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Environmental Process Control: Strategies and Implementation

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Abstract: *The structure and mathematical presentation of the optimal strategy for environmental process control is presented. This approach covers a wide variety of control systems, which have been constructed and analysed at the Institute of Environmental Engineering during the last fifteen years. Special attention is paid to the preventive environmental control and its tools: pollution prevention, life cycle assessment. The implementation results of preventive environmental control from more than 150 companies are presented in the paper.*
The investigations on water quality control issues are evaluated from the point of view of the interface between physico-ecological and socio-economical systems and decision support system based on river water quality model is suggested.

Keywords: *Systems theory, Pollution prevention, Life cycle assessment, Environmental control systems, Water quality management.*

Introduction

There is no doubt that attitudes towards the control of environmental systems are strongly conditioned by our view of the essential structure of these systems. In any event, reliance on mathematical models is based on the underlying belief that the real world operates with the same logic that human beings think in, and this “of course” is the most striking assumption, made by A. Einstein [1].

A model is a representation of an object, system or idea in some form other than that of the entity itself. No modelling techniques can guarantee completeness. Indeed the only complete model is the reality itself; all systems models are abstractions and simplifications. The main thoughts that are basic to the development of an environmental system model are:

- There is a principal line, consisting in the materials flow through the economy, through the environmental system, through the system of production and consumption. Many materials, once extracted from the environment, are usually subjected to a sequence of various phases of transformation.
- The beginning of the materials flow is the natural environment. The end of the material flow, again, is the natural environment. At the end of the sequence of material transformations, the material no longer serves as a useful purpose for the people, and the material is then returned to the environment again.
- Along the material flow, many material transformations occur. As each and every transformation involves the input of the material and the energy, waste materials and emission will emerge, that could pose problems.

Therefore, a control system may be characterised by the three elements of which it is composed: input, output and transformations/models linking the two. The inputs of the environmental system are fuels, foods, substances, raw materials, etc., which are partly converted into final goods and partly become residuals.

In practical environmental systems control, it is usually necessary to build up a complex set of feedback, feedforward adaptive control systems capable of representing the whole range of system disturbances and changes, which may occur.

Theory

The common characteristics and structure of the most controllable problems are shown in Fig. 1. Two system inputs an uncontrolled input sequence {F}, representing stimuli to system action, and additional control input sequence {U} are considered. The control input sequence represents a variable (or set of variables) that can be manipulated by the controller and decision-maker to influence the system under consideration and induce the output to approach more closely to reference settings. In overall control system any given output is compared with the reference input or target, which represents the desired response of the system. The difference between the real and desired output generates an error sequence which weighted by the chosen performance index or objective function, is used by the controller to manipulate variables amenable to control. The performance index is a “figure of merit” by which deviations form the desired response are scaled.

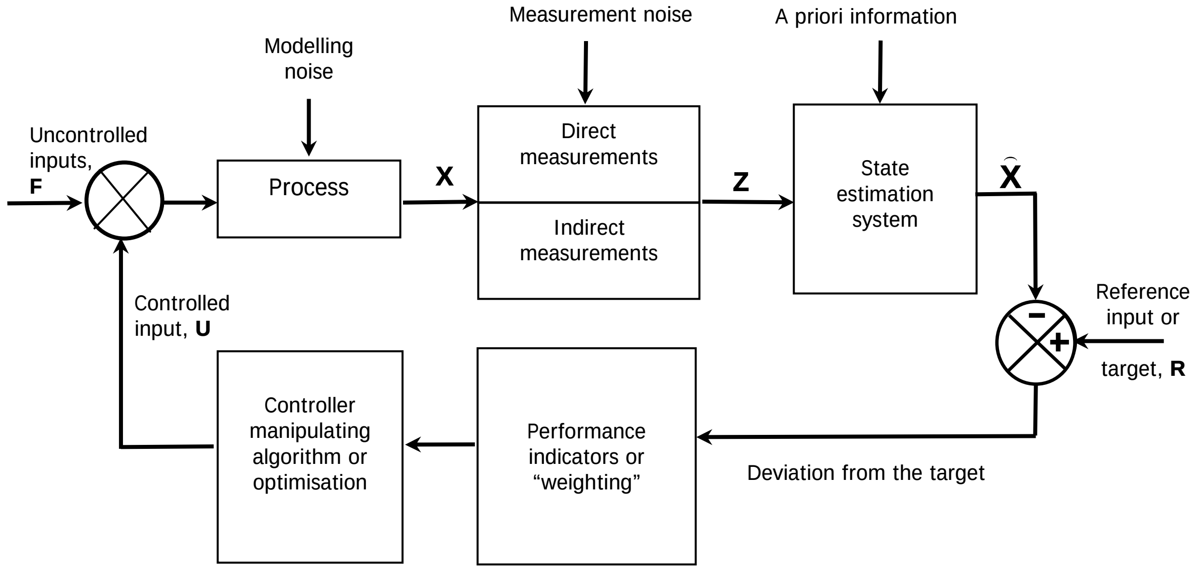

Fig. 1 The basic components of the control system

In practice, optimal controllers employ a combined performance index or objective function, incorporating two elements: the cost of deviations from targets, and cost of employing a given control instrument. A common choice is the quadratic control objective function [2, 3]:

$$W = E\,(MX^2 + NU^2), \qquad (1)$$

where: M and N are arbitrary weighting constants determining the relative costs of deviations from the target, and the costs of control. It is especially difficult in socio-ecologic and physico-economic systems to decide the appropriate values for the objective function terms M and N.

The overall type of control systems required in any environment is dependent not only on the available control instruments, but also upon the nature of the disturbances entering the system. According to the hierarchy of such control systems, there are:

- uncontrolled,
- open-loop control,
- environmental control,
- passive closed-loop feedback control,
- active closed-loop feedback control,
- adaptive feedback control,
- feedforward control,
- feedback-feedforward control,
- adaptive feedback-feedforward control.

Implementation

Industrial environment control systems

The industrial wastes (gas, liquid and solid) are generated from many different processes. The amount and toxicity of waste releases vary with specific industrial processes. Fig. 2 shows a typical industrial process which produces waste containing different types of pollutants, depending on the input materials and process designs. Thus, process information is critical to make accurate and reliable assessment of the potential for different environmental strategy.

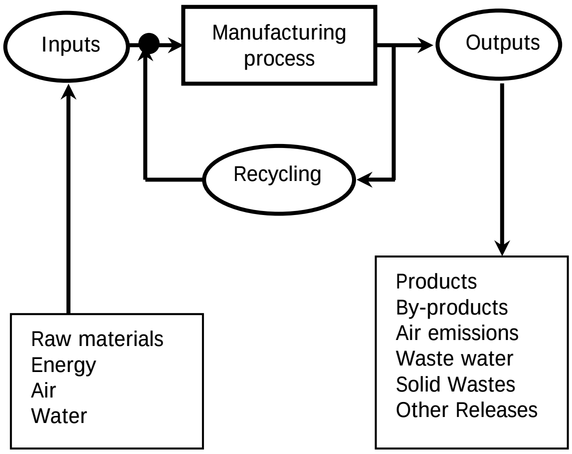

Fig. 2 A typical industrial process

Environmental control has, until recently, laboured under the assumption that environmental effects of anthropogenic activities should be addressed by carrying on the “normal” ways of production and adding on control technologies later as needed. This principle has led to attempts to protect the environment by isolation of contaminants from the environment or the use of end-of-pipe filters, treatment facilities and scrubbers. Although these kinds of solutions have undoubtedly led to short term improvements in local pollution problems but there are some significant problems associated with this approach:

- end-of-pipe abatement is in one medium risks transferring pollution from that medium to another, where it may either cause equally series environmental problems or even end up as an indirect source of pollution to the same medium;

- end-of-pipe at the abatement contributes significantly to the cost of production processes and products;
- end-of-pipe abatement of pollution requires regulation through control legislation which is often costly and cumbersome, leading to potentially inefficient regulatory structures and problems of non-compliance;
- end-of-pipe abatement technology represents a significant technological market with an associated economic inertia which encourages the continued generation of waste and works against any attempt to reduce pollution at the source.

From the systems' theory point of view this approach is reactive and could be presented as a closed loop feedback control system (Fig. 3). Taking corrective measures at the input, when deviations from the standard are recorded in measuring the output is called feedback control.

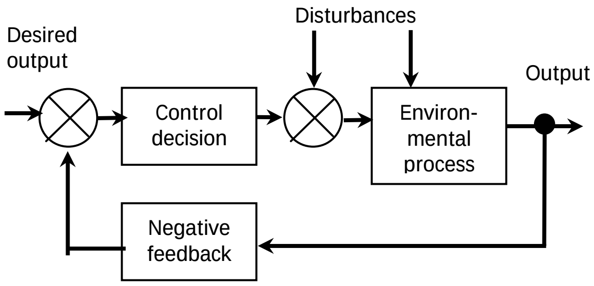

Fig. 3 Structure of environmental control paradigm

The structure of environmental control approach shows that this strategy is reactive which refers to actions taken "after the fact" in response to effects. Reactive actions focus on negative impacts and risk reduction through acting on a waste or pollutant, and thus there is an opportunity in space and time to act on what is already a waste or pollutant.

The precautionary principle, which is clearly related closely to the concept of prevention, calls for reduction in anthropogenic emissions of potentially hazadours substances into environmental medium. Preventive actions focus on identification and reduction or elimination of use of materials that could cause harm or damage to the environment. That is, preventive actions are anticipatory by definition, and act not on waste but on conditions and circumstances that have the potential to generate waste. From the systems' theory point of view anticipation and prevention of waste generation is an example of feed-forward control in the system development (Fig. 4).

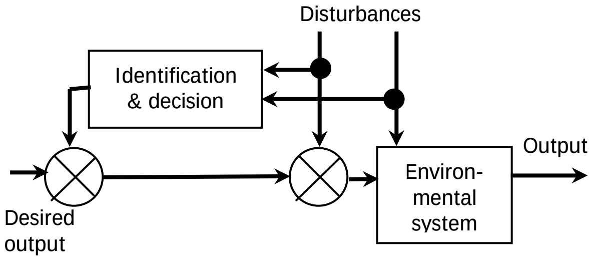

Fig. 4 The structure of preventive paradigm

The most interesting level, and in relation to the preventive paradigm also the most important, is the internalisation of environmental stewardship thinking and action. The main elements of that are:

- the recognition of the good quality of environment as an integral factor of sustainable industrial activities;
- the recognition of good environmental management as an important factor for the continuity of a company;
- the integration of environmental compatibility within the quality concept of products.

The extensive research and implementation of preventive control in more than 150 Lithuanian and foreign companies have confirmed the possibility to decrease waste generation by 30% without any investments or with very low cost investments. The further decrease of wastes up to 70% could be achieved by economically viable preventive proposals with medium size investments [7, 8].

Presently, company's attitude towards the environment could be characterised by three different levels:

- compliance with acting regulations;
- anticipation of increasingly stringent regulations;
- internationalisation of environmental steward-ship thinking.

The compliance with acting regulations in most cases is reactive, because measures are taken on an ad-hoc basis after regulations have been developed by the authorities, which is usually done after environmental damages have occurred. The anticipation of increasingly stringent regulations attitude goes further in the pollution control efforts than those strictly required by law. From tactical point of view, such approach becomes a corporate strategy since corporate leadership perceived that such activities are positive for their relationship with the authorities and for the environment. The level were preventive paradigm could play extremely important role is internationalisation of environmental stewardship thinking.

Therefore, the most effective environmental control should combine at the same time preventive and end-of-pipe strategies (see Fig. 5).

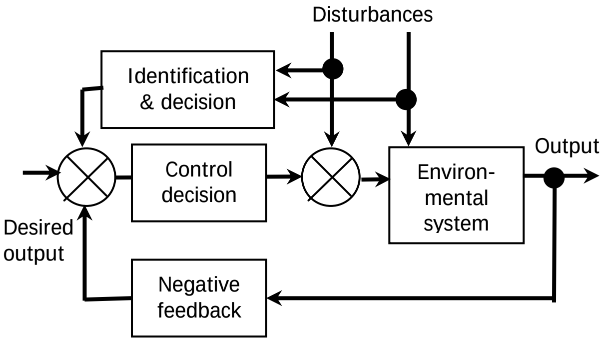

Fig. 5 The structure of closed-loop feedback-feedforward control

Reactive actions focus on explicit use of technology that is manifested as equipment. But preventive actions can be implemented completely through the application of knowledge and changed behaviour, or technology that has no apparent linkage to an environmental objective. Prevention means, during something differently so, that waste are reduced and eliminated.

At the same time the profitability of pollution prevention measures is clearly critical to the successful implementation. Unless profitability is demonstrable at the level of investment and industrial management decisions, companies will have little incentive to pursue the preventive path. Our broad experience have showed that total cost assessment (TCA) offers an alternative to conventional project analysis approaches by enlarging the inventory of costs and benefits, allocating such costs and benefits more closely to specific processes and products, using multiple profitability indicators to capture indirect, less tangible and longer term pay-offs. Therefore, TCA is an approach for refining project financial analysis such that prevention investments are treated on the same level in relation to other competing investments [3, 4].

In the early approaches to preventive control, attention has tended top focus on waste generated during the production processes, and on the need for recycling of raw materials to reduce the environmental burden of product disposal. Developments of the earlier concepts have emphasised the need for attention to be paid both to the general use of materials and to the importance of the design and concept phase of the life cycle in minimising subsequent environmental impact.

The life of any product can be divided into five more or less distinct phases as follows:

- conception, design and testing,
- production – involving the extraction and transformation of natural resources,
- distribution – including packaging, transformation, and marketing,
- the utilisation period during which the product provides some useful service,
- post-utilisation period, which involves either the recycling or the treatment and disposal.

The concepts and practices of waste prevention and control need to be applied at every stage of the product life-cycle in order to minimise environmental input [9].

By implementing product life-cycle planning into all product and production considerations, companies could drastically reduce their environmental impacts and increase their efficiency / profits at the same time [7, 8].

Preventive control measures have mainly been used to reduce energy and water consumption. In terms of innovation type, most of investments have been used for process optimisation and technology change. Detailed information about preventive control activities in selected industry sectors is presented in Table 1.

Table 1. Implementation of preventive environmental control in Lithuanian industry

Industry sector	**Number of enterprises**	**Number of preventive options analysed**	**Number of implemented preventive measures**	**Investments, EUR**	**Savings from implemented measures, EUR/year**
Textile industry	14	42	39	2 734 000	2 474 000
Food industry	13	27	25	2 027 000	1 365 000
Chemical industry	6	15	14	435 000	493 000
Machinery production	5	5	5	1 033 000	389 000
Production of radio, TV and telecommunication equipment	2	6	6	1 478 000	613 000
Furniture production	6	10	10	1 030 000	421 000
Wood industry	3	6	6	1 431 000	1 067 000

Results from implemented preventive control innovations are summarised in Table 2.

Table 2. Results from implemented preventive measures

Number of companies	126
Number of implemented CP innovations	211
Environmental results (yearly):	
El. energy consumption reduced	27 584 000 kWh
Heat energy consumption reduced	60 518 000 kWh
Waste amount reduced	86 700 t
Chemicals consumption reduced	850 t
Air emission reduced	79 500 t
Drinking water consumption reduced	297 500 m^3
Diesel consumption reduced	387 000 l
Natural gas consumption reduced	5 883 000 m3
Fuel consumption reduced	656 800 t
Wastewater amount reduced	622 500 m^3
Industrial water consumption reduced	468 900 m^3
Economic profit:	
Total investment	16 529 000 EUR
Yearly savings	9 605 000 EUR

Physico-ecological systems

There are many difficulties facing those who have interests both in the natural environment and in the man-made environment together with the problems of their interfacing. The industrial system is the collection of physical, chemical, and technological processes developed by man for the restructuring of materials. The biosystem involves the collection of natural ecosystems in the landscape. An important consideration in the problem of interfacing physico-ecological and socio-economic systems is the energetics of interaction. There are two main types of interaction between physico-ecological and socio-economical systems. Firstly, there is environmental intervention in which socio-economic systems operate apart from physico-ecological systems to cause them to react in the pre-determined and in advantageous manner. Such intervention systems involve a considerable amount of monitoring and tend to take a rather analytical view of environmental systems. It could be considered three main types of intervention [1]:

1) prediction of outputs,
2) manipulation of storages,
3) control of inputs.

Prediction of outputs may be viewed in a purely passive sense where expected outputs are predicted by the use of forecasting techniques having to do with interpretation and forward prediction on the basis of previous outputs. The classical example of this type of intervention is the model for the Nemunas river which is based on the differential equations of the first order with the possibility to analyse conservative materials transport, and to predict transport and transformation of non-conservative materials, for instance dissolved oxygen, organics, nutrients [8].

Manipulation of storages is very important method of environmental system interfacing which involves the manipulation of physico-ecological storages by the socio-economic system. Using this method water quality problem at the hot spot could be solved instead of controlling inputs by spatial distribution of pollution along rivers and estuaries. This creates the ability of the natural processes of stream channels to renew and dissipate pollution. As usual regional treatment plants are fixed in their location as a result of political and engineering considerations. Using second method of intervention, the problem instead could be solved by means of non-linear programming. In this case first of all there is a need to produce a steady state dissolved oxygen profile downstream and then to achieve the required dissolved oxygen changes in each section with a minimum cost by changing spatial distribution of pollution/waste water treatment plants [10].

The potentially most important approach is the *control of inputs*. This is very difficult to achieve except over small scales of space and time and requires a considerable input of energy and sophistication of time space application to make such control effective. The simple and very practical case of this type of intervention was designed as a decision support system for the Nemunas river basin water quality management (Fig. 6).

The developed model, which was mentioned above as the first type of intervention is used in decision support system, as an interactive computer added system, which assist the decision-makers to utilise monitoring data and mathematical models in order to solve complex management problems. The theoretical and practical investigation of the system of inputs control is meaningful due to the river management procedure and enables [5, 10]:

- to perform the identification of the river water quality,
- to predict the behaviour of the system,
- to perform various management scenarios.

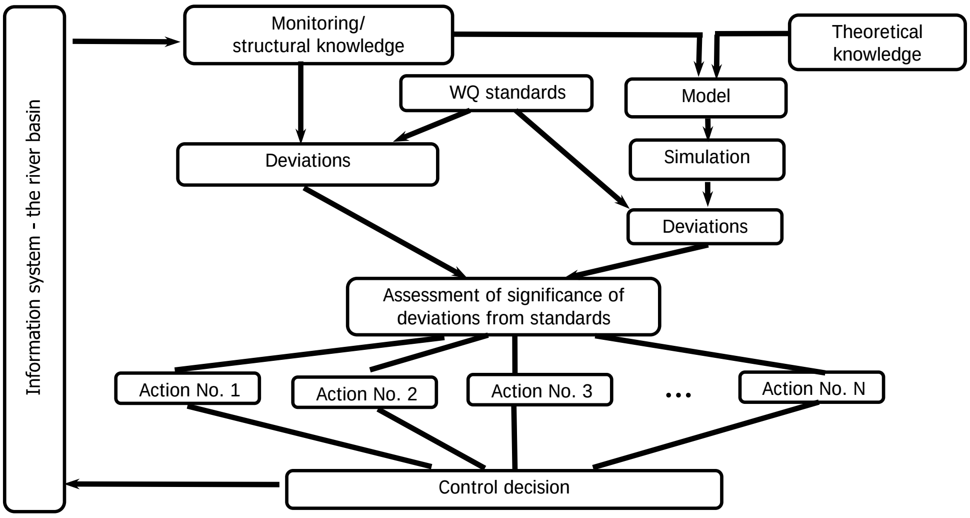

Fig. 6 Decision support system for the Nemunas river basin management

As a practical example, two different control scenarios of Kaunas waste water treatment plant (WWTP) (mechanical and biological treatment) have been analysed. The investigations showed that mechanical treatment facilities enable to decrease BOD concentration downstream Kaunas city by 10 – 12%, total phosphorus by 8 – 11% in spring. BOD concentration will be reduced by mechanical treatment by 8 – 9%, total phosphorus by 5 – 7% in late summer. The biological treatment facilities of Kaunas WWTP will decrease BOD concentration by 12 – 15%, total nitrogen by 1% and ammonia nitrogen by 5 – 8% in high flow (spring) period. BOD concentration will be reduced by biological treatment by 8 – 9%, total nitrogen by 3% in summer period [5, 10].

Considerations and conclusions

As it was mentioned before, in most environmental systems there is incomplete and partial knowledge of the system, which has to be understood and controlled. The nature of knowledge is often incremental and greater insight is gained as analysis and control continues. The consequence of the way we view a system, and hence of the way we observe and measure it, is that our understanding of the system is limited by that view of measurement. In this paper was shown how control methods can be applied to environmental process to push back information accuracy constraints, to increase the degree of understanding of environmental systems and increase the possibilities of control. It could be concluded:

1. The most environmental problems dealing with interface between physico-ecological and socio-economic systems can be formulated from the systems theory point of view. This allows using modern systems theory methods for an environmental problems solution. At the same time, two points must be clearly grasped. Firstly, that the understanding of the system does not necessarily imply that we can control it, and, secondly, that control has a meaning in terms of some stated goal.
2. The environmental process control strategies clearly show that emerging preventive environmental control paradigm differs significantly from the control paradigm of earlier management strategies and calls for new attitudes, not only to the development of production processes and the design of products but also to the relationships between consumer and environment. It must be stated, that for sustainable economic growth and development need to see the environmental prevention paradigm as a technological and

cultural means to achieve the desired compatibility between environmental and economical goals.

3. As long as the material components of products is largely based on the use of virgin resources, while energy is derived from fossil fuels, there is no way by preventive control to reduce the output of wastes and pollutants below a certain minimum point. Unless, the product cycle and materials cycle are (very nearly) closed, the system as a whole will continue to be unsustainable. In this case, preventive and reactive environmental strategies have to be used as a feedforward-feedback control structure.
4. Any organisation can only survive if it avoids a lasting conflict with society and environment. Life cycle assessment (LCA) fits very much into activities of a company, insuring that it meets the environmental demands of society. LCA is a holistic environmental accounting procedure, which quantifies and evaluates all wastes discharged to the environment and energy and raw materials consumed throughout the entire life-cycle, beginning with sourcing raw materials from the earth through manufacturing and distribution to consumer use and disposal and thus create a possibility for optimal process control.
5. The concept of total cost assessment / environmental management accounting facilitates self-regulation within industry by building a voluntary proactive approach to source reduction into corporate decision-making and control. Unlike the command and control regulations to ensure proper management of wastes already created, the role of authorities in promoting prevention might therefore be more appropriately viewed as catalytic – pressing industry to identify pollution prevention opportunities which serve both their own and the publics’ interest.
6. The systems approach relies heavily on large amounts of accurate data, which are used both to construct and test environmental models and in their manipulation. The more complex the system, the more data are required, both in space and time. At the same time in most cases there is a lack of basic environmental data existing administrative fragmentation resulting in interfacing and compatibility difficulties, lack of interdisciplinary integration and well defined social goals. One of the main problems is the divorce of the data collector and the systems modeller.

The systems approach and modern control theory provides a powerful vehicle for the statement of environmental situation of ever-growing temporal and spatial magnitude and for reducing the areas of uncertainty in our increasingly complex decision-making and management situations.

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