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11. "Manual" Control Models of Industrial Management*

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The industrial engineer is often required to design and implement control systems and organization for manufacturing and service facilities, to optimize quality, delivery, yield, and minimize cost. Despite progress in computer science most such systems still employ human operators and managers as real-time control elements. Manual control theory should therefore be applicable to at least some aspects of industrial system design and operations.

Formulation of adequate model structures is an essential prerequisite to progress in this area; since real-world production systems invariably include multilevel and multiloop control, and are implemented by timeshared human effort, this is a nontrivial problem. Since structures proposed by Haberstroh (ref. 1), Beer (ref. 2) and others appear inadequate, a modular structure incorporating certain new types of functional element, has been developed. This forms the basis for analysis of an industrial process operation.

In this case it appears that managerial controllers operate in a discrete predictive mode based on fast time modelling, with sampling interval related to plant dynamics. Successive aggregation causes reduced response bandwidth and hence increased sampling interval as a function of level.

Data of Jaques (ref. 3) on the so-called "time-span of discretion" are cited in support of specific hypotheses concerning the influence of level of control on manual control requirements of managers.

INTRODUCTION

Dated from Arnold Tustin's pioneer study of tank gunnery (ref. **4**), the engineering approach to manual control is now *25* years old and well advanced both in theoretical and design capability. The time therefore seems ripe for a serious attempt to extend its range beyond the original fields of weaponry and vehicular control and find potential applications in other major system design areas. Interpreting the term manual control in a relatively broad sense, there would appear to be many possibilities, since nearly all systems and institutions from the largest† to the smallest use manual control in one form or another. Reviewing various fields, engineers are likely to be attracted to those where **(1)** existing control structures are relatively stable, environments well-defined, and performance specifications can be agreed; *(2)* there is an existing quantitative approach with supporting data; and **(3)** some possibility exists of persuading clients to implement new or modified designs. An additional criterion would be: **(4)** an evident need due to shortcomings in, or total lack of, existing design techniques.

One field meeting the first three of the above criteria is plant level industrial process control, used extensively in the oil, chemical, paper, food, and other industries. My earlier explorations (ref. **6**) suggested that manual control models could be of significant value in process plant design; however, automatic control techniques, implemented first with analog instruments and now increasingly with online computers, have been so successful here as to leave only a small field for manual control technology, however expert.

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† Tustin himself gave an early automatic control (frequency domain) analysis of macroeconomics (ref. 5), and suggested some "Equalization" policies. However, he did not consider manual control as found at Treasury level!

The picture is entirely different and in my view more promising at the next higher level of industrial control. We consider the production sector only here, though marketing and sales present similar problems. Analog instrumentation cannot be used, and as yet there are extremely few (if any) fully effective online computer control systems operating above the plant level, even in process industries which at first sight would appear to lend themselves to total automatic control (see for example, refs. 7 and 8). Thus almost all industrial control (as distinct from data acquisition, storage, and retrieval) is still implemented manually, sometimes based on explicit decision rules but much more frequently on human judgment. At a conservative estimate, a typical industrial plant employing 100 people implements some 500 to 1000 manual control loops, effective in frequency bands ranging from seconds to years; this estimate of course includes only sampled data or continuous control, and excludes other manual activities such as manipulation, data acquisition, and communication.

Techniques used by industrial engineers and management consultants to design and assist in implementing these highly important control processes, which are needed to meet product specifications and maintain quality, minimize cost, increase yield, and insure prompt delivery, do not currently include automatic control in any form, still less human operator theory. Among quantitative tools used are statistical quality control which is based on time domain statistics, and such operations research techniques as static optimization by linear programming, and network flow models. However, fully engineered dynamic design methods are conspicuously lacking, and in most practical cases good or improved dynamic response is secured only by online intuitive trial and error. In other words, viable control systems are not designed, but grow (if they do) organically.

This situation appears to present a direct challenge to the automatic and manual control fraternity, a challenge which has as yet elicited little response except from a few pioneers such as Sheridan (ref. 9). The present paper seeks to structure some of the problems involved in responding and to draw attention to some existing data which may be useful for this purpose. It also presents, on an admittedly speculative basis, the beginnings of a model structure which I feel may form the necessary basis for a rational design procedure. Unfortunately time and space constraints have permitted no more than a sketch map, which I hope will be expanded into a substantive contribution at a later date.

SYSTEM MODELS FOR INDUSTRIAL CONTROL

To arrive at a workable system model incorporating human control elements, we need (1) a valid flow diagram showing the control relationships between systems elements, both human and otherwise, and **(2)** compact quantitative characterizations of the various elements, expressed in input/output form.

Role Structures

In the industrial management case we cannot readily specify or trace a precise wiring diagram, since the intercommunication pattern found in even a small industrial plant is very involved (ref. 10). Nor are the individual response patterns of managers amenable to simple description. Brief field observation will readily confirm these statements. To simplify reality we must work with idealized role relationships and prescribed role behaviors, as indicated for example in job descriptions, rather than with actual behavior. Roles can be conceived as idealized "programs" which each role incumbent is supposed to execute; programmed behaviors include seeking and accepting specific types of data, processing it in a certain manner, outputting specific types of data or commands to other role players, and in some cases manipulating machine controls. The operating role structure and programs of a particular organization may, of course, depart widely from that given in written job descriptions; in case of doubt we must ascertain or reconstruct the true role structure from interview data. The control system is then abstracted from the role structure thus determined. Conversely, a control system designed for an industrial control application is implemented by written instructions to role players, supplemented by training on the job.

Previous Model Structures

The classical control model, after which most industrial organizations are patterned, is the bureaucratic hierarchy first described by the sociologist Max Weber late in the 19th century (ref. 11) and now familiar as the "organization chart" (see fig. 1). Taken literally, this describes an open-loop command structure, the only parameters being number of levels and span of control. A United Kingdom study by Joan Woodward (ref. 12) recently showed (fig. 2) that both of these vary widely with type of product and production technology. Span of control frequently, but by no means universally, decreases with managerial level. This parameter clearly describes a human timesharing phenomenon, and some attempts have been made to derive optimum values from a queueing model, but without marked success.

Considered as a control flow model the organization chart is obviously incomplete, making no provision for feedback and failing to identify system inputs and outputs. Despite much discussion, for instance by Beer (ref. 2) and Buckley (ref. 13), very few attempts have been made to construct more realistic and satisfactory structures adapted to theoretical analysis. Haberstroh (ref. 1) has provided perhaps the best case study to date, concerning the safety subsystem of an integrated steelworks. Figure 3 presents his model structure, together with a time history giving some indication of dynamic response. While interesting, this study was obviously far from complete, and failed to cover the actual production process for producing steel. A recent paper from the glass industry by Mouly (ref. 7) comes nearer to presenting a true system and begins to exploit the frequency domain approach to system response.

Proposed Model Structures

Model elements.—In this section we develop a control flow * model structure which seems in principle capable of representing fully functional control systems found in industrial production plant, without undue forcing or resort to ill-specified functions. The structure is based primarily on the familiar type of single or dual input/single output elements, here identified according to function as effectors, control elements, and receptors (see table 1). These are

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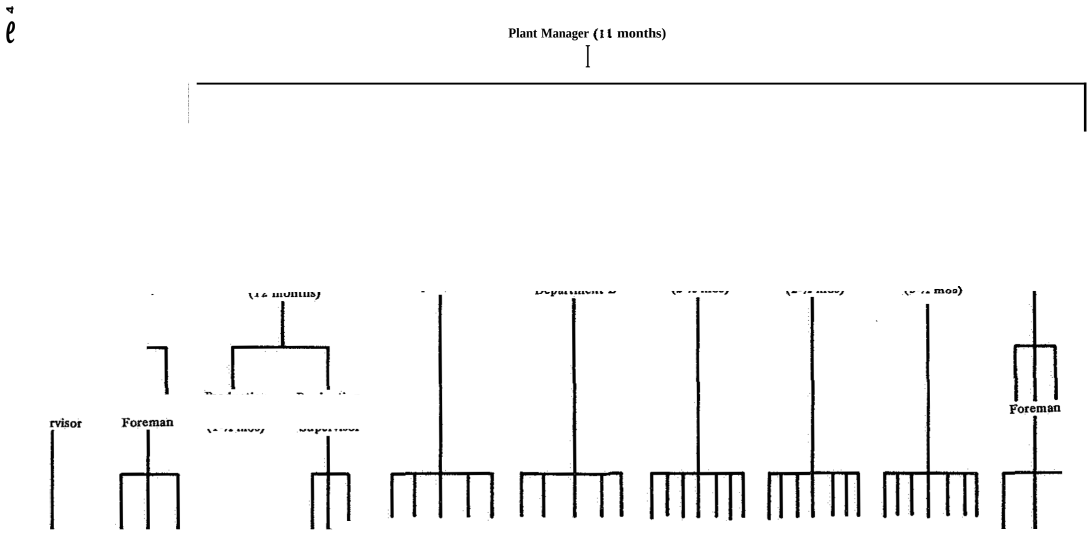
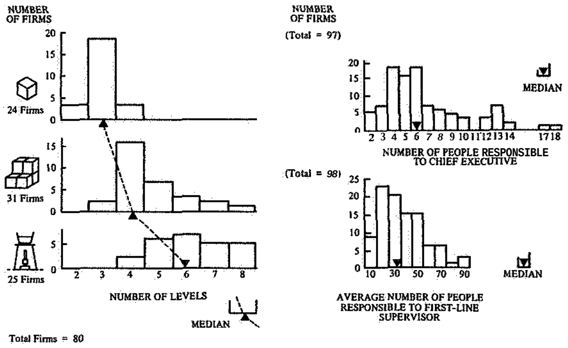
*One must, of course, carefully distinguish flow of control from flows of materials, power, labor, etc.

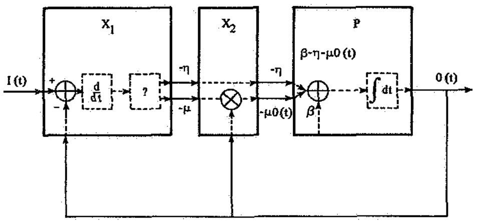




a) Distribution of number of managerial levels in firms using three types of production technology

b) Distribution of span of control at two organizational levels

FIGURE 2.—Field data on organizational levels and span of control (from ref. 12).



a) Model Structure

Year			Disabling Injuries					Total Injuries		
	Average All Plants	Error	Δ Error	Plant Performance	Error	Target	Plant Performance	Error	Target	Innovation
1	529	98	98	6 17			357			moderate
2	495	13	.85	5.08			422			none
3	541	1.77	1.64	7.18			407			heavy
4	466	124	53	5.90			302			none
5	366	61	51	433			244			
6	355	65	. 02	420	46	374	210	0	238	light
7	3 W	83	18	383	50	333	196	0	210	moderate
8	238	.81	02	319	12	247	183	11	172	light
9	2.07	63	18	210	.54	2.16	133	0	168	none
10	193	.91	28	284	80	2.04	128	0	133	heavy

connected in cascade, with loops closed around those elements (the effectors) which are most susceptible to disturbance and loading. Where implemented by human role players, these elements are assumed to function only intermittently, multiplexing switches being included to indicate the presence of timesharing.

Despite several attempts I found it impossible to construct a complete model using only these three elements and I have therefore introduced two new ones, termed respectively “multifiers” and “unifiers.” These are intended to represent control aspects of the branching structure seen on the organization chart (fig. 1), a structure which arises in practice out of three specific functional requirements, (1) more than one operation (or transformation) is usually needed to turn raw material into product, (2) most processes and operations are multidimensional, (3) production volume usually requires simultaneous performance of the same operation on different batches of raw material or semifinished product.

The unifier element represents the combination or melding of several initially distinct product dimensions or process outcomes into a single complex but measurable result or product dimension. For example, in blending gasoline, measured amounts of various paraffins and additives combine or are (‘unified)’to yield a certain octane rating. The unifier is a multi-input single-output element characterized by single-valued function of several variables, which may or may not include time.

The multifier element performs an inverse function to the unifier, and represents the process of generating two or more simpler subobjectives, goals or reference signals from a single complex objective. Thus the objective of producing a certain quantity of gasoline of a given octane rating must be “multified” or split up, into a series of production targets (or purchase orders) for the various components later to be blended. The multifier is a single-input multioutput element, and is characterized as a set of functions of a single input variable and time.

For simplicity, only four types of control variables or signals are identified here; these are (1) command or control variables *c*, (2) output or result variables *r*, (3) feedback variables *f*, and (4) disturbance or noise variables d. These will generally be available as time functions, but can be transformed into spectral functions for analysis.

Nested structure.—Using the five elements described above and listed in table 1, we can readily construct a multiloop hierarchical control structure capable of controlling or (‘managing’’ any number of effectors in the pursuit of a single complex time varying objective. The simplest possible inner-loop structure would be that of figure 4(a), with a single output dimension of a given process following up a single-dimensioned

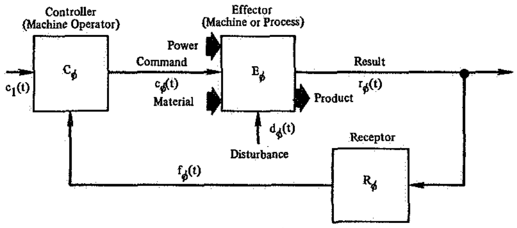
TABLE 1.—*Inventory of Model Elements*

	Function	Input	Transfer	output
Effector	Transforms incoming raw material or data into a desired state using power and other expendable resources	1 Reference signals or commands. 2 Disturbances 3 Feedforward data (above level 1)	Usually transport lag +lowpass filter. Often high-order	Dimensions of process or product.
Receptor	Samples, measures and encodes process or product quality or quantity dimensions	1 Process or product dimensions, etc. 2 State of environment	Sampling with small lag; sometimes high-pass filter	1 Feedback signals to controller. 2 Feedforward signal to controller.
Controller	Computes and issues reference or command to a single effector.	1 Reference signal from multifier 2 Feedback signals from receptor. 3 Feedforward data from receptor.	Generally the approximate inverse of corresponding effector.	Reference signal(s) or command to effector
Unifier	Combines two or more diverse product or process dimensions into a single "result", itself measurable.	Two or more process or product outputs.	A single-valued function of two or more variables.	Single dimensional reresult
Multifier	Derives two or more subobjectives or reference signals from a single complex objective.	A single reference signal from a higher level controller	A set of functions of a single variable.	Two or more reference signals to lower-level controllers.

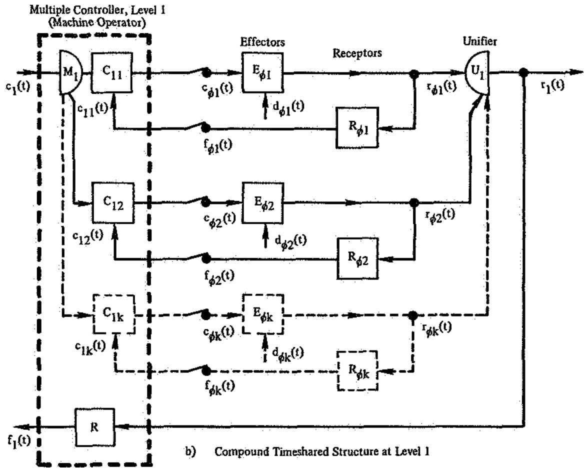
reference input under command of a controller supplied with feedback through a receptor. Typically this is implemented either as one subtask performed by a machine operator, or by a single analog process controller.

The typical skilled machine operator, however, both timeshares several such loop closures and determines for himself what the reference inputs to each loop shall be.* The outputs of the various effectors appear jointly in the product, whose overall quality and quantity should be that specified in the overall command input. Figure 4(b) shows the corresponding structure.

Since this parallel multiloop structure is self-contained, having only a single input and output, it can be regarded as a compound effector, and incorporated as a module in a larger structure



a) Innermost loop (Level ϕ + Control)



b) Compound Timeshared Structure at Level 1

FIGURE 4.—Production control structure.

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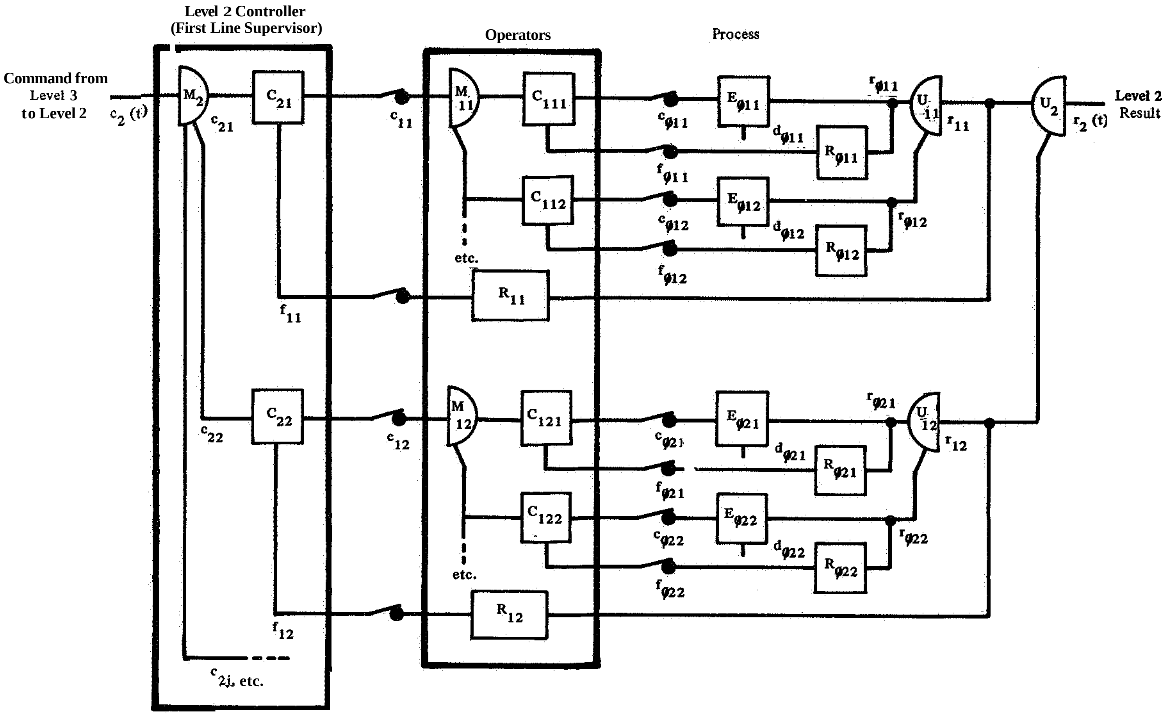
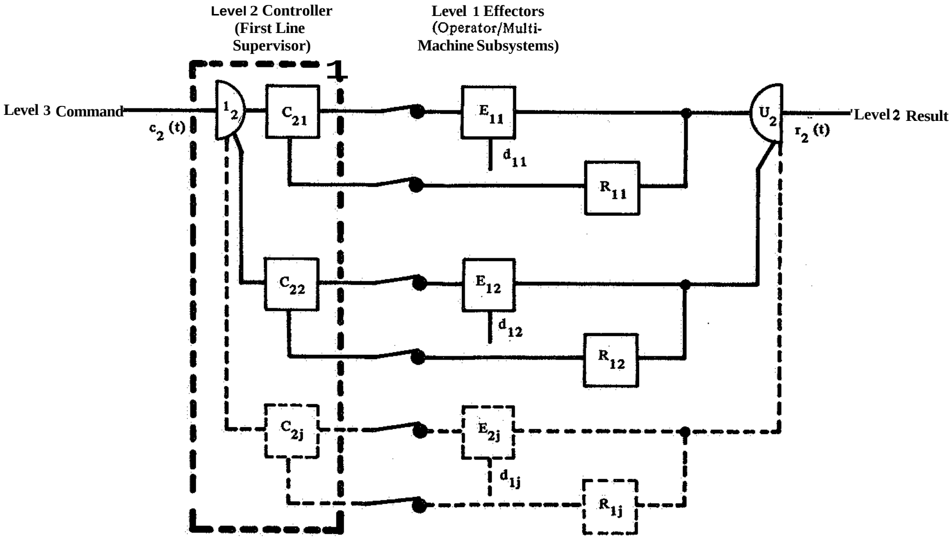
* We note in passing that timesharing need not occur at the micro level; the same structure applies to sequential performance of complete operations.



a) Full Level 2 Structure



b) Level 2 Structure Simplified by Treating Each Operator/Multi-Machine Combination as a Single Effector

FIGURE 5.—Production control structure.

comprised of elements with exactly the same interconnections as those already described. Thus we arrive (fig. 5(a)) at a representation of the industrial foreman or supervisors' function in delegating objectives to, and monitoring the results of, a number of operators, shown in simplified form in figure 5(b).

The modular structure thus developed can be nested to any desired depth (fig. S), provided that (1) all component results are at some stage molded in a single overall result, (2) all subobjectives devolve ultimately from a single global objective, and (3) all activities can be related in the same time frame. We note that forcing functions are represented as being injected into specific control loops by two distinct routes, one deriving ultimately from the global objective, and the other through individual innermost loop effectors. While the latter does not directly model human error, little is lost by failing to distinguish this from machine and environmental disturbance.

Cross-coupling between effectors is a leading feature of most production systems, but is not represented in the above structures. Its control effects can be shown by transfers between effectors as shown in figure 7.

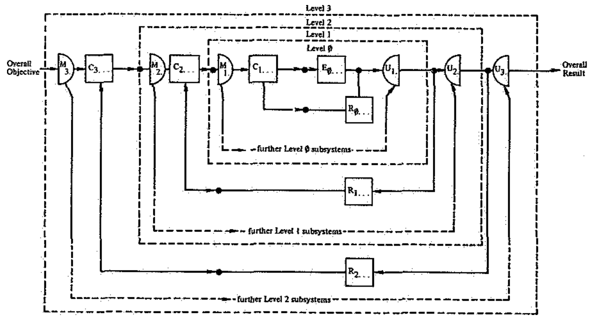
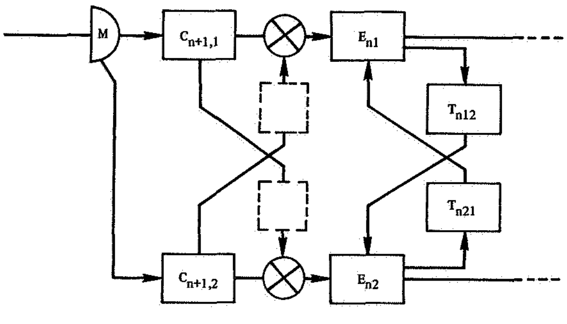
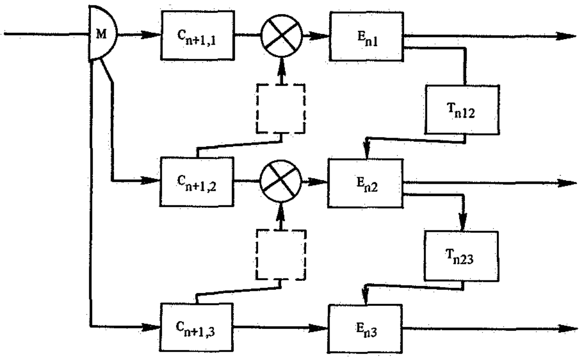


FIGURE 6.—Generalized multilevel timeshared production control system configuration.



a) Mutual Interaction



b) *Downstream* Interaction (Typical of Sequential Process)

FIGURE 7.—Representation of interaction patterns among effectors in an industrial process.

A case study.—With Office of Naval Research support, we have recently been able to obtain field data to permit modelling of the control aspects of two actual production systems using the structure described above, with coordinated time-span measurements as outlined below. The full details are, of course, quite voluminous and no attempt will be made to present them here. *As* an illustration of the structures obtained, figure 8 shows a single operator/machine model, including six loop closures and using a further subordinate man/machine system. This system produces a continuous product by processing given incoming materials to quality specifications laid down in standing instructions to the operator, in quantities specified in production schedules supplied by the foreman. Overall quality is subjected to inspection, but, as shown in the diagram, the operator performs online quality checks in each of the several quality dimensions involved. The operator in this case is experienced but not highly skilled in the conventional industrial sense. Disturbances arise as drifts and fluctuations in the process itself, in its environment (such as the power supply) and from fluctuations in raw material composition. In practice these are largely eliminated by the control mechanisms shown in the diagram, at least as far as the operators control "authority" reaches.

We hope to give a complete account of this case on a later occasion.

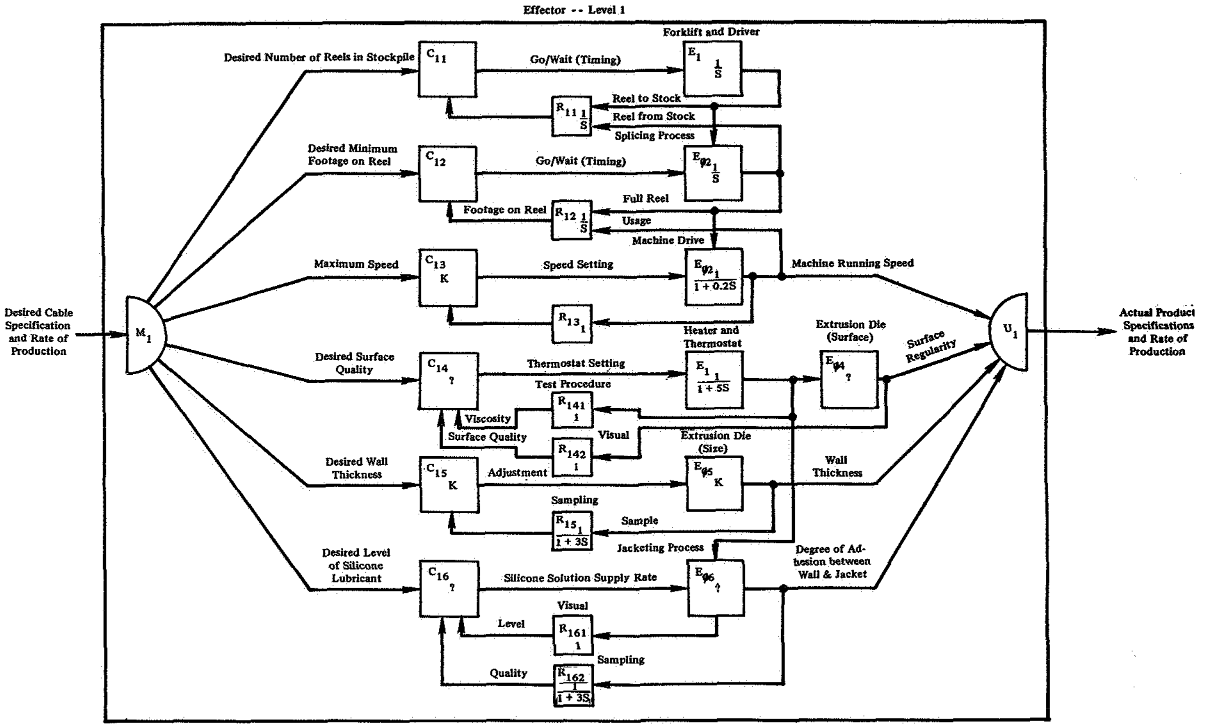


FIGURE 8.—Control structure for level 1 of a manufacturing process involving a continuously running special-purpose machine. Transfers expressed in cycles per minute. Control and receptor functions are timeshared by a single operator. One effector function is performed by a separate man-machine system (forklift truck and driver).

Application Goals

Assuming that models such as that described could be completed, and spectral descriptions of the various inputs and linearized transfers developed without large remnant terms, it would become possible to analyze system response to objective functions in the frequency band of interest to top management and disturbances expected to continue in the future. Components primarily responsible for steady state error, avoidable lag, and instability (if any) could then be identified and equalization forms developed. These would be implemented either by way of instrumental aids to the operator or manager (including computer-processed data) or through changes in role structure and required response of operators or managers. The latter would be installed by instruction and training; continued until the desired transfer was obtained. Such application possibilities seem, however, somewhat remote at present.

MANAGEMENT CONTROL CHARACTERISTICS

Since the control structure developed above is modular, it can in principle be nested to any desired depth; or, put the other way round, expanded to any level. We now consider the generalized role behavior required of the n^{th} level manager.

Desired Transfer

Figure 9 shows the generic control model of the level n manager, implementing one multifier function and two or more online controllers, the latter serving to regulate corresponding effectors, which (except at level 1) themselves contain complex control systems. Each such effector will be subject to disturbances not entirely eliminated by its own control system, hence creating a certain workload for its corresponding level n controller. Some of these disturbances will be predictable based on environmental data, and others

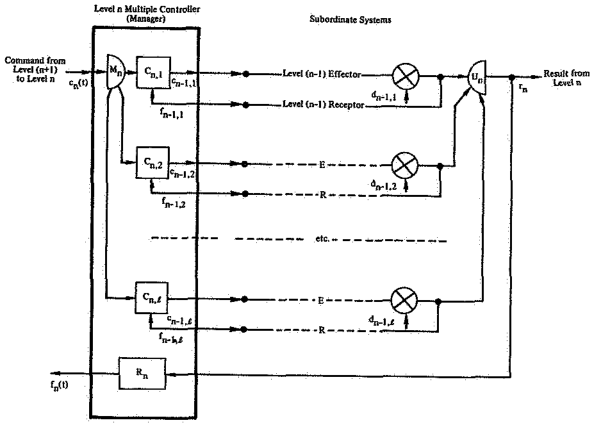


FIGURE 9.—Generalized manager model.

will arise from known cross-couplings between effectors, while still others will be random, hence unpredictable. Generally speaking, only disturbances within the pass band of the level $(n-1)$ effectors can be entirely eliminated, while the bandwidth of response to inputs from level $(n+1)$ is limited by the lowest level $(n-1)$ cutoff frequency. Hence, we would broadly expect managers at successively higher levels to operate in successively lower pass bands, and adequate control would require successively lower sampling rate.

The minimum transfer tolerable in the time-shared level n controllers would presumably be lagged (due to timesharing) proportional error feedback following up the current objective. However, low frequency disturbance would be poorly corrected by this policy, and a degree of integral feedback control would seem highly desirable. With effectors having second and higher order dynamics, some damping, by derivative control would also be needed for stability. Classical human-operator research has demonstrated human capacity to provide all these types of error feedback at high frequencies (on the order of radians per second). To cover the managerial case, however, radical relocation of the operating frequency band down to frequencies on the order of radians per day, week, month, and year is required and direct data in these ranges appear to be entirely lacking.[*]

In addition to responding to error in a three term manner, we may also, following various studies of pursuit, preview and precognitive tracking (ref. 15) expect the level n controller to improve system response by (1) use of feedforward data to assist in regulating against predictable disturbances, both internal and external, and (2) use of fast time effector response modelling (Ziebolz control) to optimize approach to desired states and generate relatively high order control policies. These modes are less well understood, and it is not at present clear how much weight should be attached to them even in the fast tracking case, still less in low frequency managerial control.

Possible Relevance of "Time-Span of Discretion"

Some empirical evidence for frequency domain models of managerial control at successive levels can be gleaned from the work of Elliott Jaques and his successors on the nature and level of managerial work. Starting in the early fifties in a United Kingdom metal working company[*] (refs. 3, 16, and 17) Jaques has developed a quantitative technique for measurement of the so-called "level" of work in managerial roles, which in the present context may be recognized to require mainly control system implementation. His earliest method (described fully in ref. 3) consisted in determining, by interview of the immediate (level $n+1$) superior, the longest extended period over which the level n manager's exercise of discretion is allowed to remain unreviewed; or, to be more precise, the earliest time at which possible substandard exercise of discretion in the given role would be positively identified by the superior. As applied by Jaques, this quantity, termed "task extension," varies from assignment to assignment and the longest extension is taken to measure the "time-span of discretion," itself identified with level of work. While Jaques' method has proved difficult to apply in practice, and has certain theoretical difficulties (ref. 18), our own field trials have resulted in development of what we regard as an improved method, without changing the essentially time based criterion for measuring level of work (ref. 19).

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[*] Though indications may perhaps be gleaned from Forrester's studies of Industrial Dynamics (ref. 14).

[*] Glacier Metal Co., London.

Jaques obtained striking support for the validity of time-span as an index of level of work by studying its relation to salary level, either directly or through what he termed "felt-fair pay." In widespread industrial sampling, salary levels were found to increase monotonically with measured time-span over a very wide range (1 hr to 10 yr); the regression takes a roughly bilinear form, with a breakpoint around **3** months (see fig. 10).

Jaques has (so far unsuccessfully) proposed adoption of wage and salary policies based solely on level of work as determined by time-span. While this scheme has obvious difficulties, it is nevertheless clear that the industrial value of a manager is closely related to his time-span capacity; that is, the role of highest time-span that he is capable of successfully occupying. Salary progression curves show that this capacity develops predictably through a given individual career, and can be used to provide advance warning of organization problems (refs. **17**, 19, and 20).

Workers in the time-span field have also found a definite relationship between organizational level and time-span of role, to the point where some analysts are prepared to recommend organization structures with successive time-spans in a ratio not less than two. Our field studies show that, overlapping and discrepant time-spans are frequently associated with organization dysfunction. The organization depicted in figure 1 is a case in point; the general association between time-span and level will be evident to the reader, but a discrepancy is seen at plant manager level. This was associated with organizational trauma which cannot for reasons of confidence be described here.

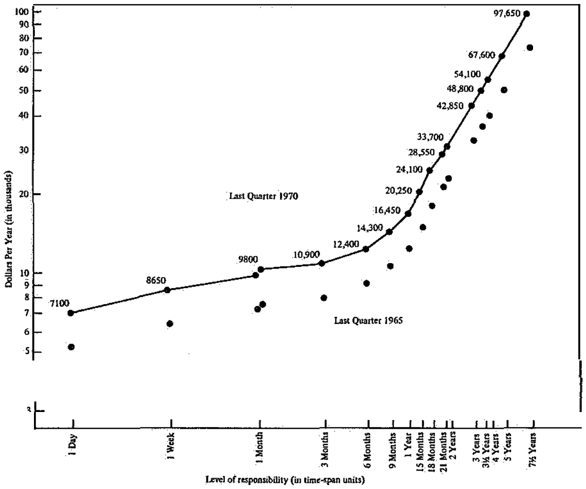

FIGURE 10.—Average managerial salary **as a** function of "time span of discretion." (Prepared by Laner and Caplan (ref. **20)** after Jaques (ref. 17).)

A Hypothetical Half Bandwidth Rule

These time-span results could be plausibly translated into the frequency domain by viewing the review interval used at level $(n+1)$ as a sampling interval adjusted to optimize information transfer from level (n). Since the feedback data being transferred represent disturbances transmitted through the level n effector, they will in general be confined to its response bandwidth. By the sampling theorem, therefore, the review interval should be not greater than twice the reciprocal of the effector cutoff frequency at level (n).* Hence the reciprocal of the estimated time-span of discretion at level n (as determined by interview at level $(n+1)$) could be viewed as an estimate of effector cutoff frequency at that level, and we would conclude that effector bandwidths decline on average by a factor of two between successive levels. This interpretation, however, yields unduly low cutoff frequency estimates and also fails to explain the higher value set on higher level controllers as shown by salary data.

An Alternative Double Planning Horizon Rule

In my view a more plausible interpretation of the time-span data can be given by considering low rather than high frequency phenomena, and assuming that many disturbances take the form of random walks rather than zero mean Gaussian processes. For forcing function frequencies in the range studied by, for example, Elkind (ref. 21), human operators appear to behave essentially as first-order low pass filters down to a breakpoint dependent on the amount of low frequency power present in the forcing function. While we have no data for forcing functions measured in radians per minute and below, it would be plausible to suppose (1) that the low pass break frequency declines with forcing function cutoff, and **(2)** that

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* Assuming that this can be defined.

response falls off again beyond a still lower break frequency. In other words, the human controller may be imagined to behave generally as a first order bandpass filter adjusted to match the forcing function spectrum currently experienced.

The ability to provide a proportional band at relatively low frequencies with sampled data input depends, of course, on the possession of what one may loosely term leak-free memory; or in other words, the ability to retain and utilize instructions over long periods without refreshment, together with the ability to predict effector response to command inputs and known disturbances; and to output relatively precise correction signals. These requirements appear to place more demands on human control capability than does the fast action implied by extended high frequency response.

With these considerations in mind we may interpret the time-span data as reflecting the minimum input data rate required from level $(n+1)$ to support specified controller performance at level n, rather than the reverse. In this connection it is perhaps of interest that our field informants respond better to inquiries about their subordinates' projected future deployment of resources, than to those about the periods used **for** (retrospective) review of past performance. Managerial control appears to be based more on feedforward than feedback, and the time extent of the planning horizon used in resource deployment seems more important than the feedback sampling period (ref. 18).

Within this frame, we may perhaps interpret time-span as reflecting the low frequency cutoff applying to feedforward control at a given managerial level. The recommended time-span ratio of two between successive levels, would then imply successive halving of the managerial controllers' low frequency cutoff. In other words, higher level managers must respond coherently to lower frequency inputs, a principle extending down to cycles per decade at the very top. This principle would not of course prevent the same manager from also responding to high frequency inputs; but if extended low frequency cutoff were a rare individual quality, market forces would dictate delegation of high frequency control to less rare (and hence less expensive) talent.

The above two frequency domain interpretations of the time-span data are, of course, speculative; further data will be needed to decide between them, and further alternatives which may be proposed. What does seem clear is that data of this type are relevant to frequency domain modelling of industrial management. And, as I have said, management is a very widespread form of "manual" control.

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