DESIGNING AND ASSESSING THE BENEFITS OF CONTROL POLICIES FOR CONVEYOR BELT SYSTEMS IN UNDERGROUND COAL MINES

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ABSTRACT

This paper describes the application of System Dynamics in what is traditionally a hard engineering area, but where the application of analytical techniques are limited by the stochastic nature of the system driving forces (coalface output rates) and the need for highly credible, management orientated results. Methods of analysis have thus centred on using discrete simulation techniques based on open system models, primarily to assist in capacity design.

The use of System Dynamics in this context is based on two premises. The first of these is that System Dynamics has, in addition to its softer areas of application, considerable potential to both supplement and enhance Operational Research approaches in the analysis of such systems. Secondly, it is the author's belief that the key to further development and acceptance of System Dynamics lies in bridging the gap between itself and associated subject fields, such as Operational Research, by direct demonstrations of the approach within these fields. Recent technological advances within the coal clearance field have provided an excellent form for such a demonstration.

The trend in the installation of micro computers for centralised monitoring of the state of underground conveyor belts and bunkers, is rapidly increasing and the scope for totally automatic, real time control of these systems has, consequently, been greatly enhanced. However, the progress in information retrieval has outstripped the development of compatible advances in methods of designing total system controls to make best use of collected information, and the research work described here concerns how System Dynamics can assist such design. This centres on the development of a System Dynamics model of an underground conveyor belt system, incorporating realistic production generated patterns. The model is used to test out and improve the design of alternative policies for bunker discharge rates under a wide range of system parameters. The final policy evolved in this way has general applicability and is shown to maximise conveyor belt utilisation, be independent of limitations in the maximum bunker discharge rates and to require only the monitoring of bunker levels. Finally, the model is used to quantify the benefits of such improved control in terms of savings in physical capacity required to obtain maximum system efficiency.

INTRODUCTION

The majority of Coal Mines utilise conveyor belt systems to transport coal from the working coal faces to the surface. The major problems in designing the capacity of such systems are that coal face output rates fluctuate over time, due to variations in the shift patterns in operation, variations in the coal cutting speed (due to geological changes) and the reliability of coal face machinery. Further, since reserves of coal are depleted by extraction, the layout of coalfaces in a colliery is a geographically dynamic phenomena.

The capacity of coal clearance systems must hence be designed to cater both for short term fluctuations and longer term changes in coal production rates. As a result of major developments in coal mining technology over recent years, and the consequent trend towards concentrating production on fewer and larger coalfaces(1), the situation where colliery coal clearance systems are working at or above their design capacity is frequently encountered. Consequently, attention is now being focussed on the use of more sophisticated control of these systems in order to make the best use of existing capacity. The feasibility of such control has been enhanced of late by technological advances in the development of mini and micro computers for real time control.

The installation of small computers is currently taking place on an increasing scale at colliery level, and these are being used to monitor and display up to date information (on both coal clearance and many other underground systems) in central control stations. The implementation of action based on this information is at present largely manual (2)(3)(4)(5)(6) but the ultimate potential of these applications is that decision rules or control policies can be automated and, hence, control action can be fed directly back to the operations.

The fundamental difficulty in attaining this potential in any information and control system are those of determining which information sources to monitor, and what form of control rule to use. This presents somewhat of a dilemma, because control rules cannot be formulated unless a choice of information has been made, and it is difficult to choose which information to monitor unless the benefits of using it in control rules have been assessed.

System Dynamics is a technique for applying control engineering ideas to complex management systems[7] and system dynamics models have been used in a wide range of industrial and socio-economic systems, to help overcome the above mentioned problems. The technique involves modelling a system in terms of its constituent levels and rates and developing this into a continuous simulation model, incorporating both physical flows and information feedback. The merits of alternative forms of rate (control) equations can, therefore, be investigated based on a variety of information inputs.

To achieve this end continuous simulation software is available and the main purpose of the current research has been to investigate the merits of applying such a general suite of programmes (DYSMAP)[8] to study the specific issues of coal clearance. This approach is intended to provide an interesting contrast with the well developed and long standing discrete simulation programmes currently used in the British Coal Industry in this context. These programmes have been extensively and successfully used to study problems of coal clearance capacity, but only lately have been extended to allow investigations of control.

MODEL DESCRIPTION

In order to test the general feasibility of building continuous simulation models, capable of investigating alternative aspects of control, a model has been developed of a simple three bunker coal clearance system. It is assumed that each bunker is fed by a single coalface and that the bunkers discharge onto a drift conveyor, which transports the coal directly to the surface of the mine. The physical flows of this system are shown diagramatically in Figure 1. The overall aim was to develop and test alternative discharge policies for the bunkers, measured against an efficiency criterion based on the ratio of cumulative coal output cleared to the surface, over a given period of time, to that potentially available for the three coalfaces. The model was developed in modular form so that at a later stage any configuration of faces, belts and bunkers could be represented.

Figure 2 shows a slightly more detailed, but still simplified, diagram of the model, indicating some of the composite steps involved in building up the sectors for coalface 1 and bunker 1. The diagram includes some information feedback links to demonstrate how bunker discharge policies were incorporated in the model. This structural representation, which was replicated for the other coalfaces and bunkers, is explained in the following sections.

In order to produce a realistic pattern of coal output over time, the coalface sectors of the model were designed to take into account shift working times, variations in the rate of coal cutting and stoppages due to machinery breakdowns. Figure 2 shows how the first two of these factors are initially superimposed onto a 'base' coalface output rate to model the pattern of available coal output over time. It was assumed that once randomly set the available coal output rate would hold for 30 minutes before being reset. The actual coalface output is then generated by superimposing randomly generated coalface breakdowns. This is achieved by alternatively sampling a length of production run and a length of breakdown period from normal distributions for these factors, with adjustable mean and standard deviation.

Full details, including equations, of the coalface model used to generate the output will be found in a separate paper (9). Examples of the dynamics produced by the model, at each stage of the procedure, are presented in Figure 3.

The actual coalface output rate is then fed directly into the bunker (see Fig.2) with a provision that the coalface will be switched off if the bunker capacity is exceeded. During such periods the cumulative available output rate is measured to represent the lost production due to inadequate bunker capacity.

The bunker itself is discharged onto the conveyor belt, according to the discharge policy to be investigated. For demonstration purposes Figure 2 gives an example of how such a discharge policy might be constructed. Here, it is assumed that the desired rate of discharge of the bunker will be a function of the bunker level (or other bunker levels), and that the actual discharge rate will follow this, subject to there being coal available in the bunker and space available on the conveyor belt at the discharge point. The actual discharge rate, once determined, then depletes the bunker level and the coal leaving the discharge point is the sum of that arriving and this discharge rate. Additionally, the coalface is also switched off whenever the desired discharge rate exceeds the belt capacity available and the bunker is full. Cumulative coal lost during such periods is measured and classified as losses due to lack of belt available capacity.

Figure 2 also shows how the cumulative coal reaching the surface is compared with that available at the coalface, to produce the efficiency measure.

By converting Figure 2, and similar representations of the other coalfaces and bunkers, into explicit equations representing the influences shown, a composite simulation model is produced. This can then be run over many time periods to investigate the overall performance of the system under different patterns of coalface production, different values of coal clearance system parameters and different bunker discharge policies.

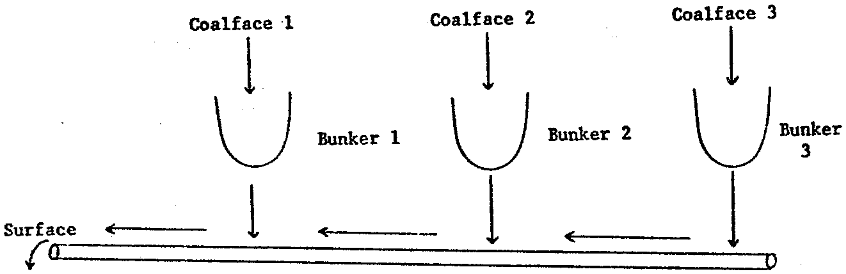
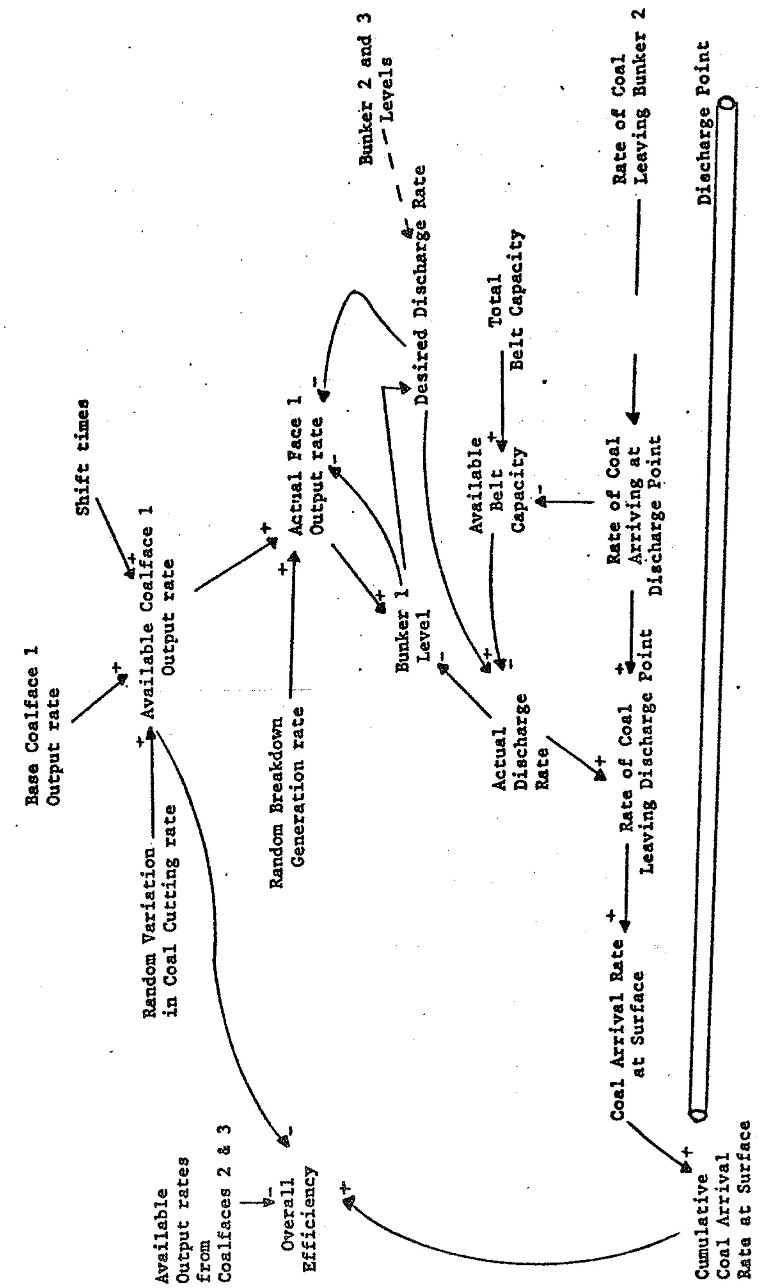


Figure 1

GENERAL LAYOUT OF SITUATION MODELLED

FIGURE 2 INFLUENCE DIAGRAM FOR COALFACE 1 AND BUNKER 1



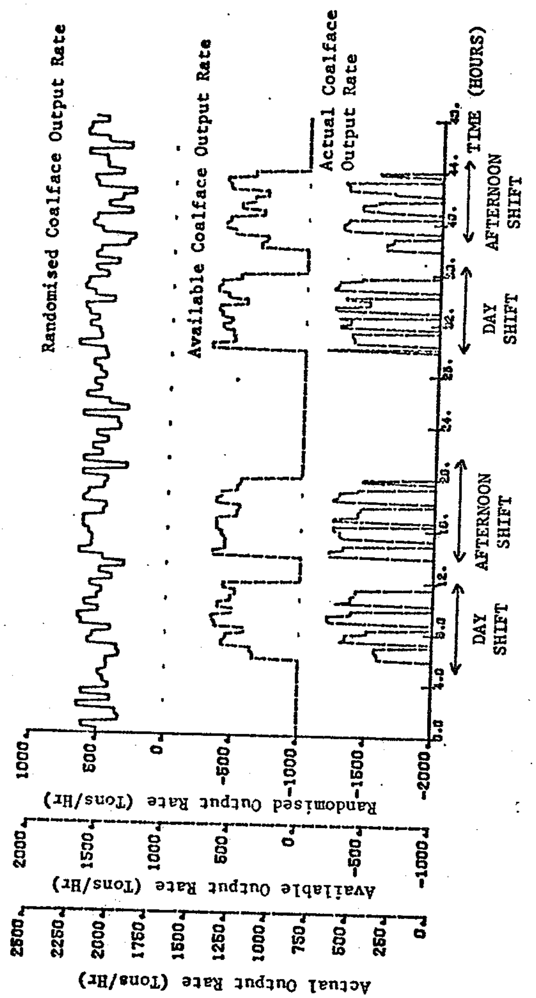


FIGURE 3 DYNAMICS OF COALFACE OUTPUT PROGRAM.

EFFECTS OF ALTERNATIVE BUNKER DISCHARGE POLICIES

Design of Experiments

All experiments and results presented in the report are based on varying the coal clearance parameters and bunker discharge policies. Common features of all the model runs were that the conveyor belt could operate throughout the working day, but that the coalfaces were operated over two six hour shifts, each with a base output of 1000 tons per hour and a range from 600 to 1400 tons per hour. The length of production and breakdown periods were specified separately for each coalface but mean lengths were in the order of 120 minutes and 10 minutes respectively. Also the model was run in each case for one complete day (24 hours) starting from an equilibrium situation and using the same stream of random numbers for each coalface on each run.

Each experimental model run was defined in terms of the coal clearance parameters used, and these runs are listed on the left hand side of Figure 3, against which various bunker discharge policies were subsequently tested. Although the three bunker coal clearance system model outlined represents a simple type of such a system, it can be used, by suitable choice of parameters, to model a wide range of conditions encountered in practice. The experiments defined in Figure 3 can be seen to fall into two blocks.

In the first block the belt capacity (2000 tons/hour) is chosen to be less than the sum of the base output rates of the three coalfaces, and hence these parameters represent a storage bunker situation. Here, the purpose of the bunkers is to act as storage over the day to match face outputs with inadequate belt capacity, and scope exists to trade off bunker capacity against improved control of bunker discharge rates. Four experiments are defined here which examine the effects of lowering the maximum bunker discharge rates from their base value of 1000 ton/hour to 700 ton/hour, and increasing the capacity of all bunkers from their base value of 500 tons to 1000 tons and 1200 tons respectively.

The second block of experiments represent a surge bunker situation, where the belt capacity is first set to 2,500 tons/hour which (after allowance is made for coalface breakdowns) is approximately capable of dealing with the sum of the base output rates of the three coalfaces, but not the sum of their maximum rates. Here, the purpose of the bunkers is to smooth out instantaneous fluctuations in coalface output rate over and above belt capacity. Obviously less bunker capacity is required in these circumstances, than in the storage bunker situation, and experiments are hence defined in terms of 150 tons and 500 tons bunker capacity respectively. The belt capacity is secondly set to 3500 tons/hour, which is considerably more capable of dealing with instantaneous peaks in coalface outputs, and similar bunker capacity increases examined.

Simple Bunker Discharge Policies - definition and results

The model was first tested using rather obvious and crude discharge policies as follows:

Policy I : Fixed Discharge Policy

Here it was assumed that each bunker could only be operated at zero or its maximum discharge rate, and that the latter would be used as long as there was coal available in the bunker and room available on the belt.

Policy II : Variable Discharge Policy

Here it was 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 the bunker level:

$$\text{i.e. Desired Discharge Rate} = \frac{\text{Bunker level} * \text{Maximum Discharge Rate}}{\text{Bunker Capacity}} \quad \ldots\ldots \text{(i)}$$

Again subject to coal being available in the bunker and room being available on the conveyor belt.

The result of applying these simple bunker discharge policies to the runs previously defined are shown in Figure 4.

		DEFINITION OF EXPERIMENT			OVERALL SYSTEM EFFICIENCY	
		Total Belt Capa-city (Tons/Hour)	Maximum Discharge Rate of each Bunker Tons/Hour	Capacity of each Bunker (Tons)	Bunker Discharge Policy I (Fixed Discharge)	Bunker Discharge Policy II (Variable Discharge)
BLOCK 1	Run 1	2000	1000	500	70.1	71.9
STORAGE	Run 2	2000	700	500	53.7	69.1
BUNKER	Run 3	2000	1000	1000	72.9	76.7
SYSTEM	Run 4	2000	1000	1200	73.9	78.7
BLOCK 2	Run 5	2500	1000	150	65.4	75.8
SURGE	Run 6	2500	1000	500	70.1	84.0
BUNKER	Run 7	3500	1000	150	83.7	77.4
SYSTEM	Run 8	3500	1000	500	91.8	85.8

Figure 4 Overall System Efficiences for Bunker Discharge Policies I & II

With a conveyor belt capacity of only 2000 tons/hour (block 1 results) and a maximum discharge rate from each bunker of 1000 tons/hour, Policy I exhibits efficiences between 70.1% and 73.9% (runs 1, 3 and 4), since, at best only two bunkers can discharge at any one time. The difference between these runs demonstrates the increased efficiency resulting from increasing the bunker capacity and run 2 indicates the reduced efficiency resulting from a lowering of the maximum bunker discharge rates. When the conveyor belt capacity is increased to 2500 tons/hour (runs 5 and 6 in block 2) no improvement in efficiency results because, due to the policy, it is still only possible to discharge at most two bunkers at any time. Consequently, run 6 gives the same result as run 1 and run 5 is reduced to 65.4% due to less bunker capacity available. Increasing the belt capacity to 3500 tons/hour results in improved efficiencies (runs 7 and 8), since all three bunkers can now be discharged together. (This result would also be expected at a conveyor belt capacity of 3000 tons/hour).

Under policy I the discharge rates from the bunkers can only be either zero or the maximum discharge rate. Hence there are times, particularly between shifts, when some discharge could take place but doesn't (because this would be at less than the maximum rate), and it is to be expected that the conveyor belt capacity is somewhat under utilised. One of the most important conclusions from the experiments in this section is that when both sufficient bunker and belt capacity exist the maximum theoretical efficiency for the system (given the coal face breakdown pattern used) is attained (run 8). This result gives confirmation of the fact that if total system capacity is adequate then the only control necessary over bunker discharge rates, is to deploy their maximum setting.

The results from using Policy II are also shown in Figure 4. This variable bunker discharge policy overcomes the major deficiency of the previous policy, in that discharge can now take place at any intermediate rate between zero and maximum. As a consequence improvements in overall efficiency are achieved in most cases relative to Policy I. This is particularly noticeable at a conveyor belt capacity of 2500 tons/hour, where, unlike Policy I, advantage can now be taken of the additional 500 tons/hour conveyor capacity available over block 1 experiments. The exceptions to the improvements in efficiency, relative to Policy I, occur in runs 7 and 8, associated with a conveyor belt capacity of 3500 tons/hour.

These reduced efficiencies do in fact highlight one major weakness of the policy used. Once sufficient conveyor belt capacity exists the bunker discharge rates under Policy II are simply a function of the bunker level (see equation (i)) and the maximum discharge rate is only employed when the bunker is full. Consequently, if the bunker capacity is almost adequate to cope with the coalface output (run 7), 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 (run 8). This is an interesting disadvantage of what would intuitively appear to be a sound discharge policy. It should, however, be noted that at lower conveyor belt and bunker capacities (run 1 - 6), increases in bunker capacities have a greater effect on efficiency under Policy II than was apparent under Policy I.

The foregoing results from simple policies indicate 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. The overall aim being to maximise the utilisation of the available belt capacity. Further, however, it is clear that both of the simple policies used represent essentially priority policies. Examination of the distribution of coal losses by coalface resulting from Policies I and II indicate, as expected, that the last coalface in line (Coalface 1) 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 the bunkers.

Bunker discharge rates based on allocated belt capacity - definition and results

Policy III

This policy 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 following steps are hence involved:

(i) Determine how many bunkers are full

$$NOBF = INT\left[\frac{BUN1^{+.1}}{BCAP}\right] + INT\left[\frac{BUN2^{+.1}}{BCAP}\right] + INT\left[\frac{BUN3^{+.1}}{BCAP}\right] \quad \ldots\ldots \text{(ii)}$$

where NOBF = number of bunkers full
BUN1 = level of bunker 1
BUN2 = level of bunker 2
BUN3 = level of bunker 3
BCAP = bunker capacity (same for all bunkers)

(ii) Determine belt capacity to be allocated

$$CL = BELT - [NOBF*DMAX] \quad ..... \quad (iii)$$

where CL = belt capacity remaining to be allocated = BELT if all bunkers not full

BELT = belt capacity

DMAX = maximum bunker discharge rate

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

$$SLIUB = SUMB - [NOBF*BCAP] \quad ..... \quad (iv)$$

where SUMB = sum of bunker levels

(iv) Determine individual bunker discharge rates

$$* \quad DDIA = CLIP(DMAX, \frac{BUN1}{SLIUB}*CL, BUN1, BCAP) \quad ..... \quad (v)$$

where DDIA = desired discharge rate Bunker 1 (A)

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.

$$ADIS1 = CLIP(\frac{BELT}{3}, DDIA, 0, DDIA) \quad ..... \quad (vi)$$

where ADIS1 = 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 hence negative DDIA, 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.

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* This is a DYSMAP function the interpretation of which is:

If X = CLIP (A,B,C,D)

Then X = A if $C \geq D$

X = B if $C < D$.

The foregoing policy was applied to a similar set of simulation runs as outlined in Figure 4 and the results of these applications are shown under the heading of Policy III in Figure 5. It can be seen that Policy III gives an improvement in overall efficiency, over Policies I and II, on all runs. This is due to a combination of the facts that better use is now being made of conveyor belt utilisation and also that discharge is not now on a priority basis. In particular, the effect of increasing the bunker capacity at low belt capacities is much more marked. For example, comparison of runs 1 and 3 for Policy II in Figure 4, show a 4.8% improvement in efficiency, whilst comparisons of runs 1 and 3 for Policy III in Figure 5 show an 8.3% improvement in efficiency. In other words, the improved belt utilisation, which results from the improved control policy, can be interpreted as a saving in bunker capacity to achieve a given efficiency. As in Policy I results run 8 for Policy III confirms that the maximum efficiency of the system, under the coalface conditions simulated, is 91.3%.

		DEFINITION OF EXPERIMENT			OVERALL SYSTEM EFFICIENCY	
		Total Belt Capacity (Tons/Hour)	Maximum Discharge Rate of each Bunker (Tons/Hour)	Capacity of each Bunker (Tons)	Bunker Discharge Policy III (First Belt capacity Allocation Policy)	Bunker Discharge Policy IV (Second Belt capacity Allocation Policy)
BLOCK 1	RUN 1	2000	1000	500	73.2	73.3
STORAGE	RUN 2	2000	700	500	71.5	73.3
BUNKER	RUN 3	2000	1000	1000	81.5	81.6
SYSTEM	RUN 4	2000	1000	1200	84.6	84.9
BLOCK 2	RUN 1	2500	1000	150	78.9	79.4
SURGE	RUN 2	2500	1000	500	88.0	88.7
BUNKER	RUN 3	3500	1000	150	84.2	84.5
SYSTEM	RUN 4	3500	1000	500	91.8	91.8

Figure 5 Overall System Efficiences for Bunker Discharge Policies III & IV

Of special interest in the results from Policy III, is that associated with run 2, which shows the effect of reducing the maximum discharge rate of the bunkers and emphasises the importance of this parameter. Even though the maximum discharge rate used for each bunker of 700 tons per hour (2100 tons/hour in total) is in excess of the total belt capacity (2000 tons/hour) for this run, a reduction in efficiency is shown over run 1, where the maximum bunker discharge rate was 1000 tons/hour. This is due to the fact that circumstances can arise in the application of Policy III, where the belt capacity allocated to a bunker is in excess of its maximum discharge rate and is, consequently, terminated at this value as directed in equation (v). This results in a loss of belt utilisation. Hence Policy III can only be used where maximum bunker discharge rates somewhat in excess of basic bunker input rates are specified. Since this arrangement is not common in practice, provision must be made in policy design for the effect of low maximum bunker discharge rates. This can be achieved by modifying Policy III to carry out a secondary allocation of any spare belt capacity, resulting from such termination, between the other bunkers as outlined in the next section.

Policy IV

This policy represents an extension of Policy III to overcome problems associated with low maximum bunker discharge rates. Having set all full bunkers to discharge at their maximum rates, as in Policy III, Policy IV then determines whether or not the allocation of the remaining belt capacity to the other bunkers will result in their maximum discharge rates being exceeded by calculating the level of each bunker at which this situation will occur. This is referred to as the saturation level. If the bunker level exceeds this saturation level then the discharge of that bunker is also set to its maximum and any remaining belt capacity allocated between unsaturated bunkers in proportion to their levels. The following steps are involved over and above those outlined in Policy III.

(i) Calculate the bunker saturation level (SLEV)

$$SLEV = \frac{DMAX}{CL} * SLIUB \quad ..... \quad (vii)$$

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

$$NOBS = INT\left[\frac{BUN1}{SLEV}\right] + INT\left[\frac{BUN2}{SLEV}\right] + INT\left[\frac{BUN3}{SLEV}\right] \quad ..... \quad (viii)$$

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

$$NCL = BELT - (NOBS*DMAX) \quad ..... \quad (ix)$$

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

$$SLINS = MIN\left[BUN1,SLEV\right] + MIN\left[BUN2,SLEV\right] + MIN\left[BUN3,SLEV\right] - \left[NOBS*SLEV\right] \quad ..... \quad (x)$$

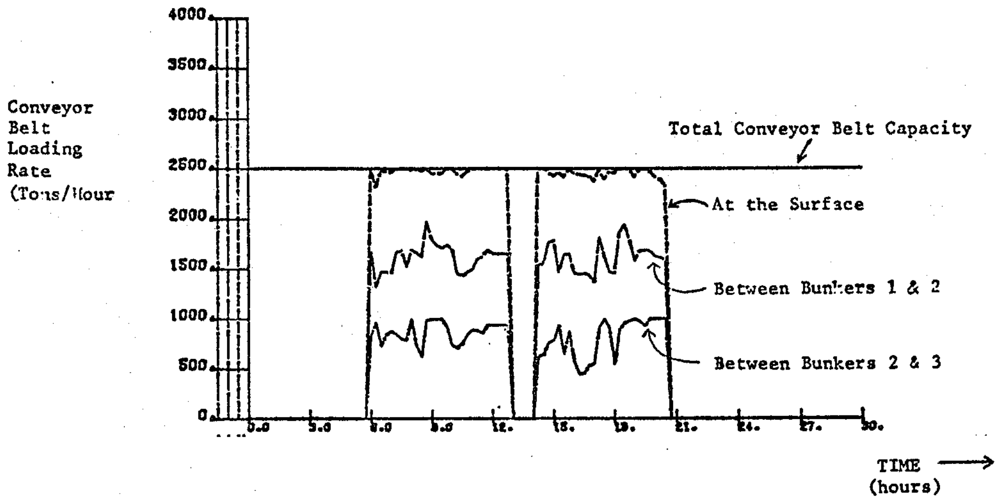
(v) Determine individual bunker discharge rates

$$DDIA = MIN\left(DMAX,\frac{BUN1}{SLINS} * NCL\right) \quad ..... \quad (xi)$$

ADIS = as equation (vi) ..... (xii)

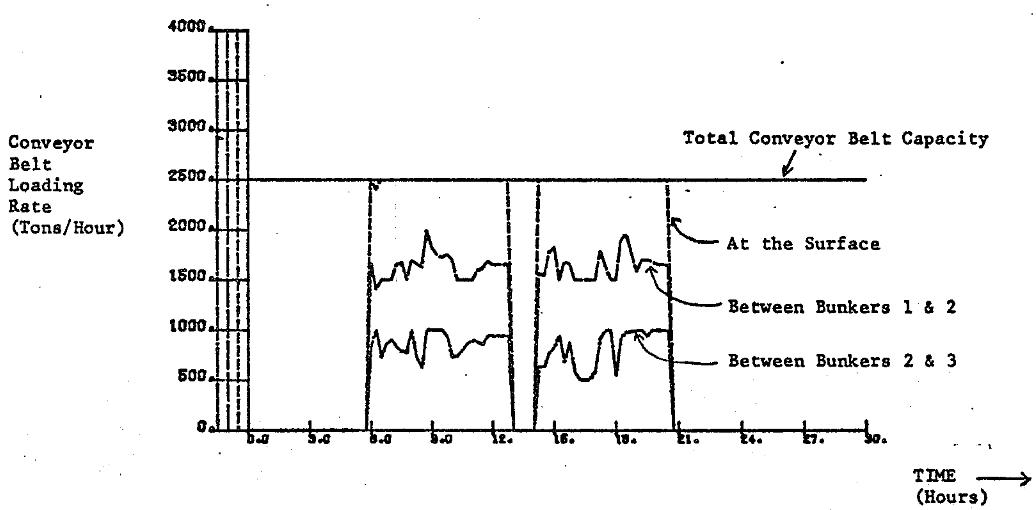
The actual discharge rates for other bunkers are determined by similar equations.

The results of applying this modified policy to the previously defined runs are again shown in Figure 5, where it can be seen that there is an improvement in efficiency over Policy III in all runs, except, of course, run 8. Although these differences and efficiencies are apparently small, an example of their significance is demonstrated in Figures 6 and 7, which show how the rate of coal arriving at the mine surface compares with the belt capacity for Policies III and IV respectively. Run 2 (Figure 5) now achieves the same efficiency as Run 1, confirming that Policy IV is independent of the maximum bunker discharge rate. In fact, Policy IV totally maximises the utilisation of the available belt capacity and hence provides a method of control which cannot be improved for any given set of system parameters. In addition it will be noted that runs 1 and 2 in Figure 5 are now identical, indicating that Policy IV is also independent of the maximum bunker discharge rate.



Rates of Coal Flow at different points on the
Conveyor Belt for Bunker Discharge Policy III
(First Belt Allocation Policy)

Figure 6



Rates of Coal Flow at different points on the
Conveyor Belt for Bunker Discharge Policy IV
(Second belt allocation policy)

Figure 7

QUANTIFYING THE BENEFITS OF ALTERNATIVE BUNKER DISCHARGE POLICIES

The foregoing results clearly indicate that it is possible to improve the overall efficiency of a coal clearance system by increasing the belt and/or bunker capacities and/or by instigating more sophisticated control over bunker discharge rates; which leads to the interesting question as to which alternative method should be employed. This is best answered by considering how much bunker capacity would be necessary to achieve maximum efficiency for each belt capacity, and bunker discharge policy used. Such figures were determined by repeating the previous simulation runs under the assumption of infinitely large bunker capacities, and measuring the maximum level achieved in each bunker. These results are shown in Figure 8.

Belt Capacity (tons/hr)	Bunker Discharge Control Policies			
	POLICY I Maximum Bunker Level (Tons)	POLICY II Total Maximum Bunker Level (Tons)	POLICY III Total Maximum Bunker Level (Tons)	POLICY IV Total Maximum Bunker Level (Tons)
2000	7,564	6,150	5,372	5,300
2500	7,564	3,000	2,513	2,390
3500	1,288	1,854	1,346	1,288

Figure 8. Feasible, total maximum bunker levels required to achieve maximum efficiency (i.e. no coal losses) for each combination of belt capacity and bunker discharge policy.

In Figure 8 the bunker level quoted is the sum of the maximum levels achieved in each bunker. All runs, with the exception of those associated with Policy II, resulted in the attainment of maximum system efficiency of 91.8% with no coal face stoppages. Under Policy II problems occur in determining the maximum bunker levels required. Since, as explained in an earlier section, the bunker discharge policy itself interacts with the bunker level. If a large bunker capacity is introduced the bunker levels rise to use the available capacity and the efficiency falls.

The problem cannot be totally overcome without destroying the policy, but can be partially overcome by fixing the bunker capacity not at an infinite value, but at a level only slightly in excess of the maximum level anticipated in each run. The results for Policy II in Figure 6 were determined in this way and, hence, represent approximation to the total bunker capacity required.

Nevertheless, the results of Figure 8, which are interpreted graphically (for Policies II, III and IV) in Figure 9, clearly show:

(i) that for a given bunker discharge policy there is a trade off between bunker capacity and belt capacity to achieve maximum efficiency. i.e. at low belt capacity very high bunker capacity is required which decreases as belt size is increased. The ultimate extension of this is that at very high belt capacity no bunkerage is necessary and that at very low belt capacities infinite bunkerage is necessary.

(ii) that improved bunker discharge policies can reduce the physical capacity necessary to achieve maximum efficiency.

Obviously the ultimate criteria of choice between the alternative methods of achieving maximum efficiency is that of cost, and Figure 10 presents the results of Figure 8, converted to cost terms. Each belt/bunker combination, has been converted into total capital cost terms by summing the required belt capacity at £300/tons/hour to the required bunker capacity of £750/ton. These are average costs/unit of capacity and are taken as approximately representative of those necessary to uprate capacity (10).

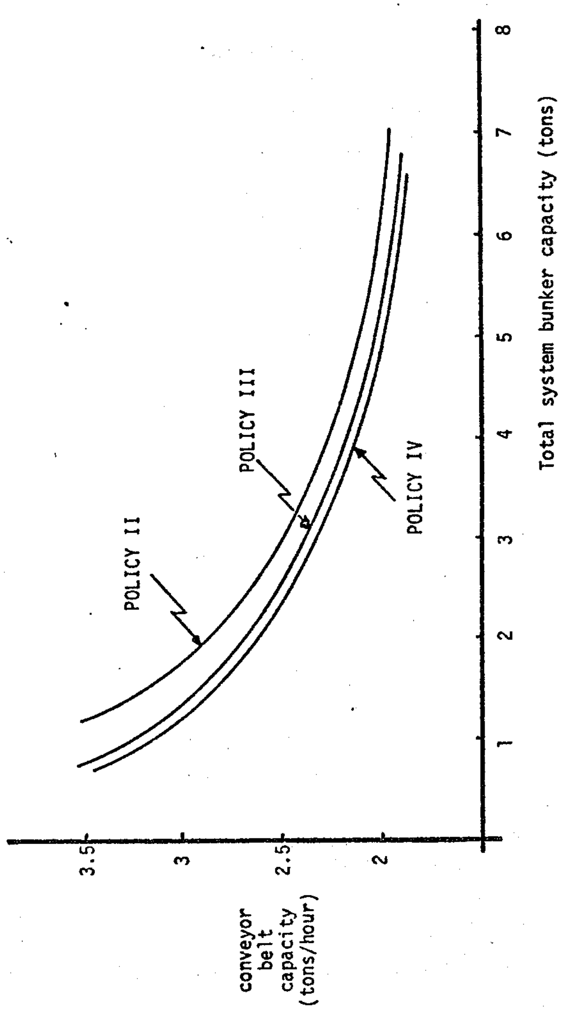


Figure 9 Variation in conveyor belt capacity with total system bunker capacity to attain maximum system efficiency (Policy II, III and IV)

It will be seen that the lowest total cost of each bunker/belt combination occurs for any given policy by using the largest belt size, which implies that it should always be more economical to maximise belt size and minimise bunker capacity. This does, however, ignore the risk of breakdown associated with such an arrangement. It can be shown that, in fact, unit conveyor belt costs need to be of the order of four times bunker costs before smaller belt sizes and larger bunker combinations become economical on a simple average cost criterion.

By reading across the rows, Figure 10 also shows the order of savings associated with the type of control policy used, which are attributable to better conveyor belt utilisation and hence, lower bunkerage requirements. In all cases these will be seen to be very substantial. As a more moderate example the effect of using Policy III rather than II at a belt capacity of 2500 tons/hour, results in a capital saving of £366,000 (less of course the cost of control).

BUNKER DISCHARGE POLICY											
POLICY I			POLICY II			POLICY III			POLICY IV		
Belt Capa-city	Bunker Capa-city	Cost	Belt Capa-city	Bunker Capa-city	Cost	Belt Capa-city	Bunker Capa-city	Cost	Belt Capa-city	Bunker Capa-city	Cost
Tons/Hr	Tons	£m	Tons/Hr	Tons	£m	Tons/Hr	Tons	£m	Tons/Hr	Tons	£m
2000	7,564	6.273	2000	6,150	5.213	2000	5,372	4.629	2000	5,300	4.575
2500	7,564	6.423	2500	3,000	3.000	2500	2,513	2.634	2500	2,390	2.542
3000	1,288	2.016	3000	1,854	2.440	3000	1,346	2.059	3000	1,288	2.016

Figure 10 Capital costs of each belt/bunker combination for each bunker discharge policy.

IMPLICATIONS OF RESULTS AND CONCLUSIONS

The report demonstrates that coal clearance systems can be effectively modelled using system dynamics techniques and that, since such models incorporate continuous information feedback they allow a system to be designed in the operational control sense as well as in terms of engineering capacity. In addition to aiding the development of automatic control rules for bunker discharge rates, models of the type developed have been shown capable of quantifying the trade off between improved control and the total physical capacity of any coal clearance system. The results presented clearly show the relative merits of increasing system efficiency by improved bunker discharge control, compared with the alternatives of increasing either conveyor belt or bunker capacity. This has obvious implications both in the design of new systems and in improving the efficiency of existing ones.

Using the model, a control policy based solely on bunker levels has been developed and tested, which is capable of maximising conveyor belt utilisation, under any range of values of physical parameters in the coal clearance system described. It will be noted that since such maximisation is achieved then by definition no further scope for improvement exists, for any specified combination of parameters. This is particularly important in the context of using additional information sources in control rules. For example, many other sources of information other than bunker levels could be specified on which to base bunker discharge control rules. In particular, it is often postulated that bunker discharge policies could beneficially be based on coalface information, in addition to bunker level information; either in the form of current average output rate or the time to the next planned stoppage. The effect of such modification to the developed control rules is under investigation in this and other system configurations but, since conveyor belt utilisation can be maximised under the existing control rule, this additional information is likely to be redundant.

It should be emphasised that the model and results described, represent a situation where automatic continuous scanning of the states of the system can be carried out, and indicate what is possible if automated control action could be continuously fed back to the bunker discharge equipment. This presupposes that continuous adjustment of the equipment is possible and, in practical cases, the system performance will be proportionately less, depending on the actual bunker discharge increments which are feasible.

ACKNOWLEDGEMENTS

The authorwould like to acknowledge the assistance of J.Zachoval, R.G.Coyle and A.K.Ratnatunga, for their co-operation in various stages of development of this research.

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