A SYSTEMS APPROACH TO CONTROLLING SEMICONDUCTOR MANUFACTURING OPERATIONS

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ABSTRACT

Semicoductor manufacturers, faced with stiffening competition in both product cost and quality, require improved utilization of their development and manufacturing resources. Manufacturing philosophy must be changed, from focusing on short term results, to support continuous improvements in both output and quality. Such improvements demand better information management to monitor and control the manufacturing process. From these considerations, a process control methodology was developed using concepts and tools from cybernetics and statistics and was successfully applied in semiconductor fabrication plants. Three case studies are included to demonstrate the use of the methodology on specific manufacturing problems.

INTRODUCTION

American industries are increasingly supporting the idea that the best way to handle competition is to focus their efforts on meeting the expectations of customers. These expectations generally are for improved quality, reduced prices, on time delivery, and better service. Unfortunately, while there is a lot of agreement on what industry should accomplish, there is much less agreement on how to go about it. investments in new technology, and judicious selection of suppliers and markets are certainly necessary, but are not sufficient to maintain competitiveness in the long run. Quality and productivity programs, even when successful, generate improvements too slowly to keep pace with the constantly accelerating demands of the market. Furthermore, these programs create a drain on management's time and attention which should better be directed toward long-range corporate planning and technological issues. The evaluation and improvement mechanisms we apply to our manufacturing systems must become an integral part of the system itself, as opposed to the add-on 'programs' we apply today.

Modern manufacturing systems are typically part of an extended chain, which 1 inks suppliers, producers, and consumers. Each manufacturing system acts as both a customer and a vendor. Quality and quantity problems arise in the manufacturing chain, as a resuit of the complex cause-effect and input-output relationships which exist both between operations and between manufacturers. Consequently, management is presented with complex problems which extend beyond the boundaries of individual plants, increasing the difficulty of realizing quality and productivity goals. In many cases, the harder management pursue such goals, the more elusive they become (10).

Without knowledge of the range of achievable levels of performance, it is impossible to know the effort required to reach a specified goal, or to know if that goal can be attained at all. Based on proper information, however, realistic achievements can be defined and comprehensive measures can be developed to evaluate management performance. This requires an organization for collecting data with the intent of producing useful information. Such information is necessary for any meaningful change to occur. Facts about past performance, alone do not reveal what levels of performance are possible, or how to achieve them. For example, equipment utilization levels are facts and they indicate where we are, but they do not tell us how to achieve better performance. Information related to equipment reliability and equipment loadings, etc. must be available to explain if better performance levels are possible. When the system and personnel are confronted with goals based on incomplete or conflicting standards of performance, the system responds in an unpredictable manner.

In summary, the generation and processing of manufacturing information can accomplish four tasks. First, it indicates where we are in terms of performance. Second, it shows where we can go, i.e., it establishes our goals. Third, it tells us what changes are necessary to achieve the goals. Fourth, by creating meaningful measures of performance, it provides the correct incentives to respond to information and implement necessary changes.

The systems methodology which is the subject of this paper will create the information organization needed to meet our information requirements. The reader may reasonably ask why such a methodology is not being applied in manufacturing today, or how manufacturing could have gotten by for so long without it. The reason is that the need for such a methodology was not acutely felt in earlier manufacturing systems due to their modest information requirements. Also, in the complex systems of today the application of the methodology is far from trivial. Translation of systems concepts into actual manufacturing changes will involve developing an understanding of manufacturing complexity at a higher level than has been attempted before. The language of systems terminology must be developed to enable communication of the concepts among manufacturing personnel.

The rate of change in market conditions, in prices, and in product designs and specifications is greater in the semiconductor industry than in almost any other sector of manufacturing. Furthermore, these rates are constantly increasing. Prices drop so quickly that previously successful product lines can be rendered uncompetitive in a matter of weeks. Demand fluctuations make the planning of investments in equipment capacity and process technology very difficult. Expermentation with manufacturing technology and operations is done under increasing time pressure.

Independent of these difficult market conditions, the inherent complexity of semiconductor process development and manufacturing creates serious management problems. A very large number of engineering parameters must be controlled to produce a functional product. Quality standards are measured in parts per million, making it difficult to estimate quality levels.

Articles and books are published castigating management for having created their own problems, without however proposing any real solutions. Management is being admonished to improve quality, productivity etc., on the assumption that if management will simply adopt the right attitudes, participate in the improvement efforts, hire management consultants to advise on special programs or use the right slogans (e.g. talking about 'excellence', 'zero defects', etc.), success will be just around the corner. We propose that most management problems originate not in managers per se, but rather these problems originate in the information managing structure of our industries, or perhaps more correctly, in the lack of an information managing structure. Our information managing sophistication has fallen far behind the technological sophistication of the operations we attempt to run. What is needed today, and what we are proposing in this paper, is a information management technology.

Disciplines such as operations research and statistics provide tools to **improve** managerial and engineering decisions. The use of such tools is a necessary, but not a sufficient condition for major improvements in the performance of our industries. In other words, simply generating quantities of information with analytical tools will not help. An organized system for assessing the needs for and responding to information must also be designed. The design of such systems has been largely neglected by both operations research practitioners (1), and by practitioners in the information sciences.

Although the terms 'systems' and 'information' are widely used in management circles, they are used without understanding the depth or utiliity of systems theory and information theory. Our operations remain strikingly unsystematic. The design of integrated systems, which is one of the tasks of the systems methodology, is a synthesizing rather than an analytic activity. It involves putting things together instead of taking things apart. Systems are designed based on purposes and goals rather than simply adjusting some existing system to achieve an objective.

This systems methodology introduces concepts from cybernetics and general systems theory to organize the information requirements necessary for improving the efficiency and competitiveness of manufacturing. A large number of ρowerful systems concepts such as stability ,self regulation, feedback, etc. are available to us from previous work (2, 3, 4). This paper introduces some fundamental principles fur modeling manufacturing operations. These principles are used to build a structure for managing and controlling manufacturing processes. This structure allows for an intelligent decomposition of an entire manufacturing process into component parts. The information requirements for improving each part, and the synergy requirements between parts, are then assessed. Thus, the structure designs an integrated information network and the feedback mechanisms necessary for controlling individual operations within the process.

The methodology utilizes tools which ae divided into three categories, planning, analysis, and control, based on the function they perform. Planning tools are used to define, organize and communicate information. Analysis tools are used to generate information, from engineering and production data, based on specific objectives. Control tools are used to provide feedback to individual parts of the process. The structure and the tools, together, provide the means for handling manufacturing complexities.

This paper is divided into three parts. The first part introduces some of the basic concepts used in this methodology. The purposes is to emphasize the connection between meaningful changes in a system and the information required by such changes. The concept of 'constraint' is used to characterize the intrinsic structure of a system and the organization of that system. The second part develops a model for the manufacturing operation, including its interfaces with the rest of the process. The purpose of the model is to assess the goals of the operation, define the needs for information and organize and communicate the findings. Finally, the third part applies the conceptual framework and the model to process control problems. Three case studies, detailing excellent results using systems methodology in manufacturing, are discussed.

BASIC CONCEPTS

A. STATES, VARIETY AND CONSTRAINTS

The purpose of this section is to introduce and emphasize the connection between basic concepts such as system, complexity, organization and information. This is important if we want to answer questions such as the following : How complex can a specific system be? How can we measure its complexity or reduce it? How much do we need to know to control a system,or to change it ? To understand what kind of answers can be expected for such questions, we may start with some very simple systems to illustrate the fundamental principles.

In practical applications we are faced with the problem of controlling the output of a system. In general, this output is determined by the input and the internal workings of the system. Thus, to control the output we must understand how the input and the changes within the system affect it. Given a particular definition of input and output, a state of a system is associated with a particular transformation of input to output. Figure 1 displays a simple system, with two binary inputs, and one binary output. For example, states of the system could be logic gates such as AND, OR, NOR, etc. For the observer of the system, each state changes its behavior in terms of input-output transformations. The first point of interest is to measure the variety of the states of the system.

We define the variety of a set as the number of distinct elements in that set. The variety of a system is the number of possible states of that system. Similarly, the variety of the input or output is the number of possible inputs, or outputs, respectively. To calculate the variety of the states of the system, we raise the output variety to the power of the input variety (4). In the above example of the system with binary input and output, the input can assume four values and the output is of variety two. Hence the system variety is equal to 2 raised to the 4th power, or 16, and the system has 16 possible states. The variety of the states increases rapidly with increasing the input or output variety.

INPUT		STATES															
A	B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	0	1	0	0	0	1	1	1	0	0	0	1	1	1	0	1
0	1	0	0	1	0	0	1	0	0	1	1	0	1	1	0	1	1
1	0	0	0	0	1	0	0	1	0	1	0	1	1	0	1	1	1
1	1	0	0	0	0	1	0	0	1	0	1	1	0	1	1	1	1
		NULL	NOR	B > A	A > B	AND	NOT A	NOT B	EQUAL	A ≠ B	B	A	NAND	B ≥ A	A ≥ B	OR	UNITY

FIGURE 1

All possible states of a system with two binary input variables and one binary output

We are next concerned with the reduction of the variety of a system, given . set of input and output parameters. In the above discussion, we have implicitly laced no limitations on either the inputs to the system or its states. Since the va-iety of states is the output variety raised to the input variety, a restriction on the nput values reduces the system's variety.

A measure of the complexity of a system is the variety of that system. In Figure 2a, an arbitrary system with 5 binary inputs and one binary output has up to 2 to the (2 to the 5th), power, or about four billion possible states. If however, a structural constraint exists within the system, the variety of the system will be reduced, as is shown in Figure 2b. The system of Figure 2b has five inputs, and rne output, but it is decomposable into two subsystems, each with three inputs and one output. The complexity of each of the subsystems, assuming no further constraints exist within them, is 2 to the (2 to the 3). The complexity of a system composed of two subsystems can be no greater than the product of the complexities of the subsystems. In this case the square of 2 to the (2 to the 3), or about 65,000. This example illustrates the importance of utillizing constraints to reduce the complexity of a system by orders of magnitute, by partitioning the system into subsystems.

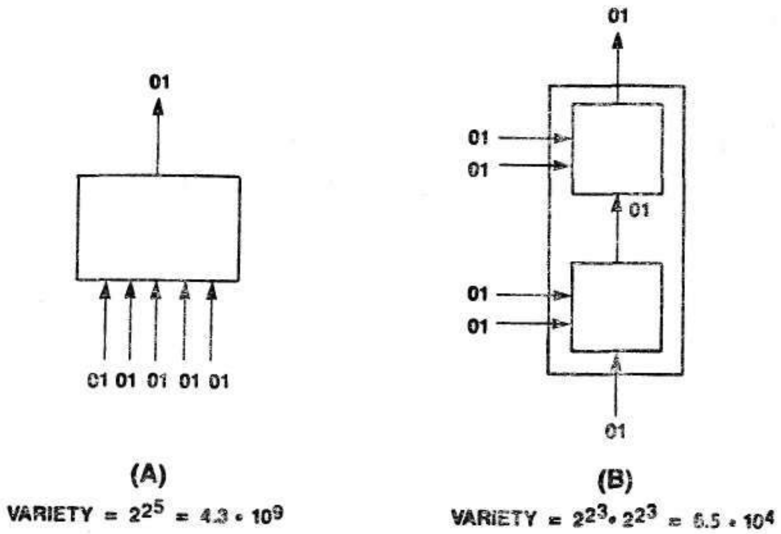


FIGURE 2

Reduction of variety using structural constraints.

Note : The assumption that the input-output relationship is sufficient to defie nthe states of a system is rather restrictive, and is used in the example for simplicity. In general, the concept of state involves the system's intrenal workings, and goes beyond simply being an input-output description. Any number of different states of a system can be indistinguishable from the tsandpoint of input-output. In practice however, there is no restriction on the use of additional input-output variables, internal to the system. Modelling these internal variables allows for additional states of the system to be distinquisabie.

B. VARIETY, INFORMATION AND ORGANIZATION

Given a system, we want to ask, (what is the state of the system?) Given no a priori constraints, we simply have to apply all possible inputs, and observe the output values. For the simple system, with two binary inputs and one binary output, there are 16 possible states. We may start by selecting (0, 0) as input. The output will be either 0 or 1, as shown in Figure 3. In either case the uncertainty of the

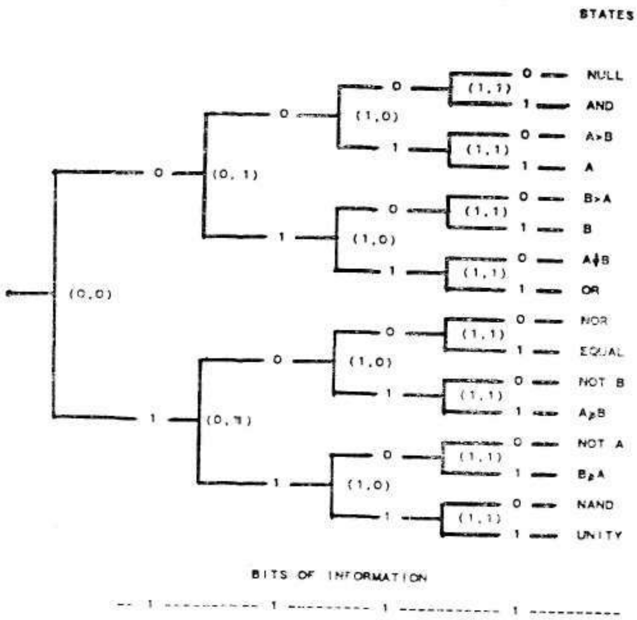


FIGURE 3
Selection of states and information requirements.

state of the system is reduced from 16 to 8, since there are only 8 states that yield zero, when both inputs are at zero. The information needed to distinquish between two values, such as 0 or 3, is called in information theory a bit. As Figure 3 illustrates, four bits of information are sufficient to specify the specific state of the system. Each time one bit is used to reduce the uncertainty by half. In general, a determination from among 2 to the N states requires a minimum of N selections or, N bits of information (2).

These simple exampies illutrate two important ideas which are relevant to real manufacturing problems. First they show how the complexity of a system can be greatly reduced when the intrinsic constraints of the system or any restrictions on its input-output values are considered. This is of great importance for understanding and managing the system's behavior. A good organization of the system is only possible when a proper structure of minimum complexity is formed incorporating all states needed for achieving the goals of the system.

Second, the selection of a proper state for the system, besides the specific goal for selecting that state, imposes certain information requirements. It turns out that such requirements are proportional to the complexity of the system. Management can only achieve its goals when the appropriate state selection is made. This selection occurs only if management receives and processes the necessary amount of information.

THE MANUFACTURING OPERATION

A. SYSTEM, ENVIRONMENT AND COMPLEXITY

A manufacturing process viewed as a system encompasses resources such as equipment, materials and people. This manufacturing process coupied with process technology resources are organized and utilized to yield certain products. Such a system is embedded in its environment, which includes the equipment and materia! vendors, the work force, the customers and the competitors. Such an environment is constantly changing : vendors introduce new equipment and competitors new products; prices are constantly fluctuating: changes in technology require new product and process design. Within the system, there are two basic needs for change; continuous improvement of existing resources and introduction of new technologies. For the system to be efficient, it must learn how to organize and utilize the existing resources to produce more and better products with minimum waste. To be competitive, the system must adapt to its environment by successfully introducing new equipment, process and product technologies. In any case, for meaningful changes to occur in the state of the system, relevant information is necessary. Figure 4 illustrates the management problem of coordinating such needs.

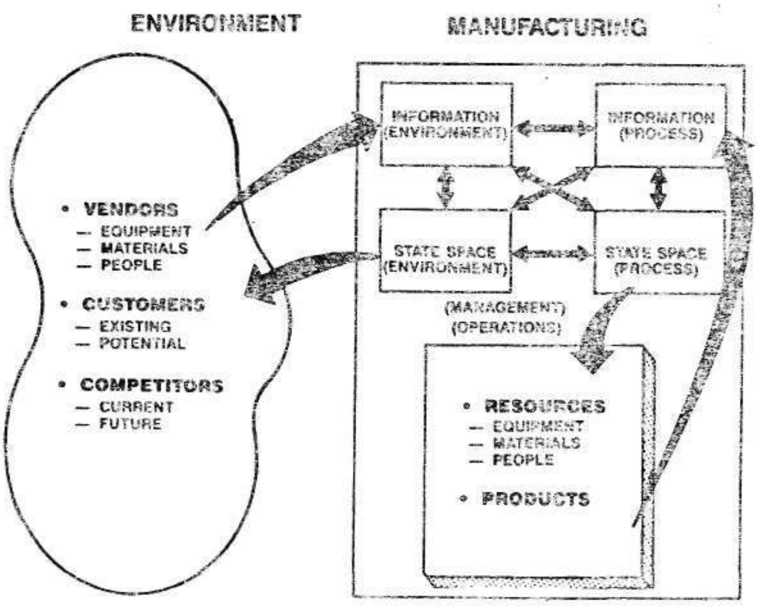


FIGURE 4

The system and its environment

If the basic systems concepts discussed above are to be of any use to management, the implication of such concepts to manufacturing problems must be carefully examined.

Unlike the simple deterministic systems considered so far, a manufacturing process is extremely complex. At each moment, there is a huge number of possible allocations of resources to specific tasks, each resource or product characterized by a large number of attributes. We define the state of a process at a given moment to be a unique description of everything characterizing that process. For example, the way lots are assigned to machines, operators to pecific tasks, the status of product parameters, etc., define the state of the process at each instant. As state space, we define the set of all possible states. The definition of the state space for real manufacturing is subjective. In general, such a definition depends on the observer of the system and his purpose (5, 6). For example, Production may define as a state of the process the attributes related to quantities, such as equipment availabilities work in progress operator schedules, materials inventory, rework levels, performance against schedules, etc. For Engineering, the state of the process may include attributes such as initial conditions, product quality characteristics, process variations, etc. In both cases, the state space must include sufficient resolution to distinquish between states which represent materially different operating conditions. For example, the color or car the process operator drives to work would not be distinguished in the state space.

We saw that the complexity of the simple systems considered earlier, as measured by their variety, was very large. We should have by now deduced that systems with only a few more input and output parameters could have literally astronomical variety. In such cases, the value of measuring complexity is only qualitative. We also saw that restrictions on the input values or constrainst within the system could be used to drastically reduce system complexity.

Real manufacturing systems have, in comparison with the simple systems discussed above, a much larger number of input and output parameters, and a much larger number of values which can be assumed by these parameters. Nevertheless, it is possible to manage manufacturing systems for two reasons. First, in real manufacturing systems, a large number of inherent constraints are present. Second, a great deal of complexity is simply ignored in practice. This ignored complexity is either imposed by the system's organization, by not allowing certain interactions between parts of the system to occur, or simply overlooked. In the case of ignored complexity, the reduction of complexity is obtained at the cost of discarding much valuable information, which results in a loss of opportunity.

This section develops a simple structure for modeling a manufacutring operation, based on the system's inherent constraints. The goal is to find the necessary and sufficient conditions for handling the complexity of the manufacturing operation without overlooking any states which may provide useful information for achieving the goals of the process, The organization of the structure should be thought of as something which is part of the system, not something added to it. Such a structure will provide the flows of information both within and between operations.

B. OPERATIONS ORGANIZATION

In a complex process involving a large number of operations, if every aspect of the process had to be decided consciously at the process level, the resulting information overload would bring the process to a stop. On the other hand, if each decision was made independently by each operation, the result would be chaos Thus we encounter the issue of centralized versus decentralized management. An analogy can be drawn for illustrating the two extreme cases. A ship is managed by a strict centralized command. A soccer team on the field is completely decentralized. If we think of both cases as a system, the first system is far less complex than the second. For the first system to work, most decisions must be made at the top, orders are given to subordinates, which in turn report the execution of such orders. In the second case most decisions are decentralized. Each player in the team has two specific tasks. The first is to match the variety of the opponent and seconf is to play synergistically with the rest of the team. This analogy suggests that for a simple system, with a limited amount of interactions between its parts, a centralized command is sufficient. As the system becomes more complex, with a large number of interactions between its parts, then the matching of complexity and the synergy between its parts become very important.

In this methodology, the ordering and reporting activities related to the parts of the system constitute the centralized management of the complexity of the system. On the other hand, handling the variety of each part of the whole is a decentralized activity. However, complexity concerning the synergy required between parts is part of both centralized and decentralized management.

A useful way to apply the systems concepts is to specify a set of subsystems (parts) and the connections between them, in a way that the criteria concerning the efficiency of the whole are met within the parts and their interactions. The subsystems may be considered as generating their own states, either independently of other subsystems, or constraint by those to which they are connected. This connectivity between subsystems create input-output connections internal to the system, as it was shown in the previous example (Figure 2). Also, the two subsystems, using the same example, were represented by subsets of the set of states associated with the overall system. Thus, the complexity of the whole is partitioned into its much less complex parts. Such a partitioning of the state space defines the structure of the system as dominated by the general characteristics and the purpose of the whole.

Returning to the manufacturing process, the answer to the problem of centralization versus decentralization, given by the systems methodology, is to use the constraints of the system to design a structure relevant to the goals of the process as a whole. This structure will allow the information requirements concerning the process to remain intact and, at the same time, the structure will reduce the complexity of managing the whole process.

Physically, each manufacturing process consists of a number of operations, each operation including its own resources, which are equipment, materials and people. These resources are utiliized to add a certain value to the end product. Based on the arguments given above, the following conditions are necessary and sufficient to handle the complexity of the system as a whole:

First, each operation should adjust its own activities to improve the overall process performance, independently of the other operations. These activities are related to the efficiency of existing resources, I.e. equipment, materials and people within operation used to meet process goals, such as product quantity and quality requirements. Second, each operation should work synergistically with other operations toward goals consistent with the goals of the process. This synergy is concerned with the interactions between operations and with the way each operation affects the others. In addition, the process must be able to impose changes in each operation dictated by the requirements for new technologies which may include changes in equipment, new processes, reduction of the work force, etc. This decomposition into individual operations, shown in Figure 5, allows for the process itself to be concerned with only part of the states of the system, the rest of the states being the responsibility of the operations.

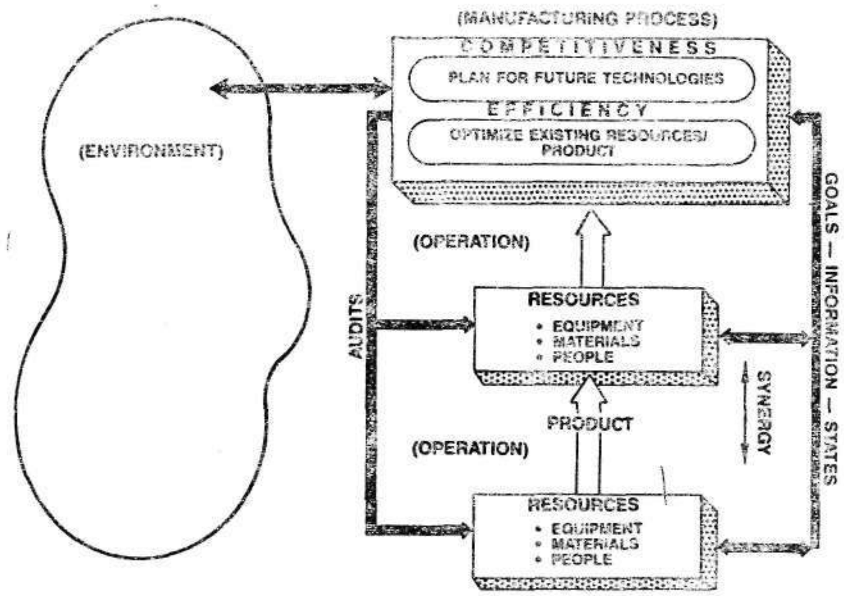


FIGURE 5

Process decomposition

C. ATTRIBUTES ORGANIZATION : QUANTITY AND QUALITY

A further constraint that we can use to reduce complexity is the symmetry between quality and quantity attributes. Both can be modelled under the same operational structure. We may view each operation as a system with a product entering the operation and then leaving after the operation is completed. The term Producer can be appled to indicate the attributes of both, the incoming product and the operational resource attributes. The term Product indicates the outgo ing product attributes. The state space of the operation can then be divided into states corresponding to the two basic product and resource characteristics, I.e. quality and quantity. For production problems, the input-output relationship is used to indicate this producer-product relationship. In engineering the term cause-effect is commonly used. Such a decomposition of the state space does not eliminate any operational states. Instead it is intended to integrate the needs for quantity activities under the same modeling structure. Then, a common language can be developed to model both quantity and quality problems within the same information channel.

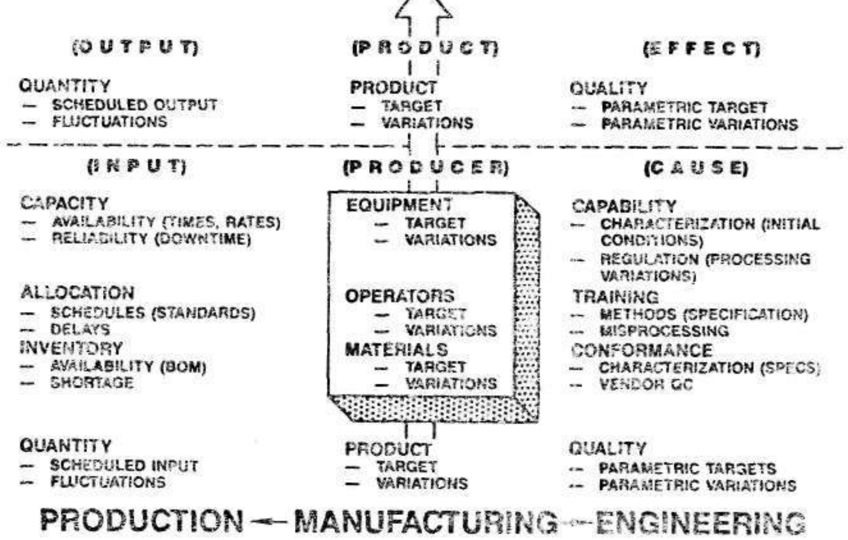


FIGURE 6

The producer - product classification

If the operation is viewed as a system with producer and product, with objectives and suitable measures of performance, then there is a correspondence between production (or quantity), and engineering (or quality). Figure 6 illustrates this correspondence, or duality, between quantity and quality.

In terms of quantity, the producer (input) may be the resource capacities, such as equipment availability, uptime, rates, etc. along with the product inventory while the product (output) will be the product inventory available for the next operation.

For quality, the producer (cause) may be the quality characteristics of the incoming product, along with initial conditions, such as equipment parameters (temperature, pressure, etc.), and the product (effect) will be the product quality characteristics after the operation is completed.

The metric used for quantity is a set of standards, such as run rates, operator standards, etc., where for quality the corresponding metric is a set of specifications for equipment parameters, engineering parameters, etc.

D. INFORMATION CHANNELS FOR THE OPERATION

Based on the constraints described earlier, i.e. the process decomposition and the quality and quantity symmetry, the centralized and decentralized information requirements are listed below :

a. At the process level (Centralized) :

1. Information concerning operational efficiency :

    I. Resource capacity and product quantity indicato rs
    II. Resource capability and product quality indicators

2. Information concerning synergy between operations :

    I. Operational interactions concerning product quantities.
    II. Operational interactions concerning product quality characteristics.

Such information requirements are not concerned with any transactions at the operational level. Individual operations can create their own information concerning their resource efficiency. However, data and information concerning such operational transactions should be stored and be available for process audit.

b. At the operation level (Decentralized) :

1. Proper information channel within each operation :

    I. Information to generate resource capacities.
    II. Information to generate resource capabilities.

2. Proper information channel between operations :

    I. Information related to the effect on other operations.
    II. Information related to the effect from other operations.

E. TOOLS ORGANIZATION : PLANNING ANALYSIS AND CONTROL

For manufacturing operations, we have so far assessed only the needs for information. Now we become concerned with the generation of that information. There is a plethora of statistical and operations research tools which are available provide useful information to management about a particular operation. Statistics provide tools ranging from simple histograms to factorial experiments and control charts. Such tools are tailored to assist the engineer to gain insight into the process by : identifying important factors to control, providing an understanding of the process variations, etc. On the other hand, Operations Research tools, ranging from simple planning networks to mathematical optimization and simulation can assist production in utilizing the resources more efficiently. Though there are areas of overlap, statistical tools are focused primarily on quality, while operations research tools are focused primarily on quantity.

How many tools are available ? What does each tool do? How can we select and apply the proper tool ? These are typical questions that practitioners in manufacturing are faced with. Each tool has a specific capability and makes certain assumptions, which the user must understand. In this methodology, we classify all such tools into three major types, based on the tasks they perform related to information needs :

The first type of tool is related to the planning for information, or the definition of the state space. This requires the input of experts, such as engineers, production managers, etc. This input includes a description of the manufacturing system, i.e. the state space of the producer and the product and an understanding of the goals of the operation. The second type is related to the generation of information, or the analysis, or search, or the state space and the selection of acceptable states. This requires an understanding of analysis tools and how to collect proper production or experimental data. The third type is concerned with information related to the control for specific states. This type creates feedback for the operation when an out of control state occurs. For each basic function, Figure 7 iliu strates examples of tools for quality and quantity problems.

For example, in the planning phase of an engineering problem solving effort concerning a specific a specific operation, a cause and effect diagram may be used to describe the relationship between initial conditions and product quality characteristics, *to* define needs for specific information and to document and communicate the problem. In the analysis phase a factorial experiment may be used to generate information concerning the important factors to be controlled (7). '

Finally, a control chart can be implemented in the control phase to monitor the product parameters.

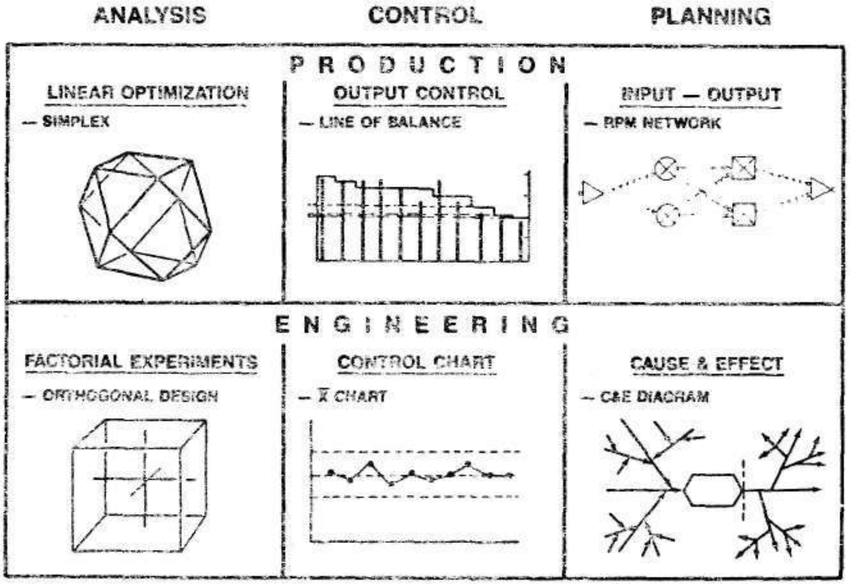


FIGURE 7

Planning, analysis and control tools for quality and quantity

In a production problem, the same approach can be used to define and create the relevant information. An input-output model between operational resource capacities and product output volumes may be developed for planning of production (8). The model defines the needs for specific information, and documents and communicates the information. The simplex algorithm may be used for analysis to provide a production schedule. Finally, the line of balance (9) can be used for control to monitor the performance against schedule.

E. THE OPERATIONAL MODEL

Using the few concepts explained so far, we are now able to put the pieces yogether for modeling the complexities of manufacturing operations. Our purpose is to implement the concepts of systems, the structure for handling complexity, the functions of the operation and the tools together in the same framework.

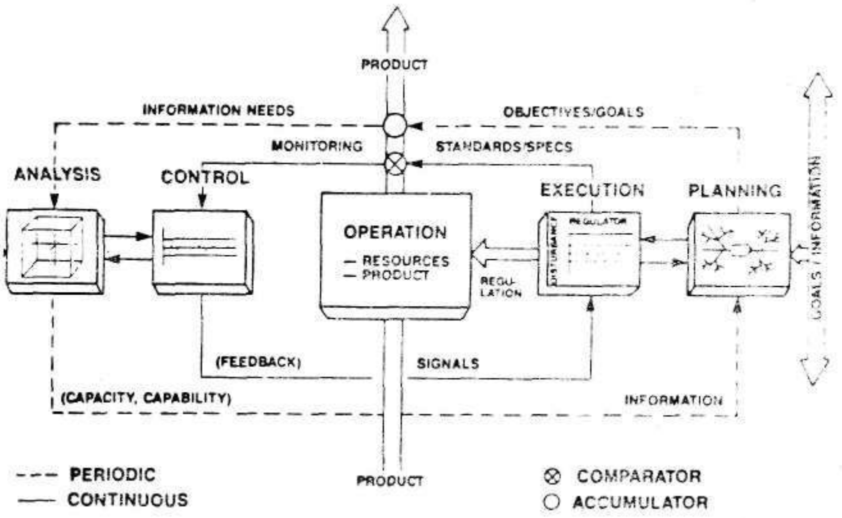


FIGURE 8

The model of the operation

Figure 8 Illustrates the systems modeling for the manufacturing operation. Within the operation the equipment the people and the materials are organized to work on the product that enters the operation after the previous operation is completed. Product attributes from previous operations are available to the operation. There are two loops in the information model, the outer loop which ties the planning and analysis functions, and the inner loop which ties control with execution. The purpose of the outer loop is to define and generate the information requirements related to the efficiency of the operation, and to the synergy between the operations, based on process goals as a whole. Then, the plans are sent for execution. Part of the planning and analysis function is the design of proper control mechanisms for the inner loop. The purpose of the inner loop is to receive the plans, to execute according to the plans and to report to planning. To insure that the goals will be achieved, the control function monitors the state of the operation continuously. Feedback is generated when an out of control state is present.

APPLICATIONS

The application of this methodology to specific process control problems is shown in this section. For such problems a cause and effect methodology was developed to define the problem and the goals of the operation, and to organize the information available at each stage of the problem solving effort. This cause and effect analysis is organized to take advantage of any constraints which may used to reduce the complexity of the state space of the problem. Figure 9 shows the Cause and Effect diagram based on such considerations.

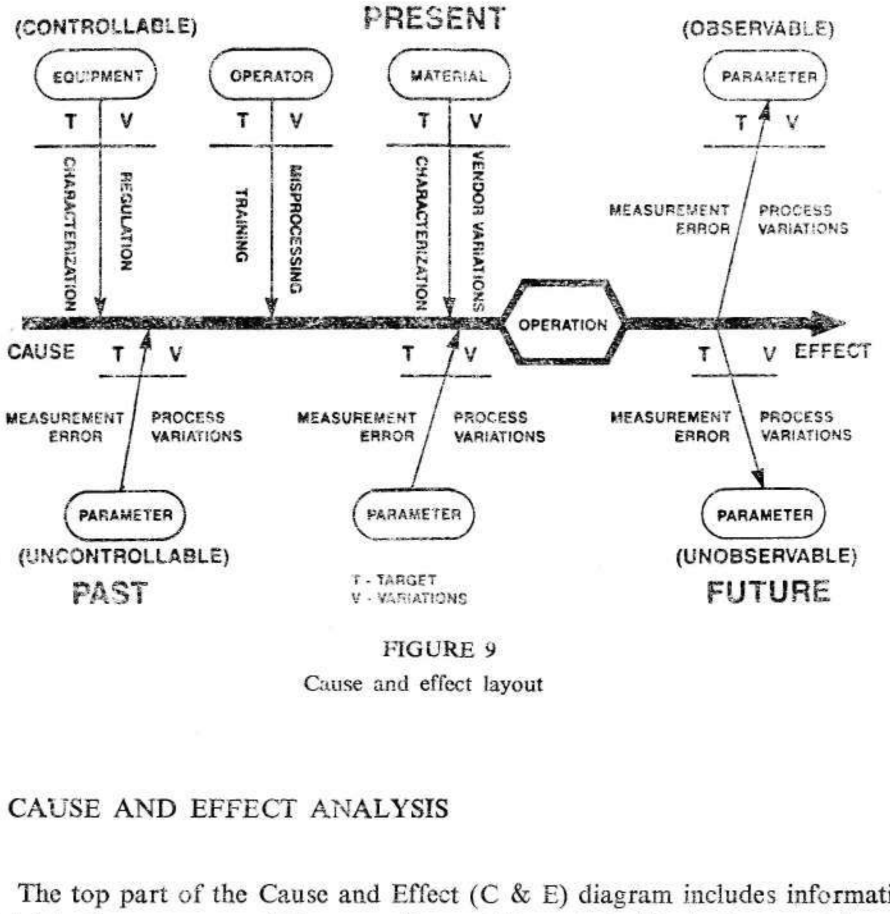


FIGURE 9
Cause and effect layout

A. CAUSE AND EFFECT ANALYSIS

The top part of the Cause and Effect (C & E) diagram includes information related to the resources of the operation and its output. The bottom part is used for information related to the synergy with other operations. Figure 9 illustrates the layout of the C & E model. The idea is to decompose the causes and the effects according to the dynamic environment of manufacturing.

For this decomposition to occur the following definitions are important. The term Controllable is used for the resources such as the equipment and operators of the operation. Uncontrollable refers to the product parameters coming to the operation from previous steps in the process and affecting its output product parameters. Observable refers to the ability to monitor a specific product characteristic before any other operation takes place. [Inobservable refers to the effect on the product observed in a later step, or at the end of the process. Thus, controllability and observability refers to the specific operation within the process and the other two terms refer to the synergy between operations.

Effects are normally characterized by their statistical distribution. The important parameters of such a distribution are the target value, such as the mean, and their variation about this central value, such as the variance. Causes typically act on either the central value, or the variability of the effect. Causes which affect the centra! value are usually controlled. Equipment parameters such as, temperature, pressure, processing time, etc., are generally of this type. More complex causes occur due to production variations and affect the variability of the output. Such sources of variation include either variations in equipment, materials, etc. The C & E diagram is designed to distinquish between these two different sources of process variations.

I. Observable effects :

Observables are product characteristics visible from within the current operation, either engineering parameters or defect rates. For each of these data types, there are two sources of variation, measurement error, and variation in the process itself. Measurement error is of three types, (i) measuring equipment error, (ii) operator variability, and (iii) sampling procedure. Process variation occurs (i) within, a unit, (ii) between units, (iii) lot to lot, (iv) shift to shift, etc. Observables are typically characterized statistically, as by their mean and variance, for example.

II. Unobservable effects :

[Inobservables are product characteristics which are not known until later steps in the process have been performed. To control unobservable parameters, we require their correlation with observables, such correlations being part of the information needs. Like observables, unobservables are characterized statistically.

III. Controllable causes :

Controllables are causes of product variations due to operational resources e.g. equipment, operators, etc. For each resource, information is needed concerning its relationship to the observable and unobservable effects. The systems methodology serves to define such information. Specifically, for the equipment we include variables such as temperature, pressure, etc., which affect the target values for the parameters. On the other hand, equipment drifts, preventive maintainance schedules, equipment to equipment differences, etc. may create variations in the output parameters and they are also part of the C & E diagram.

IV. Uncontrollable causes :

Uncontrollable s are product characteristics coming from previous operations. Such parameters may create causes of variation for the observable parameters and should be identified and controlled.

B. CASE STUDIES

The process control methodology based on these principles was tested in a semiconductor fabrication plant. The particular process was a CMOS technology for 256 K DRAMS. Briefly stated, the fabrication of integrated circuits requires a method for accurately forming patterns on a 100 millimeter circular substrate of silicon called a wafer. This procedure is repeated for different layers on the same product. A photoengraving process known as photolitho-graphy, or simply masking, is employed for the purpose. The basic operations in masking are : (1) Photoresist : the wafer is coated with a layer of light sensitive material called photoresist; (2) Expose : the wafer is exposed to ultraviolet light through a photomask, which is a glass plate bearing the pattern for a single layer of integrated circuitry; (3) Develop: removal of unwanted photoresist leaving the desired pattern on the wafers; (4) Etch: the wafer is next exposed to an agent, which selectively attacks the film formed in the previous processing steps transferring the photoresist pattern to that film. Since this cycle is repeated many times during the fabrication of a specific product and due to tiny geometries involved, photolithography is in many ways the key to microelectronic technology (11).

The first three case studies were from photolithography. The results of the application of the methodology in these three cases are briefly described below. The planning, analysis and control functions are represented by some simplified examples. The reader should be informed that the actual problem solving exercises were far more demanding than the simple descriptions may suggest. In rach case a large number of factors were involved. Noise in the data created in many instances major problems. Such noise is due to the difficulty in making accurate measurements with geometries such as the ones involved in wafer fabrication. In addition, when the problem solving is done under production pressures, it is not easy to plan a large number of experiments for evaluating all possible factors nvolved in each case.

CASE STUDY !

-

The Problem :

This case study relates to a sequence of etching operations occurring in one of the masking layers. Approximately 40 % of the lois processed through the final etching operation were falling outside the specification limits. These limits were set *to* control the observable parameter (thickness). The out of spec lots had to be re-etched creating a manufacturing bottleneck due to limited etching equipment capacity. At the end of the whole process lots that did not pass the electrical testing were screened and scrapped. Some key aspects of the case study are given by function :

Planning :

A cause and effect analysis was initiated to evaluate the sources of the parametric variations. The following parameters formed the state space for the C & E diagram. (Fig. 10).

(1) Controllable factors such as the etching equipment.

(2) Uncontrollable causes coming from previous etching steps, such as engineering parameters.

(3) The observable parameter.

(4) The Unobservable parameter (electrical test at **the** end **of the** process).

Analysis :

(1) The components of process variations for each engineering parameter, such as location to location across the same wafer ,wafer to wafer within the same lot and lot to lot were estimated using a statistical routine known as nested design (7). These components were found to be almost identical, between the in process and the electrical parameter, both with a large lot to lot component.

(2) A correlation between one of the uncontrollable parameters and the observable was found from production data indicating a transmission of error due to targer variations coming from the previous step. This transmission error explained most of the remaining process variations. (Fig. 10).

(3) Equipment to equipment variations in the output parameter was **found to** cause some of the re-etches.

Control :

(1) A new sampling procedure to account for across the wafer monuniformities was put in place at the end of the study.

Results :

The information thus obtained was used to eliminate the causes of the major process variations. As a result the operation ceased from being a manufacturing bottleneck, the electrical parameter fell within the specification limits (Fig. 10) eliminating the need for screening and scrapping out of spec wafers. The monitoring procedures were also considerably reduced, eliminating unnecessary inspe" ction.

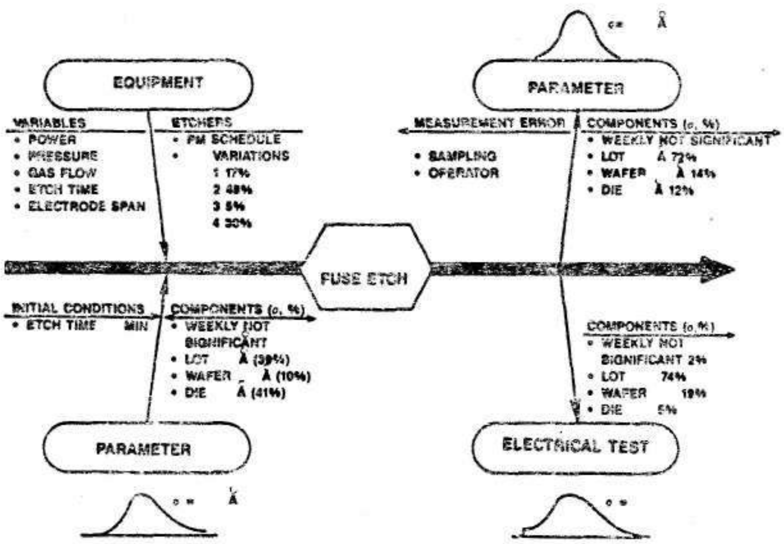


FIGURE 10A

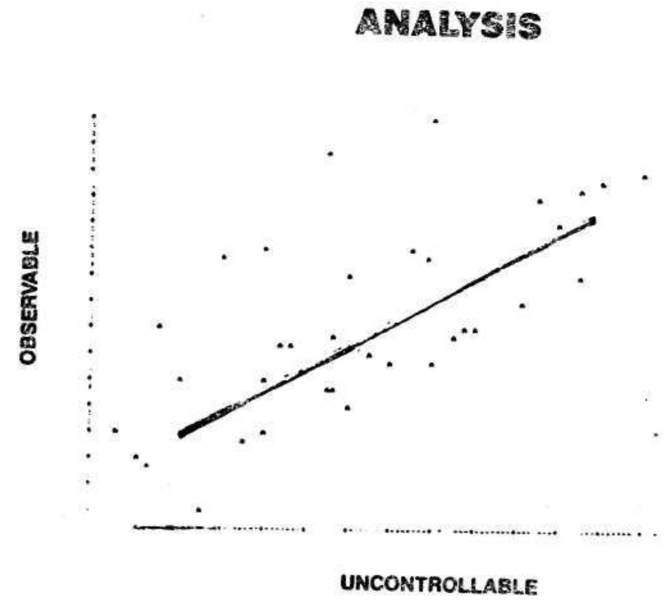


FIGURE 10B

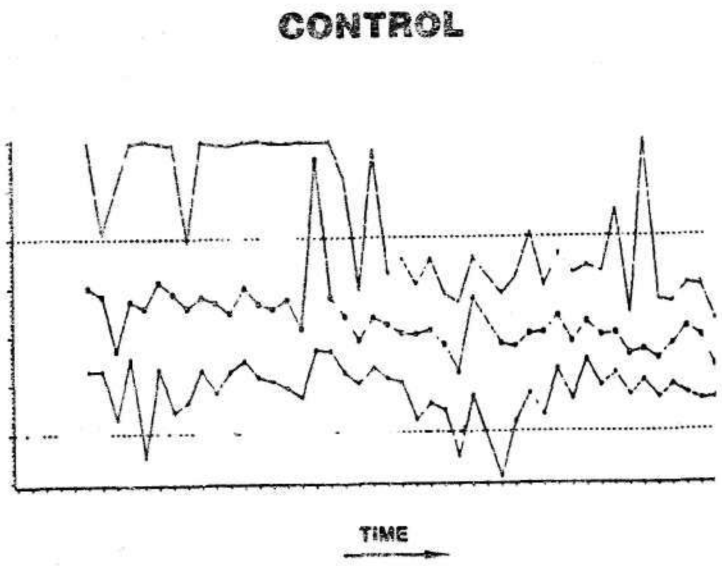


FIGURE 10Γ

FIGURE 10A, B, Γ= Case Study 1 : Planning, analysis and control tools

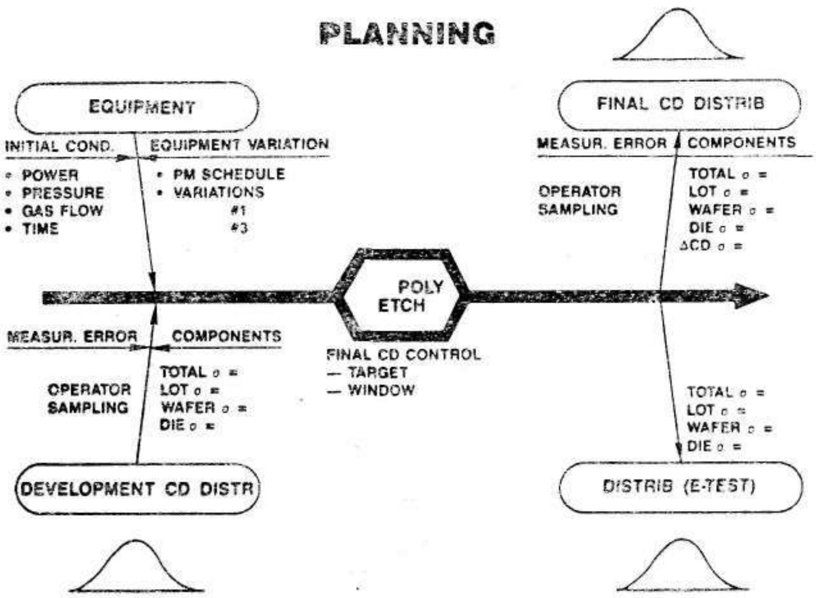
CASE STUDY 2

The Problem :

The second case study involved the control of the critical dimensions of polysilicon lines. The variation of the critical dimensions around a targeted value resulted in an estimated 10 % loss in product yields. This estimation of the loss was a result of correlation between the critical dimensions and the product sort (i.e. good from bad die) yields. Thus the need to tighten the output parameter.

Planning :

A cause and effect analysis was initiated for assessing the state space and the information needs (Fig. 11).



FIGUE 11A

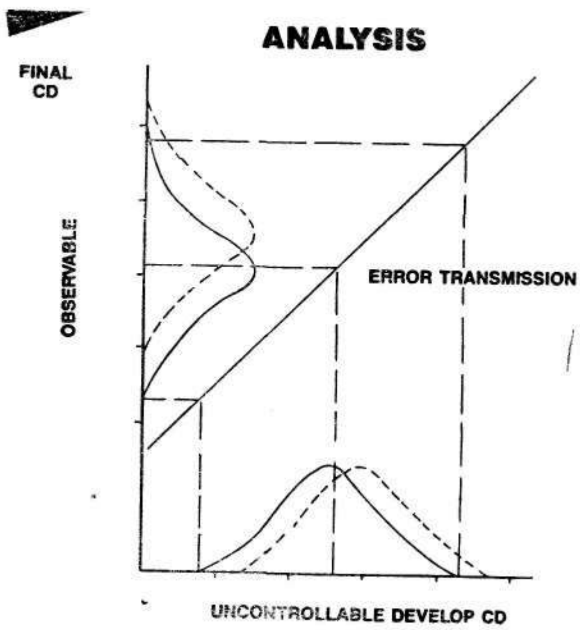


FIGURE 11B

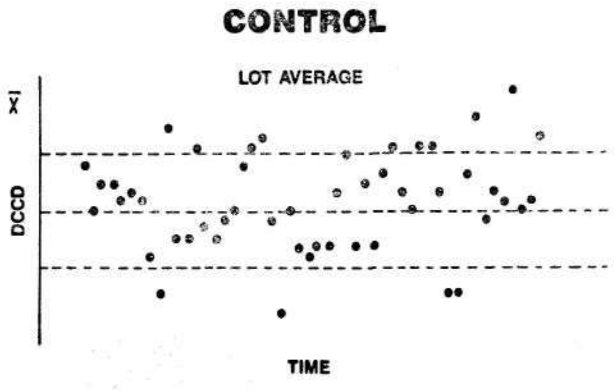


FIGURE 11Γ

FIGURE 11A ,B, Γ=Case Study 2. Planning, analysis and control tools.

Analysis :

(1) A component analysis for location, wafer and lot level process variations indicated a large lot to lot variation.

(2) Analysis of variance showed that such a variation was not due to controllable factors.

(3) Correlations between uncontrollable (develop CD) and observable (final CD), showed transferred error from the expose and develop operations. This is shown in Figure 11.

(4) One of the photomask plates used during expose was found to contribute to the variations of the incoming parameter, as shown in Figure 11 (control). I was eliminated to reduce the transmission of error from expose to etching.

(5) Also, one of the pieces of equipment was found to create a large across the wafer variation.

Centre! :

(1) A sampling procedure and control charts were used to indicate out of control conditions.

Results :

The process standard deviation was reduced to a half of the previous value. As a result of the tighter control of the output parameter there was no yield loss due to that specific parameter.

CASE STUDY 3

The Problem :

The third case study is related to the expose operation for all the masking ayers in the process. Before each lot was exposed, one wafer from the lot was Iprocessed through the expose and develop. After develop, the wafer was checked for proper alignment and critical dimensions. If the sample wafer (or test wafer) was within certain limits, then the remaining wafers in the lot were processed through the same steps. Otherwise, based on the test wafer results, an adjustment was made to the initial conditions of the expose operation. The test wafer feedback mechanism was creating long idle times for the manufacturing line.

Planning :

The cause and effect procedure was used to evaluate the complexity of the large number of resources, such as the equipment, the materials such as photomasks, the operators, etc. Also, a pilot line without test wafers was set up to evaluate no test wafer' production. (Fig. 12).

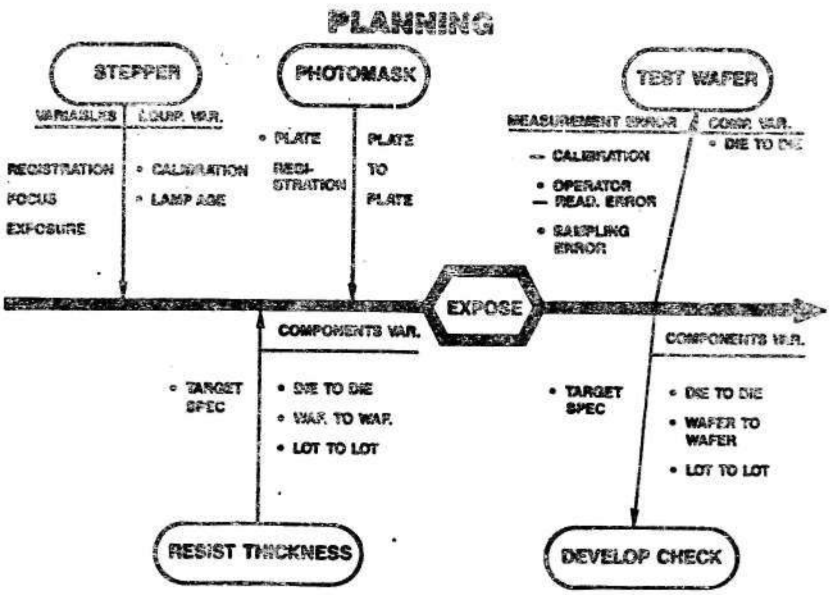


FIGURE 12A

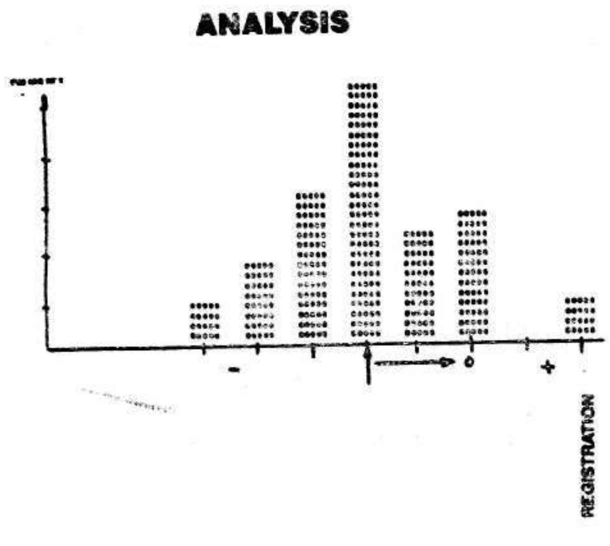


FIGURE 12B

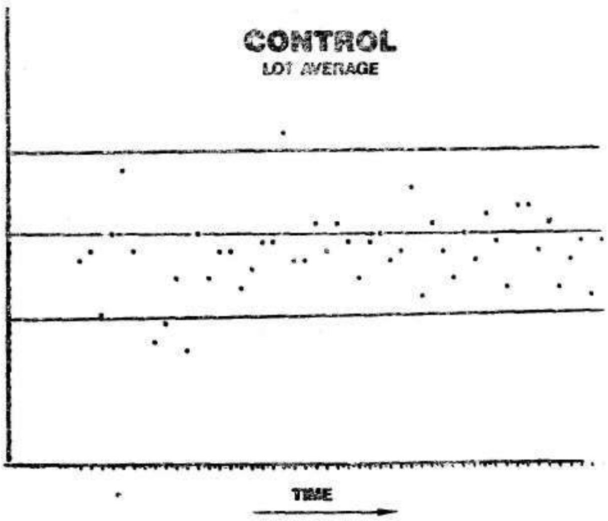


FIGURE 12Γ

FIGURE 12A, B, Γ=Case Study 3. Planning, analysis and control tools.

Analysis :

(1) To evaluate the effects, a component analysis to estimate the output variations was undertaken, based on historical data. These output variations included develop check operator consistency, operator to operator reading errors and sampling error.

(2) The dominant variation was the operator to operator reading error. The readings were made visually on wafer structures.

(3) To explain the output variation, equipment to equipment and plate to plate differences were analyzed.

(4) Equipment calibration errors were analyzed by equipment. (Fig. 12).

(5) A number of plates were found to create large variations in the output.

Control :

(1) Visual inspection changed to minimize reading errors.

(2) Equipment calibrations changed. The new calibrations were made based on production trends.

(3) Initial conditions were changed based on signals from control charts. (Fig. 12).

The results showed that an average of 42 % more wafers were processed without test wafers. At the same time the output parametric distributions were kept with the same standard deviation and the percent rework was slightly reduced. The process inspection procedures and sample sizes were significantly reduced.

SUMMARY

This paper introduced some fundamental notions of a systems approach to manage manufacturing operations. It was argued that management needs a new approach to handle the complexities of their sophisticated operations. The systems methodology addresses the information organization required to bring meaningful changes for continuous improvements and new technologies. The design of efficiently managed manufacturing systems is possible, if we only persist in becoming familiar and utilize such concepts.

ACKNOWLEDGEMENT

The author is grateful to Bruce Graether, Gene Meieran an Court Hilton for their valuable input concerning the clarification of ideas presented in the paper and for their constructive criticism related to this methodology.

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