Algorithmic Control Modules for System Dynamics Models

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ABSTRACT

The purpose of this paper is to describe a proposed framework for policy analysis and design in complex systems based on the transfer to such systems of control modules developed for simplier and more easily quantified systems.

The framework is demonstrated by outlining the development of a dynamic allocation algorithm within a system dynamics model of an engineering system and describing its application in a much larger scale amanagement system. A generalised form of the algorithm is presented based on this experience which serves to highlight its isomorphic qualities.

It is suggested that this framework provides an integrated approach to structural policy analysis in complex systems which can also be used to generate significant insights and perspectives into both the physical and control structure systems.

INTRODUCTION

The system dynamics discipline has over many years developed excellent methods for the physical description of complex, variable structure systems as commonly found in management, society and government (Forrester 1968, Coyle 1982, Richardson and Pugh 1983, Wolstenholme and Coyle 1984). However, it is commonly recognised that the discipline has encountered difficulty in developing suitable methods of designing control for such systems.

Most methods commonly employed are based essentially on parameter and structural modifications. The former approaches, whilst being theoretically sound, are often irrelevant where structural flexibility can dominate their effect and the latter, whilst providing a systematic approach, are essentially piecemeal methods which contrast strongly with the systemic ideals of system dynamics. More recent integrative methods do exist (Keloharju 1983, Mohapatra 1980), but these are felt to be currently limited by the need for special skills and software.

The premise of this paper is that there is much to be contributed to policy design in complex systems by the development of control modules in hard systems using simple models, which can then be transferred to many different types of system. The potential of this avenue of approach is demonstrated here by outlining the development of a dynamic allocation algorithm within a system dynamics model of an engineering system and describing its application in a more complex management system.

DEVELOPMENT OF THE ALLOCATION ALGORITHM

BACKGROUND

The dynamic allocation algorithm described here was developed in the context of a study within the coal mining industry to design discharge policies for underground coal storage bunkers. A basic system dynamics model was developed for this purpose which represented the physical process of mining, and various control ideas tested out using it, under a range of system parameters and exogeneous inputs. This led to improved policies based on the most useful features of each policy and subsequently to the evolution of a generic allocation policy. The background to the model and an outline of the policy analysis stages used will now be developed. A more complete description of the model is available elsewhere (Wolstenholme 1983).

The process of coal mining at its simplest level involves the cutting of coal from coalfaces and its subsequent storage in bunkers prior to its despatch to the surface by conveyor belt. Fig. 1 shows the layout of a basic coal clearance system of the type which was modelled. The overall aim was to develop and test alternative policies by which the bunkers could be discharged onto the conveyor belt, under a range of random and time based fluctuations in the coalface output rates. The alternative policies tested were compared against an efficiency criterion based on the rates of cumulative coal cleared to the surface over a given time, to that potentially available from the three coalfaces.

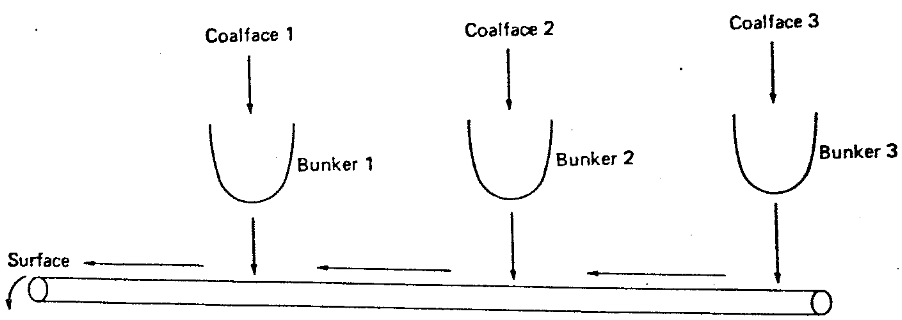

Fig. 1. General layout of situation modelled.

In order to produce realistic fluctuations in the coalface output rates sub-models representing the coalfaces were developed which incorporated shift working times, random variations in the rate of coal cutting and random stoppages due to machinery breakdowns (Wolstenholme and Coyle 1980).

SIMPLE BUNKER DISCHARGE POLICIES

Initially the problem modelled was not perceived as an allocation problem and two policies were tested, under a range of system parameters, based on those used in practice. Policy I which was referred to as a "fixed discharge policy" assumed that each bunker could only be operated at zero or its maximum rate and that the latter would be used as long as, (i) the maximum discharge was not exceeded, (ii) there was coal available in the bunker and (iii) there was room available on the conveyor belt. Policy II was referred to as a "variable discharge policy" which assumed that each bunker discharge rate could be set at any point between zero and the maximum discharge rate and would be set in proportion to its associated bunker level (for equation see the appendix); again subject to the same constraints as Policy I.

An influence diagram of the model showing two coalfaces and bunkers, the efficiency measure and the information links for policies I and II, is given in Fig. 2. For Policy I the link between the bunker level and actual discharge rate is simply a fixed constraint whereas for Policy II it becomes a variable influence.

The full results of the experiments have been presented in detail elsewhere. For the purposes here discussion will be limited to the implications of the results for policy design.

Policy II was in general, as expected, found to be significantly better than Policy I in most circumstances. The general disadvantage of Policy I is, of course, the restriction it places on the bunker discharge rates when the sum of the maximum discharge rates exceeds the total conveyor belt capacity. There are occassions under this policy when the bunkers contain coal and there is room on the conveyor belt; but this is less than could be accommodated under maximum discharge rate and hence discharge does not take place. However, when sufficient bunker and belt capacity exist Policy I does allow the maximum discharge rates to be implemented and the maximum theoretical efficiency of the system to be achieved. Whilst Policy II overcomes the problem of restricted discharge rates when the system capacity is exceeded as referred to above, it does have a major weakness when full conveyor belt capacity is available.

Once sufficient conveyor belt capacity exists, the bunker discharge rates under Policy II are simply a function of the bunker level and the maximum discharge rates are employed only when the bunkers are full. Consequently, if the bunker capacity is almost adequate to cope with the coalface output, the bunkers are rarely full and the discharge rates attained are less than the maximum. As the bunker capacity is increased, the discharge rate associated with a given bunker level decreases and the maximum theoretical efficiency for the system is never attained. This is a disadvantage of what intuitively would appear to be a sound discharge policy.

The foregoing results from simple policies indicated that substantial scope for improvement in policy design exists and that a combination of the merits of Policies I and II should be the first step. That is, we require a policy which employs the maximum bunker discharge rate wherever possible and allows for intermediate discharge rates depending on the bunker levels.

Further, however, it is clear that both of the simple policies used represent essentially priority policies. Examination of the distribution of coal losses by individual coalfaces resulting from Policies I and II indicate that the last coalface in line (Coalface I) always suffers the heaviest losses. Such an uneven distribution of delays between coalfaces will, in fact, always result from any policy where the limiting factor of the situation, in this primarily the conveyor belt capacity, is superimposed after the desired discharge rate has been calculated. It follows, therefore, that any policy design for bunker discharge rates should also include an allocation of the available belt capacity between bunkers.

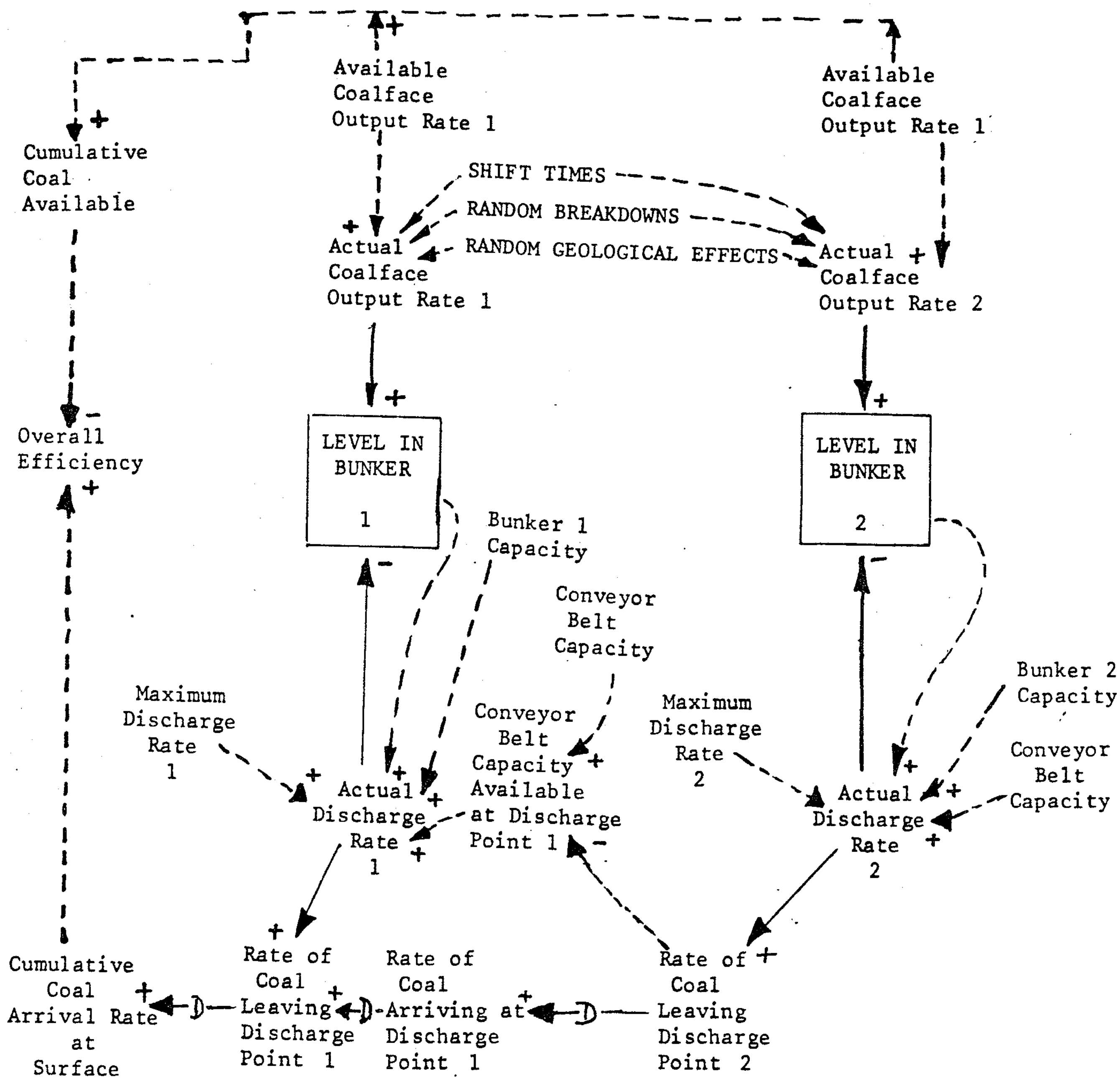

Fig.2:

INFLUENCE DIAGRAM OF COAL CLEARANCE MODEL INCORPORATING BUNKER DISCHARGE POLICIES I and II AND THE SYSTEM EFFICIENCY MEASURE.

BUNKER DISCHARGE RATES BASED ON ALLOCATED BELT CAPACITY

Policy III was designed on the basis of the points discussed in the last section. Here it is assumed that if a bunker is full it will be discharged at its maximum rate. Any residual belt capacity will then be allocated between unfilled bunkers, in proportion to the ratio of their individual levels to the sum of levels in the unfilled bunkers. The steps involved in this procedure are given by Equations (2)-(6) in the Appendix. Fig. 3 shows an influence diagram representation of the coal clearance model incorporating Policy III, again for a two bunker representation of the model.

It will be seen from Fig. 3 that each bunker level is controlled by a simple negative feedback loop (1). When no bunkers are full this loop on each bunker is undermined by the positive loop (2) if the level of that bunker is less than that in any others. When any bunker is full a reinforcement of the basic control loop for that bunker (loop 3) takes place but this is also undermined if other bunkers are also critical (loop 4). Additionally, when any one bunker is full this weakens loops 2 and 4 for other unfilled bunkers and hence weakens control of them.

Results from using Policy III in the model showed considerable improvements in efficiency and a substantial improvement in conveyor belt utilisation.

It is the premise of this paper that the dynamic control module for the allocation of capacity depicted by the dotted lines in Fig. 3 can be usefully transferred to any other system where it is required to split resource flows between different states or sectors of a system. This situation is one which occurs very commonly in system dynamics models and is usually treated by a priority type policy (where the states or sectors are ranked in some order of a preference; which themselves can be determined or based on the current magnitude of the states) or by a simple proportional policy. Apart from guidance on control this type of transfer can also result in revealing key variables and problems in the new system. However, prior to attempts to generalise the approach an account will be presented of such a transfer to a study of total coal mine management.

TRANSFER OF THE ALGORITHM TO PRODUCTION POLICY DESIGN IN COAL MINES

Here a study was undertaken to analyse the management control of production operations within a coal mine in the light of new information retrieval technology (Holmes 1980, Wolstenholme and Holmes 1985). The aim of the study was to design management policies for improving the overall level and stability of total mine output in the light of geological uncertainty.

The process of coal mining can be described as a set of sequential operations involving developing coal panels ready for production and producing from them by extracting the coal in strips along a long wall coalface. Since each mine normally has a number of such coalfaces and associated developments the problem developed into one of how to regulate output between coalfaces. This situation is, of course, entirely analogous to that encountered in the coal clearance model and hence it is possible to establish variables for a model at the total mine level analogous to each of the variables in Fig. 3. A diagram containing such variables is presented in Fig. 4. The construction of this diagram will now be described and differences from the structure of Fig. 3 highlighted.

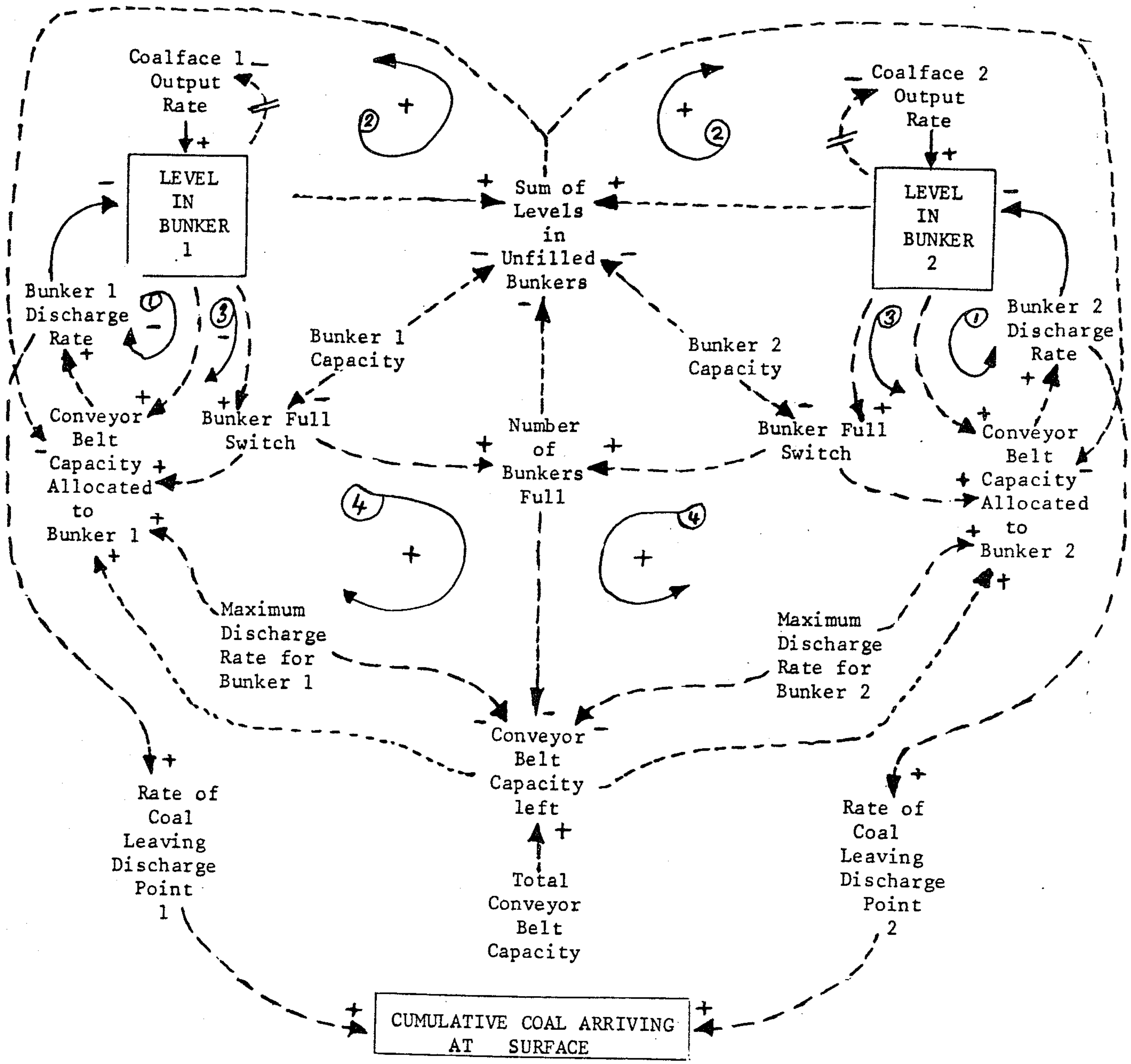

Fig 3 : INFLUENCE DIAGRAM OF COAL CLEARANCE MODEL INCORPORATING BUNKER DISCHARGE POLICY III.

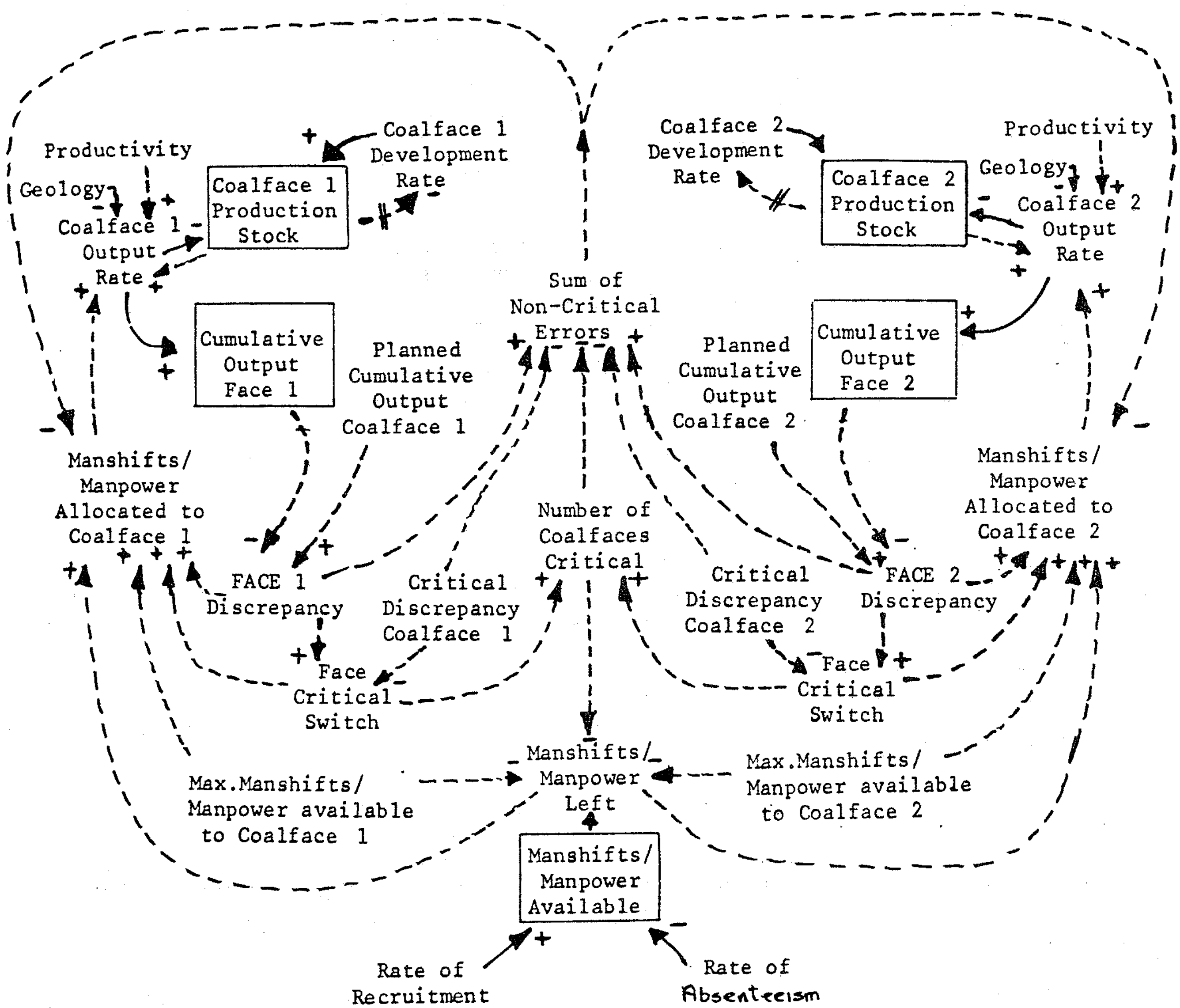

Fig 4 : INFLUENCE DIAGRAM OF COAL MINE MODEL.

The state variables of this sytems, equivalent to the bunkers of the coal clearance model, are those of the stocks of coal contained in each panel to be mined. These must be replenished by developing new faces periodically but in the short term they are depleted by a continuously applied production rate which is equivalent to the bunker discharge rate; but of course, subject to uncontrolled variations such as geological hazards. The production rate, at a given level of productivity, is a function of the manpower or manshifts used on each face and these latter variables represent the resources which must be regulated or allocated between coalfaces. A basic mechanism for doing this can be postulated in exactly the same form as for the coal clearance model. However, to cope with the additional complexity and with existing conventions some modifications are necessary.

Firstly, the convention in mine management is to measure progress by monitoring the cumulative coal cut from the mine over a period of time rather than that remaining underground in the face stock. A planned cumulative output over a given period of time is defined which is based on planned production rates. Progress of each coalface is then monitored in terms of the discrepancy between the planned and actual cumulative coalface output rates. This procedure is incorporated into Fig. 4. Secondly, for the purpose of illustration manshifts and manpower resources are shown together and thirdly the concept of a variable resource size is introduced; since in practice the upper limit of both manshifts and manpower available can be controlled but are also subject to uncertainty.

The bunker full switch of Fig. 3 is replaced in Fig. 4 by a face critical switch based on the size of the face discrepancy relative to a critical size of the discrepancy. Application of the algorithm then dictates that allocation of the maximum allowable manshifts or manpower is made to each coalface whenever the cumulative output discrepancy is critical; otherwise the allocation is made in proportion to the size of the individual coalface discrepancy relative to the sum of discrepancies on non-critical coalfaces (equivalent to the sum of levels in unfilled bunkers in Fig. 3).

This control mechanism is hence exactly the same as shown in Fig. 3. and similar feedback loops exist. It should be noted, however, that since control is instigated in terms of discrepancies in cumulative output rather than discrepancies in the stock which is depleted, the signs of some of the links constituting the major control loops are changed. The overall loop polaritites remain the same however.

This transfer of the control algorithm with its minor modifications has immediate implications for the new system in terms of the variables it suggests as important and the way these should be used. The most interesting of these in this case are the critical discrepancies to be defined for each coalface, the maximum manshifts or manpower which can be allocated, and the relationships needed between manshifts/manpower and output.

In practice coalfaces are essentially defined as being behind; or ahead of schedule and whilst every effort is made to correct discrepancies no specific mechanism for this exists. As discrepancies increase there is no physical barrier to be encountered, equivalent to the bunker capacity of Fig. 3 , which shuts the system down. Rather a gradual deterioration of total output takes place with a resultant mis-phasing of coalface finish times and problems in creating resources for future developments. There is in fact always a temptation to change the planned output figures when discrepancies become large, rather than instigate control.

Consequently the concept of a critical discrepancy captures a very important key issue for mine management, focusses attention on it an leads to open discussion of the factors determining the point at which control action should be instigated.

The need to define the maximum size of resoure allocation to each coalface also raises interesting insights. This is equivalent to defining the maximum bunker discharge rate for the coal clearance model and thought must be given as to whether coalface output can be continuously controlled in response to management inputs; or if this is effectively either switched off when insufficient manpower exists and on when sufficient exists. Attention is further directed by the diagram to the issue of whether manpower can be transferred from other tasks (for example the coalface development rate) and how much flexibility exists for changing coalface shifting patterns.

A system dynamics model, based on the outline structure of Fig. 4, was developed to investigate the merits of the control policies suggested by the algorithm to a range of more intuitive policies (Holmes 1981). To facilitate this a number of structural expansions and variable restrictions were superimposed to capture the colliery situation more closely. Two concentric control structures were created; one representing the day to day allocation of manpower, and taking into account resource fluctuations due to recruitment and absenteeism, and the other representing a monthly and quarterly revision of manshifts subject to: (i), a maximum and minimum limit on the feasible number of shifts per day which could be worked on each coalface and (ii), a change of only one shift per day per coalface on each resource revision. Additionally each control process was applied to development as well as production activities.

The use of the algorithmic control policy described, taking into account the needs of all coalfaces and developments, was compared in the developed model with other more conventional mine management policies (Wolstenholme and Holmes 1985), for a typical coalmine operating three coalfaces and subject to deteriorating geographical conditions. This model provided a clear demonstration of the substantial output improvements which are possible from such policies given improved information retrieval methods and also highlighted some of the changes which needed to be made to some management practices in order to implement the policies; in particular the need to have more flexible and responsive shifting patterns and the need to accept some decrease in the stability of output.

GENERALISATION OF THE ALGORITHM

The foregoing example has demonstrated the application of the derived allocation control algorithm in a specific management system. A generalisation of the algorithm can now be presented in the light of the experience gained and this is shown in the influence diagram of Fig. 5.

The resource to be allocated is designated as the controlling resource for the system, which is to be allocated between a number of competing processes, two of which are represented in Fig.5. The rate of allocation in each process generates a rate of conversion of the resource involved in the process (the controlled resource), depending on the productivity of the controlling resource in that process. The resource conversion rate can also, of course, be subject to exogeneous shocks which, by definition are outside the control of the system. The rate of conversion of the controlled resource in each process transforms this resource from a prior to a post state. Either the prior or post state of the processes can be used for control depending on interpretation or convention used in a given system. Fig. 5 shows the use of the post state for this purpose, which is compared with its planned version and any discrepancy is, in turn compared with a pre-defined critical discrepancy value. The rate of allocation of the controlling resource to each process is then made at a defined maximum feasible rate if the discrepancy is critical for

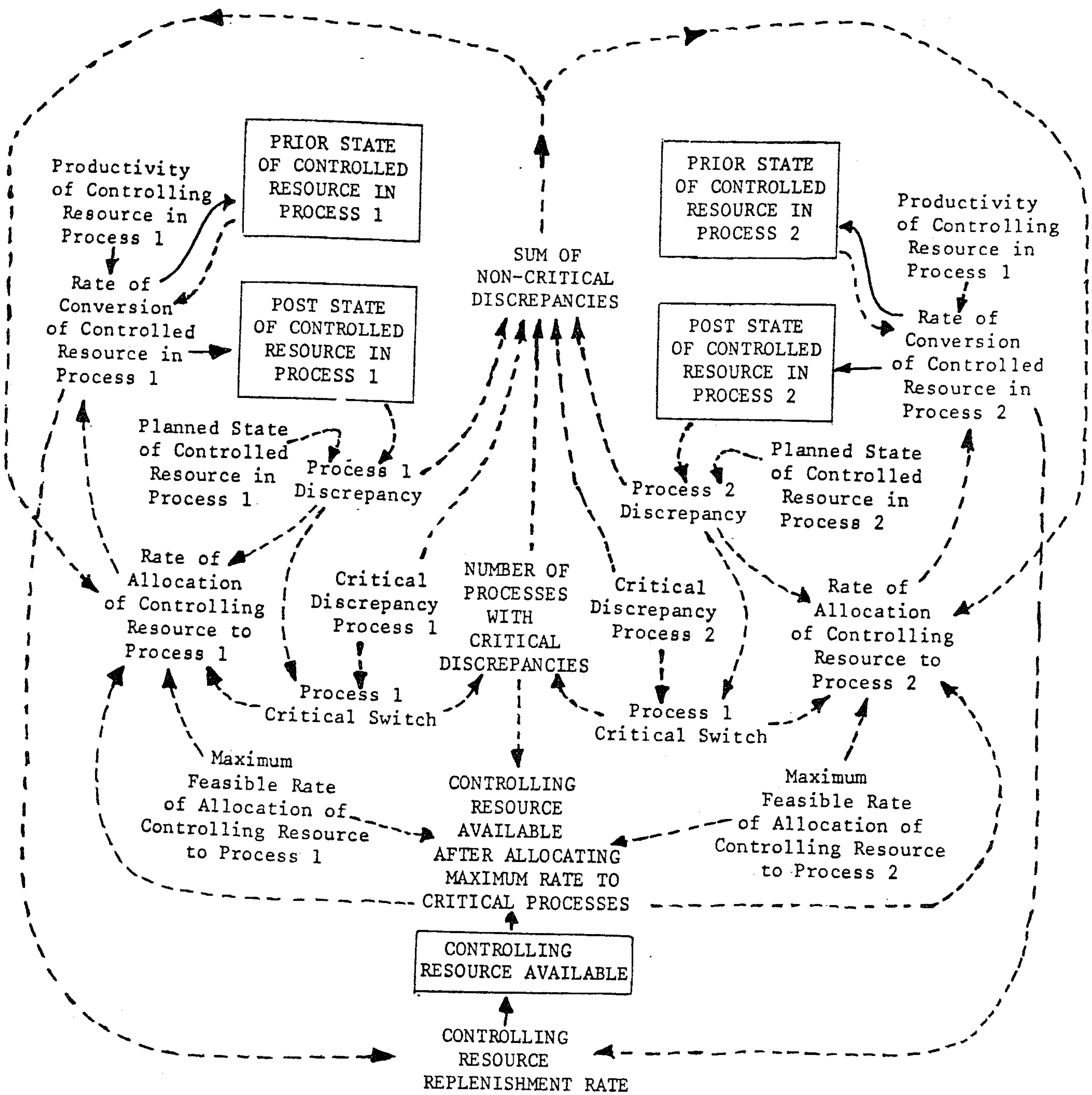

Fig. 5 : GENERALISED INFLUENCE DIAGRAM FOR THE ALLOCATION ALGORITHM.

any process or, otherwise, in proportion to the ratio of the discrepancy to the total discrepancies associated with the non-critical post states. The resultant rate of conversion of the controlled resource in each process then influences the size of the controlling resource available.

CONCLUSIONS

This paper has demonstrated that generic control structures can be developed which are applicable in a wide range of systems, and that the application of these structures can help in both conceptualizing physical models and in improving control in the recipient systems. This is seen as a significant step forward from the transfer of simple physical generic structures between systems which exist at present.

The specific interpretation of one such structure for the control of allocation has been shown to generate interesting insight and understanding in a complex management system. It is felt that the definition of the generalised influence diagram of this control structure highlights the portability of the concept in general and presents a formalised approach to the process of inter-systems transfer of the allocation algorithm in particular. Introducing the idea of controlling and controlled rates creates an interesting heirarchy of resource priorities and identifying controlling resources can be seen as subsuming the more specific system dynamics concept of identifying control variables.

One of the major problems in this type of framework in the management context is that of creating structures which are simple and general enough to transfer between systems and yet sophisticated and specific enough to generate new insight in the recipient system. There is obviously a danger of transferring to complex a structure which can lead to inappropriate control design. The structures must be capable, at a fundemental level, of being independent of the physical system to which they are applied and yet capable of providing a basis from which they can be trailored to match the reality of the environment into which they are placed. Whilst it is important to recognise that the basic transfer can itself change thinking by transferring the technology of donur system to that of the recipient system, it must also be appreciated that the tailoring process usually means relaxing some of the assumptions contained in the simple structure and that this might ultimately in some cases undermine the advantage gained.

In the case of the algorithm presented here, the development took place in the context of a system which had perfect information inputs and a capability for real time control. Whilst modern technology is moving towards such ideals the reality in most management systems is that such sophistication does not exist and attention is drawn to the fact that it was necessary to introduce a degree of crudity in many factors when tailoring the algorithm to meet the needs of the full mine model. Examples of this were the delays in monitoring the resource states and the restrictions on the rate or frequency at which control changes could be made.

Appendix. Equations used for the bunker discharge Policies II, III and III(A)

Policy II.

Desired discharge rate

$$= \frac{\text{Bunker level x Maximum discharge rate}}{\text{Bunker capacity}} \qquad (1)$$

Policy III.

(i) Determine how many bunkers are full:

$$NOBF = INT\left[\frac{B1}{BCAP}\right] + INT\left[\frac{B2}{BCAP}\right] + INT\left[\frac{B3}{BCAP}\right] \qquad (2)$$

where

NOBF = number of bunkers full,
B1 = level of bunker 1,
B2 = level of bunker 2,
B3 = level of bunker 3,
BCAP = bunker capacity (same for all bunkers).

(ii) Determine belt capacity to be allocated:

$$CL = BELT - [NOBF \times DMAX] \qquad (3)$$

where:

CL = belt capacity remaining to be allocated
= BELT if all bunkers are not full,
BELT = belt capacity,
DMAX = maximum bunker discharge rate.

(iii) Determine sum of levels in unfilled bunkers (SLIUB):

$$SLIUB = SUMB - [NOBF \times BCAP] \qquad (4)$$

where SUMB = sum of bunker levels.

(iv) Determine individual bunker desired discharge rates

$$DD1 = \begin{cases} DMAX & \text{if } B1 \geq BCAP \\ \frac{B1}{SLIUB} \times CL & \text{if } B1 < BCAP \end{cases} \qquad (5)$$

where DD1 = desired discharge rate Bunker 1.

This will always ensure that the bunker discharges at its maximum rate if full; otherwise it will receive a portion of the belt capacity left. The desired discharge rates for other bunkers are determined by similar equations.

(v) Determine individual bunker actual discharge rates:

$$AD1 = \begin{cases} DD1 & \text{if } DD1 \geq 0 \\ BELT/3 & \text{if } DD1 < 0 \end{cases} \quad (6)$$

where ADISI = Actual discharge rate Bunker 1.

This second stage is necessary because if all bunkers are full *and* total belt capacity is less than the sum of all maximum discharge rates, then negative capacity remaining (CL) and negative DD1 will result. In this case the belt capacity is apportioned equally between the bunkers. The actual discharge rates for the other bunkers are determined by similar equations.

Policy III(A).

(i) Calculate the bunker saturation level (SLEV)

$$SLEV = \frac{DMAX}{CL} \times SLIUB \quad (7)$$

(ii) Determine the number of bunkers saturated (NOBS), which will include those full:

$$NOBS = INT\left[\frac{B1}{SLEV}\right] + INT\left[\frac{B2}{SLEV}\right] + INT\left[\frac{B3}{SLEV}\right] \quad (8)$$

(iii) Determine the new belt capacity left to be allocated (NCL), assuming all saturated bunkers will be discharged as DMAX:

$$NCL = BELT - (NOBS \times DMAX) \quad (9)$$

(iv) Determine the sum of level in unsaturated bunkers (SLINS):

$$SLINS = MIN[B1, SLEV] + MIN[B2, SLEV] + MIN[B3, SLEV] - [NOBS * SLEV] \quad (10)$$

(v) Determine individual bunker discharge rates

$$DD1 = \begin{cases} DMAX & \text{if } B1 > SLEV \\ \frac{B1}{SLINS} \times NCL & \text{if } B1 < SLEV \end{cases} \quad (11)$$

The desired discharge rates for other bunkers are determined by similar questions.

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