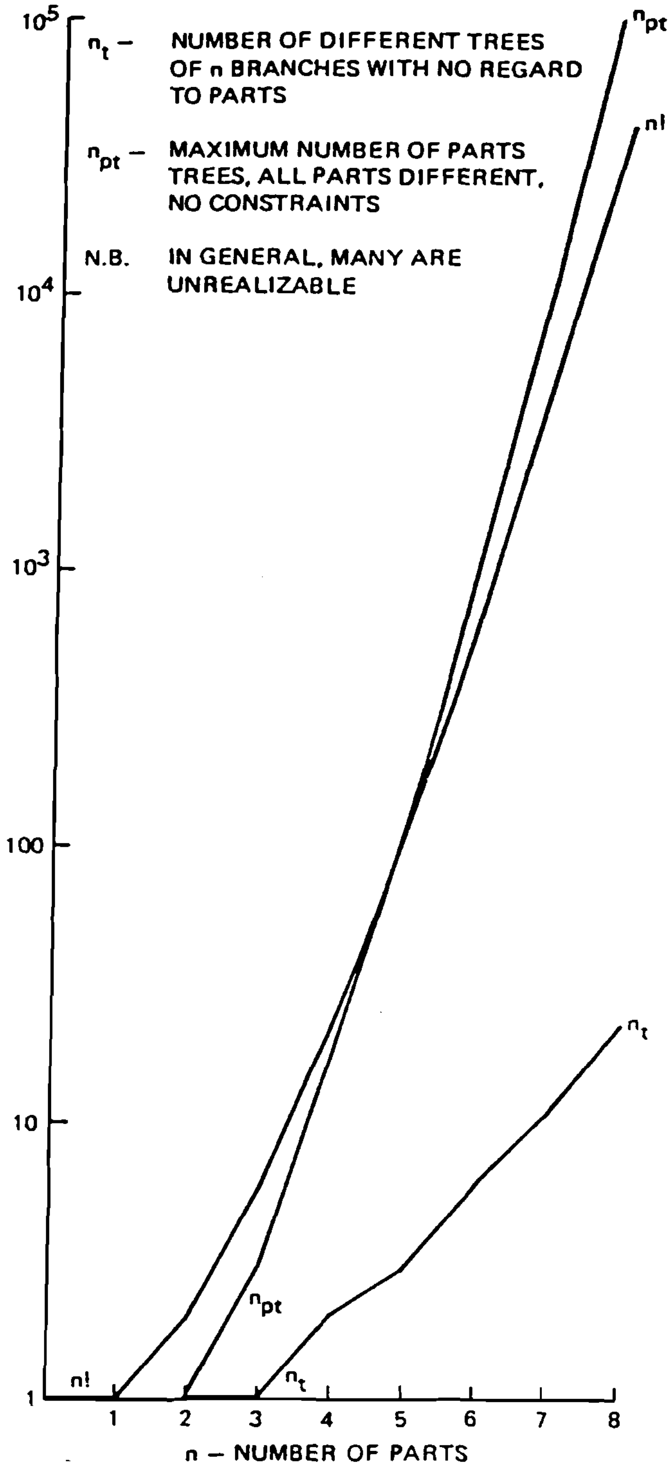
[10] Quotes cited by T.R. Reid in "The Chip" Science 85, February 1985, page 35.

Table 3. 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



Source: DeFazio & Whitney

Figure 5. The Number of Parts-Trees vs. Number of Parts.

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 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. To cite one example, the latest small IBM dot-matrix printer (introduced in 1985) involves only 60 parts, as compared to 150 parts for comparable units built only two years earlier.[11] Much of the reduction in parts number 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 example comes from Black & Decker Mfg. Co., the world's leading producer of electric hand tools. A comprehensive redesign and simplifciation 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 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.

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

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 emerge. 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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