SYSTEMS ENGINEERING AND MICROELECTRONICS IN WATER QUALITY MANAGEMENT

M.B. Beck
International Institute for Applied Systems Analysis, Laxenburg, Austria

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

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FOREWORD

In previous decades, managing water quality in river basins has generally been regarded as a matter of planning and design. However, more recently a wide variety of problems, dominated by their growing scale and increasingly complex structure, has shown that the objectives for water quality management cannot always be achieved by planning and design alone. This raises the question of the feasibility of operational aspects of water quality management.

Since this question is being faced in a number of countries, it has been one of the principal themes of the work of the International Institute for Applied Systems Analysis on environmental quality control and management.

In 1979 IIASA undertook to investigate issues related to real-time (operational) water quality management. Part of this work was to investigate what strategy is feasible in the light of the states of the relevant arts. In this regard the Institute was aided by a group of 14 experts from 11 countries who met together in March 1980 and assisted in the work's later developments.

The principal product of this cooperation was a report offering an overview of the possibilities to an audience of officials, technical experts, and planners: M.B. Beck, *Operational Water Quality Management: Beyond Planning and Design* (Executive Report 7, IIASA, 1981).

The present paper, while following the argument of this Executive Report, extends it by discussing the potential uses of microelectronics in water quality management.

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JANUSZ KINDLER
Chairman
Resources and Environment Area

1. SYSTEMS ENGINEERING AND MICROELECTRONICS IN WATER QUALITY MANAGEMENT

M.B. Beck, BSc, MA, PhD *

INTRODUCTION

The expectation that microelectronics will have a significant influence on the practice of river basin management requires the prior assumption that operational (or real-time) water quality management, as opposed to planning and design alone, is necessary and desirable. It may seem curious that this should be an assumption, yet the predominant emphasis of the past two decades has been on matters of capital investment in the design and construction of water and wastewater treatment facilities. In 1979 the U.S. Water Pollution Control Federation, for example, opened its White Paper on Operation and Maintenance of Water Pollution Control Facilities with the following, Hill et al., (1):

> Of all areas of consideration involved in the planning, design, and construction of wastewater treatment facilities, operation and maintenance (O and M) is the fundamental measurement of a facility's performance; this is also many times the area most overlooked during the planning phase. That only half of all treatment facilities in the U.S. are meeting their design standards for biochemical oxygen demand and suspended solids clearly exemplifies the result of poor O and M.

Such statements leave little room for doubting that if one does not look beyond the needs of planning and design, then the management of water quality will suffer from certain shortcomings. The objectives for management, as conceived at the planning stage, will not be achieved nor maintained because solution of the planning and design problems does not necessarily imply the solution of operational problems.

This paper is based largely upon the results of a recently completed policy study on the feasibility of operational water quality management, Beck (2). The purpose of the study was both to make the assumption that operational management is "necessary and desirable" more convincing and to bring together an analysis of those perspectives (economics, technological innovation, risk/reliability, and institutional arrangements) that influence the desirability of operational management. Management of water quality, however, is clearly not merely a matter of wastewater treatment. If the topic is to be considered in its entirety, then all the components of Figure 1 are relevant and this will also define the "system" of interest to the paper. Nor is the feasibility of operational management determined solely by advances in automation, computers, and instrumentation, although electronic engineering innovations in the water and wastewater industries have themselves made operational management, to some considerable extent, both possible and popular. It is therefore important to examine the kind of background "problems" in water quality management that will undoubtedly shape the need for further such applications; this is the purpose of the following section. Accordingly, it is equally important to discuss the potential of what might be possible for the application of microelectronics in water quality management, and this is the purpose of the third section of the paper.

*Research Scholar, International Institute for Applied Systems Analysis, Laxenburg, Austria.

An additional introductory comment is perhaps appropriate, because one might well ask what is meant by "systems engineering" and "systems thinking"? It is highly unlikely that a unique answer exists for this question and it would be presumptuous to suggest one. Simply this personal view is offered. "Systems engineering/thinking" involves the bringing together of many different perspectives in the analysis of a problem, and included among these perspectives are the macroscopic focus apparent in the discussion of the next section and the microscopic focus of the third section.

A CHANGING EMPHASIS FOR MANAGEMENT

As in all other industrial sectors, developments in the application of computers, automation, and instrumentation to water and wastewater treatment facilities have been rapid over the past 10-20 years. Indeed, developments have been so rapid that Guarino and Radziul's (3) earlier observations that wastewater treatment plants use less instrumentation and automation than related industries may no longer be relevant. A comparative study of the papers presented at two consecutive IAWPR (International Association for Water Pollution Research) workshops on automation and control (Progress in Water Technology (4); Water Science and Technology (5)) reflects the pace of change and intensification in research and development activities, and particularly so in the area of data acquisition and telemetry systems for river quality monitoring. But simply to have created the conditions under which operational management can be exercised does not mean that it will be exercised. In spite of this special issue, and in spite of the inevitable nature of the technical developments, it is still pertinent to question why operational water quality management, and by association applications of microelectronics, should be considered necessary. This section discusses five "problem" categories that may give rise to a changing emphasis for management in the future.

Growing complexity of river basin management. Taking the broad historical perspective, as a river basin becomes highly developed and its water resources are used intensively, so the activities affecting and affected by water quality become more subtle and complex. There is, as it were, a kind of implosion of interactions among the different components of the system (Figure 1) and between the individual systems themselves. The objectives of overall management multiply and become more complex; for example, one cannot focus attention only on the traditional problem of easily degradable organic wastes and their effects on dissolved oxygen. And inevitably conflicts among the achievement of multiple objectives will lead to operating decisions that have to be made on the basis of more or less imponderable trade-offs. In the developed river basin there is thus now a very definite need for the exercise of an integrated and coordinated form of operational management over all the components of the system. This implies the ability to retrieve data and to process information on the performance of the system over a wide geographical area and the accompanying key role of microelectronics, on-line instrumentation, and telemetry should be self-evident.

Changing character of the pollution problems. Again, the longer-term historical perspective is useful. A general, macroscopic conclusion to be drawn from recent surveys and reviews (for example, OECD (6)) is that water quality in the rivers and lakes of several industrialized nations is observed to be improving. Such a statement has, of course, to be qualified by adding that it is water quality, as characterized by average levels of suspended solids and easily degradable organic matter, that is improving. Almost because of past success in management there is thus now a greater responsibility to prevent failures in the system of pollution control for the following two reasons. A greater number of treatment facilities need to be operated in order to maintain the control effort; and any failure will be relatively much more apparent and "damaging" both because a transient pollution event will be readily noticed in a river restored to a good average quality, and because in an intensively used system a failure in one component is more likely to affect adversely the performance of other parts of the system. If further it is assumed that the thrust of toxic substance legislation would be to prevent release to the environment, the probability increases that such substances will be discharged to rivers not in steady, smaller amounts but in accidental, discontinuous, larger amounts. In the event of a failure or accident one of the most important aspects for operational management's response is rapid detection and communication of information about the event. Here too microelectronics has a key role to play: its applications facilitate the supply of data at a sufficiently fast rate (see, for example, Marsili-Libelli (7)).

More complex standards for water quality. It is probably a natural progression in water quality management that standards for water quality become ever more stringent. However, standards do not change only in such a manner, nor do they simply alter the focus of attention from one pollutant to another. In this third "problem" area it can be argued that microelectronic innovations and all their ramifications, rather than being influenced by the "problem", are more a contributing factor to the "problem". The changing character of instrumentation and monitoring technology creates new opportunities for the specification and surveillance of compliance with standards. If more variables can be measured in greater detail and at much shorter and more varied time-scales, then standards can be revised in like terms. The new technology tends itself to justify further applications and may indeed lead to the perception of new types of pollution problems, although this latter assumes that increased information about performance leads to increased understanding and awareness.

Changing role of treatment facilities. If the installed capacity for treating wastewater has become sufficient (over the past two decades), and if there is a tendency to change the standards required (to meet the different problems of the future), the important questions of water quality management will center less on determining how much more waste to treat and more on how to treat it differently. The implications in this case are that it will be necessary, in general, to adapt an existing system of built facilities, that the ease of adaptation may depend strongly upon flexibility of operational performance, and that flexibility is not assured by good design alone. It seems reasonable to ask whether the innovation of microelectronics would enhance the capacity to be adaptable and flexible in water quality management; one would expect that it does.

More difficult economic climate. When enquiring about the significance of operating costs in wastewater treatment, one might have been informed, at least prior to 1973 and for some time thereafter, that they could be considered negligible, amounting to perhaps 3% of capital costs, Institution of Chemical Engineers (8). That this situation has changed radically is brought into sharp focus by a survey of the (U.S.) Engineering News Record (9). The survey showed that the period covered from the time a plant was put into operation to the time at which operation and maintenance costs totalled more than the initial investment was just 6.1 years. The same kind of changes are evident in Sweden: in 1971 the operating cost of treating one cubic meter of wastewater was 1.0 Swedish kronor; by 1978 this cost had risen to 3.5 kronor. Given thus the shift in management's emphasis towards the operation of existing facilities, as opposed to the construction of new facilities, and given also the rapid rise to significance (from virtual obscurity) of operating costs, there should now be a powerful stimulus for the introduction of technology that leads to a more economically efficient treatment of wastewater. Microelectronics are undoubtedly a part of such technology. Moreover, it can be argued that part of the force of the present stimulus for change is due to the slow pace of innovative changes in the past (2).

Against the background of long-term changes underlying the five "problem" categories discussed above, the present can be seen as a pivotal point in the development and application of operational water quality management. The potential exists, clearly closely related to the developments in electronic engineering, and so too do the reasons for such change, if one accepts the preceding arguments. In the following section, therefore, a more detailed examination will be given of the kind of applications of microelectronics that are becoming, and should become, integral components of the operational management of water quality.

THE POTENTIAL ROLE OF MICROELECTRONICS

The essential influence of microelectronic developments on water quality management is that they have created the potential for operational decision-making by satisfying the prior requirement for rapid communication and exchange of data and information across the river basin. This influence is perhaps more radical than the other obvious impact of microelectronics in superseding earlier analog control devices, and it will serve as the point of departure for this section.

It is helpful to begin by considering the basic elements of a control system as shown in simplified form in Figure 2. The components of the control function are threefold: (i) the processing of data and information, which can be used for, (ii) comparison of the actual performance of the system with the desired performance, which comparison can in turn be used for, (iii) determination of the required regulatory actions if performance is not as desired. The success of control depends upon the capacity to acquire pertinent and reliable data (the capacity to "observe") and upon the capacity to implement regulatory actions (the capacity to "act"), which are respectively indicated in Figure 2 as input and output of the control function. Nevertheless, applications of microelectronics that service these latter two activities, such as those associated with on-line sensors and automatic control of pumps, blowers, and scrapers, will not be discussed here. Equally so, more sophisticated developments, such as microprocessors programmed for the compensation of instrument calibration drift or for self-tuning, closed-loop control (see, for example, (7)), will not be discussed. Rather, the central theme of this section will be concerned with potential applications of microelectronics that are likely to encourage active man-machine interaction in operational water quality management. In other words, these are applications for which it is assumed that a human element will be retained in the control function of Figure 2. This is significantly different, therefore, from the more conventional designs of control system in which elimination of the human element from the control loop is a customary objective.

Four organizing principles, which are concerned with both the needs of management in terms of operating data and the possibilities for exploiting cheap, flexible, small-scale computing facilities, will guide the discussion of the potential applications to be illustrated. These principles can be summarily stated as follows:

(a) All the variables of possible interest to water quality management cannot be measured by on-line sensors; hence, those that can be measured should, above all, be measured reliably.

(b) What the manager may wish to know for operational decision-making is not necessarily the same as what can be measured, and there exists unexplored potential for deriving more useful information from currently available monitoring networks.

(c) If only a few variables can be measured reliably, these variables should be responsive to as broad a range as possible of operating disturbances and pollution events affecting water quality.

(d) Any on-line models and statistical estimation/forecasting algorithms should be "robust" and "compact" for implementation on small-scale computing devices.

These are general principles relevant to all the components of Figure 1. However, in the examples that follow there will be a tendency to concentrate on the particularly challenging area of biological wastewater treatment processes.

Processing Data and Restructuring Operating Information

A primary requirement in the control of biological wastewater treatment processes, the activated sludge unit in particular, is knowledge of the state of "biological activity" within the process. This is not a measurable quantity and indeed is likely to be a complex function of the influent disturbances to the process, the overall process operating environment determined in part by the control actions (see Figure 2), and the subtle changes in the microbial ecology of the process consequent upon the temporal variations in the disturbances and control actions. If, however, a mathematical model for waste substrate (food)/ microorganism interaction were available, and if on-line measurements of the process influent and effluent substrate and metabolic end-product concentrations could be obtained, so it would be possible to reconstruct from the model and data information about the (statistically) estimated concentration and growth-rate of the microorganism biomass. In principal these prerequisites for controlling the dynamics of oxidising waste nitrogenous material (nitrification) are available and preliminary studies have been made using operating data from the Norwich Sewage Works (10). A similar example, but one that has advanced to a more practical stage of development, is Holmberg's (11) study of on-line estimation of the oxygen utilization rate, active sludge concentration, and influent/ effluent biochemical oxygen demand (BOD) load for an activated sludge plant operating with efficient closed-loop control of dissolved oxygen (DO) concentration. This study was based on the use of an Intel SBC-80 120 microprocessor and conducted with pilot-scale facilities at the Technical Research Centre of Finland's Suomenoja plant. It exploits the idea that if a process is effectively controlled in a "desired mode of performance", knowledge of the associated variations in the regulatory actions (air blower speed in the case of DO control) is an inverted, or surrogate form of information about the interaction between waste loading and biological activity. Holmberg and Ranta's (12) work, which draws upon innovative applications in fermentation process technology, extends these ideas to the even more sophisticated problem of estimating the age distribution of the microorganism population. All these applications, therefore, are closely concerned with principle (b) above. Olsson and Andrew's (13) study of the DO profile in the activated sludge process likewise points towards the value of principle (c) above, in the sense that the DO profile is intimately related to many aspects of process operation (such as BOD removal, nitrification, denitrification, sludge bulking) and is capable of yielding much useful operating information. It is however, pertinent to ask to what purpose the plant manager would put such information, a question to which the discussion will return later.

Comparing Actual and Desired Performance

It is also appropriate to examine questions associated with specifying a "desired mode of performance" for the process of water quality management, and, conversely, detecting abnormal or highly undesirable performance incurred by process failure. Let us start from the point that models, such as those underlying the examples quoted above, are nothing if they are not idealizations of the behavior (performance) of a system. The use of a model as a reference definition of desirable performance would seem to have attractive potential if, in combination with an information processing algorithm, it can provide early detection of incipient nonideal behavior or failure for which preemptive control action can be taken. One would not need a model for such purposes if, for instance, defining the desired performance of the activated sludge process were as straightforward as specifying particular "optimal" DO and mixed liquor suspended solids (MLSS) concentrations. However, "failure" of the process due to a bulking sludge situation, which might arise from a combination of circumstances in which the growth of filamentous bacteria is encouraged, is a good example of a more complex operating problem. It is not altogether clear how early detection of a bulking sludge condition could be achieved, although the fact that it may take several days to develop fully is a distinct advantage to be expolited. If a model for ideal growth/waste removal in the aerator and a model for ideal clarification/thickening in the clarifier can be defined and represented as sets of relationships between easily measured variables and with coefficients that can be estimated from these measurements, it would be possible in principle to detect a slow divergence between actual and desired performance. "Unacceptable" values for the model coefficients would reflect when theory could not be acceptably fitted to practice. Such an application is merely a more sophisticated extension of the notion of programming a microprocessor to detect drift in the performance of an instrument; it makes use of principles (b) and (c) above. Again, however, it is an application that begs the question of what regulatory action would be implemented given the knowledge that performance is becoming undesirable.

There are other similar applications within the system of Figure 1 where prior knowledge of an impending disturbance, together with the sometimes large lead-times afforded by processes with slow dynamic responses, might be exploited to take preemptive or contingency control action. Short-term prediction (of the order of hours-ahead) of the influent discharge to the sewer network (14) or of the influent discharge to a wastewater treatment plant (15) are more obvious examples of potential applications. Perhaps less obvious is the use of on-line conductivity measurements for adaptive estimation of pollutant dispersion and time-of-travel in a stretch of river between an upstream discharge and a downstream potable water abstraction. In the event of an upstream toxic spillage, or the failure of a wastewater treatment process, the most immediate information required by the manager of the downstream abstraction is the time taken for the pollutant pulse to reach the abstraction point and the expected peak loading. All the practical requirements for this kind of application already obtain in the Bedford-Ouse river system (16), and an extremely simple model and estimation algorithm can be used (17) and indeed programmed on a microprocessor (see, for example, Clarke and Gawthrop (18)). Since these applications are concerned largely with contingency control action, which implies also a concern for reliability, principle (a) above should be an important consideration in guiding developments.

Determination of the Required Regulatory Action

The question of what to do with the information provided, however, still remains unanswered. What would the water purification plant manager do with prior knowledge of unsuitable water reaching the raw water intake and would regulatory action be called for where coordination with the operation of the wastewater treatment plant would be required? The point about coordination, in particular, is probably a critical one for the development of decision-support systems to cope with complex operating conditions, and it relates back to the problems relevant to the changing emphasis for management discussed in the previous section. For such a system as Figure 1 it is clear that the management and control function of Figure 2 is bound to be hierarchical in nature. At the lower levels of control one would expect to have applications of microelectronics in fully closed-loop controllers, while at the upper levels, where progressively wider coordination is demanded, one would expect to have forms of control in which man-machine interaction and the practical experience of the operator/manager is to encouraged and exploited. Again, the activated sludge process of wastewater treatment provides a good example of what is intended, although at a rather low level with regard to the context of Figure 1. It may be noted that individual closed-loop control of DO concentration, MLSS concentration, and sludge recycle, for instance, can be successfully implemented. However, this does not imply that overall plant control, that is actions taken to change the desired set-points of the individual loops to manage, for example, a bulking sludge situation, can be likewise successfully implemented in a closed-loop fashion. The pragmatist would argue, and convincingly so, that such coordinating control at the "upper level" is adequately exercised by an experienced plant manager. In this sense, preliminary studies (Tong et al., (19); Flanagan (20)) on codifying the empirical operating experience of the plant manager (that is, his set of mental operating rules) appears to be a promising direction for further development. The resulting control algorithms require only a small-scale computing facility, but the essence of the approach is that the associated determination of regulatory actions should be an interactive process. It is to this end that the previously discussed use of models and information processing algorithms is directed, not only for the provision of additional information but also for rapid evaluation of the possible consequences of the decisions and actions to be taken. The codified operating rules are a basis for decision making; they do not replace the plant manager, and they should be developed further and modified in the light of subsequent operating experience.

CONCLUSIONS

Having examined the problems of water pollution control, for example, the growing complexity of river basin management, the likelihood of more complex standards for water quality, the changing role of treatment facilities, and the more difficult economic climate, one may conclude that operational water quality management is, and has to be, feasible. That the exercise of such management, in an integrated and coordinated fashion, can be contemplated is due in large part to electronic engineering innovations and indeed will call for further similar innovations. The predominant influence of these innovations is in the area of data retrieval and data/information processing, that is, in the capacity to "observe". In the third section of the paper a number of potential and partly developed applications of microelectronics have been discussed. The scope of the examples chosen has been restricted by the overriding consideration of suggesting applications that will stimulate man-machine interaction in operational decision-making. Four guiding principles for the development of potential applications have been introduced and, while some of the specific examples may eventually prove not to be feasible, the points they illustrate and the principles themselves are generally applicable to the various aspects of the system defined by Figure 1. There will inevitably be numerous applications of microelectronics performing closed-loop control and ancillary functions that do not require the intervention of a plant manager. It would be ideal, if such "conventional" applications were to relieve the manager of routine business and transfer his commitment to the much more complex decision making involved in coordination, evaluation of trade-offs, and the management of contingencies, for which less conventional approaches can be mobilized.

Several of the examples of section 3 deal with matters of reliability, transient or accidental pollution events, and process failure or serious malfunctioning. Given thus a concern with the reliability of performance in general, it is important to pass a closing remark of caution on the innovative development of microelectronics for the water industry. The basis for this remark is the assertion that the information provided is only as effective as the regulatory actions that management may find necessary to implement. Because, therefore, electronic engineering innovations have so far largely influenced management's capacity to "observe", a situation may be approaching in which, broadly speaking, management will be able to observe in splendid detail what is going wrong with the system, but powerless to implement corrective action. The complementary capacity to "act" in water quality management, which does not simply mean automation of the turning on and off of a pump, is almost entirely influenced by innovations of a civil engineering and biotechnological nature. A balanced development of both the capacities to "observe" and "act" is clearly necessary.

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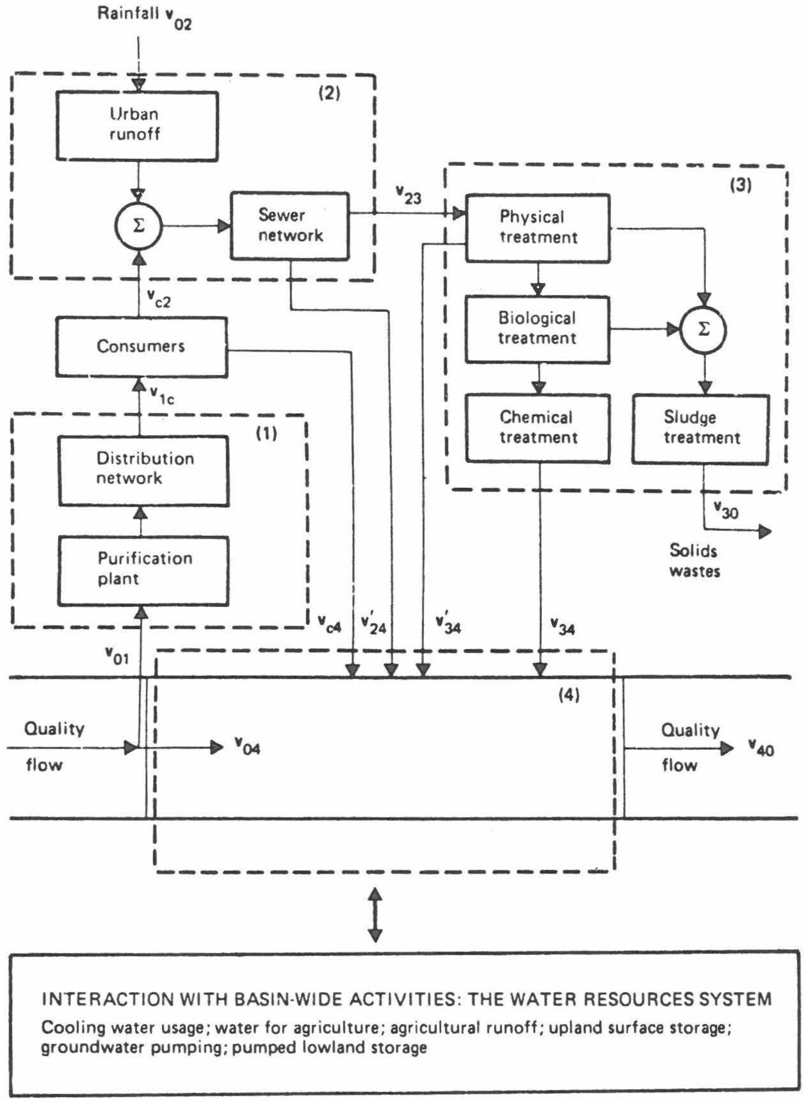

Figure 1 The water quality system (an abstracted component of the water resources system) comprising: (1) potable water abstraction, purification, and supply; (2) the sewer network; (3) wastewater treatment; and (4) the receiving reach of river

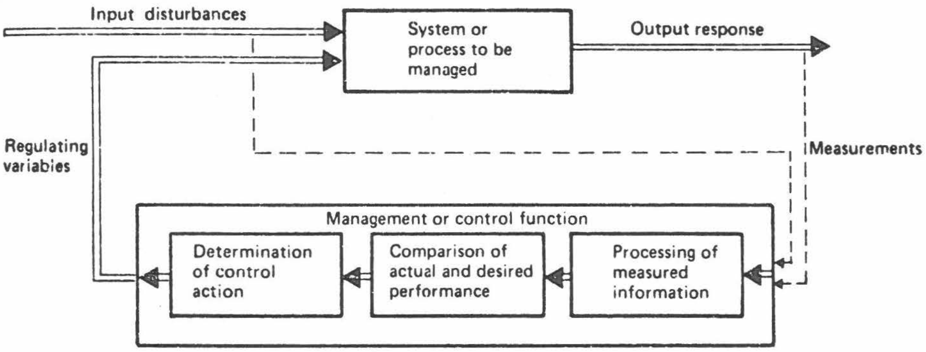

Figure 2 The basic, but much simplified, management/control system

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