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System Dynamics Applications in The Mining Industry

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ABSTRACT System dynamics is soft operational research (OR) technique, used for reflecting information feedback characteristics of complex systems. The methodology identifies causal relationships between the variables of a system and investigates the effect of these relationships to the overall system behavior. Such representation of the system enables providing an insight to the system and allows construction and testing of alternative policies in order to achieve objectives of the system. In this manner, the methodology differs from conventional OR techniques, for the properties of complex systems, such as order of the system, loop multiplicity and nonlinearity that lead to dynamic behaviors in the system are reflected and explained within the models. The methodology has been applied to many areas, ranging from business, environmental and industrial policy research to medicine, energy policy research and engineering. This paper concerns with application of the methodology in the mining industry.

1 INTRODUCTION

System dynamics is a methodology that reflects the information-feedback relationships of the complex systems. The methodology has been under use since I950's and been applied to many business and engineering cases where an information-feedback system exists."(Gielen and Yagita, 2002; Stave, 2002; Anderson, 2001; Lyneis, 2000; Abbot and Stanley, 1999) The methodology, besides providing a better understanding of the system, also allows the design and testing of alternative policies for better managerial decision making. Like most other systems, mining systems can be represented as complex information-feedback systems, in a manner that the result of each mining operation affects itself back at the next point in time. Such a causal representation provides an insight for the understanding of the system and tests how alternative information inputs can change the performance of overall operations.

System dynamics is a widely applied OR technique in the energy sector, where the interactions between variables within the sector are dynamic and complex, and therefore, hard to identify and represent with other OR techniques. The methodology has been applied as a tool for energy policy research, both in smaller scale models, which try to determine the firm's policy to meet the energy demand, and in larger scale models, in which the energy policy of a country is tried to be evaluated. On the other hand. despite the existence of complex relationships between the variables of a mine, system dynamics is not a widely used modeling technique in mining industry and the applications of the methodology in the mining industry is restricted to production planning and finding the optimum conveyor belt capacity for underground collieries, so far.

The aim of this paper is to provide examples for the usage of system dynamics in the mining sector to illustrate system dynamics as an alternative approach to system investigation and policy construction and testing in the mining industry.

2 SYSTEM DYNAMICS METHODOLOGY

2. / *System Dynamics*

System dynamics, developed by Jay W. Forrester during the mid 50's, is a methodology used for reflecting the information-feedback characteristics of complex systems through the system's structure, the amplifications and delays contained within the system, such that it provides an insight to the system behaviour.

An information-feedback system arises whenever a decision leading to an action affects itself in return. Hence, the three characteristics of an information feedback system are:

- The structure of the system
- Amplifications within the system

- Time delays

The structure of the system consists of levels and rates. Levels are accumulations within a system, resulting from the difference of inflows and outflows that take place in the level. They describe the state of the system upon which the decisions are made. A level may be inventory of goods, number of equipment or personnel, average demand or sales.

The decisions, which control the rate of change in the levels, are referred to as rates. The rate of change of the levels take place as the flows between levels in a given time interval, DT.

Rates are calculated by using the information about the current state of the levels according to the rules defined by the decision functions. Decision functions are the equations that define how the system behaves. In return, rates determine the preceding state of the levels.

Amplifications, which occur in most systems, are the actions that affect themselves more forcefully than they seem to have at first glance in return. The reason of amplification is generally the policies, which define the flow rates.

Time delays are the periods of time during which the flow from one level to another is delayed. They may occur due to external factors (transportation delays, mailing delays, etc..) and during decision-making processes. In fact, a delay is a special kind of level within which incoming flows are stored.

2.2 *Model Construction in System Dynamics*

System dynamics models must reflect cause-effect relationships, be simple in mathematical nature, be able to handle large number of variables and the continuous interactions of these variables. There are six steps of model building in system dynamics. (Forrester, 1994)

2.2./ *Define the problem and identify the structure of the system:*

This first step of model construction involves identifying and defining the problem, setting the purpose of the model and specifying the borders. Next, relationships between the parameters of the model is built, which is achieved in two ways (Wolstcnholme, 1990):

If the behaviour of the system is known to the modeller, a causal relationship is constructed first and then the levels and rates within the system are identified.

If the behaviour of the system is not known to the modeller, resources within the system are identified first, then the levels contained in the resources will be determined followed by the rates, which relate levels to one another.

2.2.2 Construct the Model Using Equations

Once the structure of the system is identified, the equation construction process starts. In system dynamics, there are mainly three types of equations:

Level Equations
Rate Equations (Decision functions)
Auxiliary Equations.

Equation construction is an iterative process, which changes over time.

Level Equations

Let J, K, L be respective points in time, separated by an time interval DT. Then, value of the level at time K becomes the resulting difference of inflow and outflow rates during the time interval JK, plus the value of the level at time J.

LEV. K = LEV. J+ DT (Ratejn JK - Rate_out JK) (Forrester, 1961)

Rate Equations

Rates are calculated by using the information about the current state of the levels according to the rules defined by the decision functions. Decision functions are the equations that define how the system behaves. In return, rates determine the preceding state of the levels.

Auxiliary Equations

Auxiliary equations are equations, which convert flows from one type to another, and provide information to change or control rates. These equations are used for breaking down the rate equations into manageable parts so that ease in computation of other equations is achieved.

While evaluating these equations, delays become important too, since a delay is a special class of level where the outflow is determined only by the internal level stored in the delay. Time delays are represented by packages, consisting of combinations of level and rate equations that are inserted in a flow channel.

2.2.3 Simulation and Testing of the Model

In order to perform simulation, all terms of the model must be expressed in quantitative form. After constructing the model in such a manner, simulation is performed by various system dynamics softwares, such as DYNAMO, POWERSIM, VENSIM AND STELLA.

After building the model, its validity is tested. Here, the most important criteria is whether the model serves for the purpose/objectives or not. Besides that, the validity of the model is based on two foundations;

- The acceptability of the model as a representation of separate organisational and decision making details of the actual system.
- Correspondence of the total model behaviour to the system behaviour. There are two aspects in

model validation, firstly a philosophical aspect that concerns with the internal structure of the model, but it can not be judged in an objective and formal way for it is an qualitative approach, and secondly there are structural and behaviour tests.

Here, the former set of tests check whether the model is adequate to represent real world by comparing model equations with the relationships within the system and available theory, while the latter set of tests compare the model's behaviour with real world behaviour system under concern to check if a major structural error exists.

2.2.4 Construct Alternative Policies And Structures

Policy is defined as the relationship between the information inputs and resulting decision flows. (Forrester, 1992) Once the model is constructed, alternative policies are simulated on the model to determine the policy with greatest benefit. The policies are generally generated by insights, from experience of the analysts and from proposals of the people involved in the real world system. In fact the major aim in constructing a dynamic model is studying the effect of alternative policies on system behaviour.

2.2.5 Educate and debate

After constructing a policy and performing the simulation, it is necessary to get people involved with the new policy so that they make contributions, reflect their ideas and experiences via education and debate sessions. In most organisations it is harder to gain people's confidence in policies than constructing the policy itself, so this step is of crucial importance.

2.2.6 *Implementation*

Once the education and debate is completed, the phase of implementing the results begins. The constructed and revised policy is implemented on the system. The current state jof the system is redefined after policy implementation.

3. SYSTEM DYNAMICS APPLICATIONS IN MINING INDUSTRY

Despite the wide application areas of system dynamics, it is not a commonly used methodology in the mining industry. Although any mine is a complex system, existence of uncontrollable factors like geology, climate., etc make it difficult to implement system dynamics in mining industry, therefore, the attempts for applications of the methodology in mining engineering context is limited.

3.1 Use of System Dynamics in Mine Planning

One of the initial works considering the system dynamics applications in mining engineering covers optimization of an underground colliery, in the paper 'The Design of Colliery Information and Control Systems' (Wolstenholme & Holmes, 1985)

The model developed in the study, identifies the colliery as a feedback system, in which the coalfaces and their associated development works are operated to reach a target output, under geological and manpower availability fluctuations.

In the colliery under concern, coal is extracted using retreat longwall mining technique, and the colliery is described at as a system for converting coal reserves buried underground to mined coal on the surface. (Wolstenholme & Holmes, 1985) The description of the system in this manner helps identifiying the boundaries of the system and the states in which coal exists. Such a description is given in Figure 1.

It is obvious from Figure 1 that, the developed capacity which is generated by the development rate, can be converted into production capacity after whole face is developed. Therefore, both developed capacity and production capacities are defined as levels. The production capacity, is then consumed by the production rate. The two controlling rates in this system are, the development and the production rates, and both of these rates are controlled by manpower, and external factors such as changing geology-

For controlling the development of coal face and hence, coal production, the desired state of the face and its divergence from this desired state in actual life , is needed to be known. Once this information is achieved, necessary corrective control actions can be implemented. Control is applied by defining the target states of cumulative development and production, and according to the information coming from the colliery, various control policies can be implemented, if necessary.

The control policies used within the colliery are constructed under two assumptions: Semi-Integrated policies, which assume that, only a subset of total information is available, while the Fully-Integrated policies suggest that, all the information about ongoing operations in the mine are available. Under these two assumptions, two policies are constructed: Manpower allocation policies and machine shift allocation policies.

When there are insufficient number of men to carry out the work, manpower allocation policies, under the assumption of fully integrated policies, suggest that, the information on the discrepancy between the actual and desired state of each coalface, is chosen as the basis for manpower allocation. The coalfaces, which most lags behind the schedule should receive the most men.

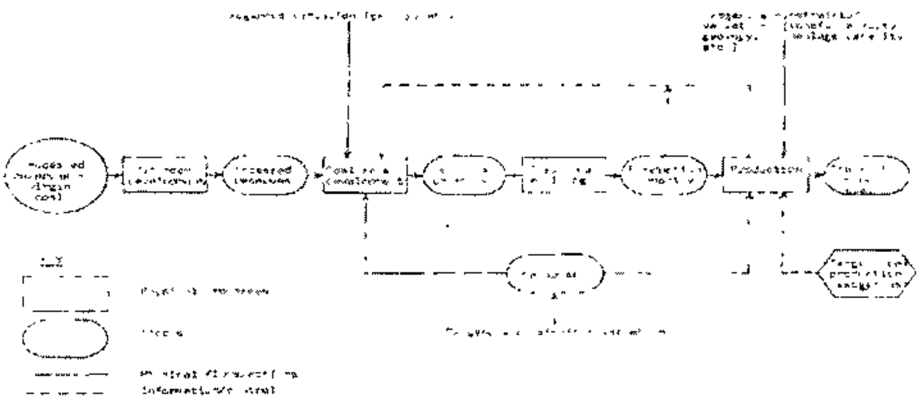


Figure I Description of the System (Wolstenhulme and Holmes 1985)

Machine shift allocation policies, are too defined on the basis of discrepancies. When the production is lagged behind the target to an extend which is considered to be critical, machine shift allocations is increased. This is achieved either by a the usage of spare man or by canceling a development shift for each extra production shift allocated.

The policies are tested tor two exogenous shocks: A changing geological situation, which slows down the work and causing a reduction in face production and a change in manpower availability. The results indicate that, for the latter shock, continuous allocation of manpower while achieving fully integrated information is the best mechanism, while machine shift allocation policies give better results under geological shocks.

3.2 Use of System Dynamics in Equipment Selection

In another system dynamics application to mining systems " Control of a Coal Transportation System', Wolstenholme (1990) tries to choose the optimum blinker- conveyor belt system for coal haulage in a three laced, longwall mine. Main levels contained within the system are. the level of bunkers, cumulative coal production rates and cumulative coal haulage rates. The bunkers discharge coal over the conveyor belt whenever there is available room on it. There are three policy alternatives for the system: The first policy charges coal at the bunker at zero or its maximum discharge rate, and the latter is used as long as there is coal available in the bunker and room available on the conveyor belt. The second policy sets discharge rate at any point between zero and maximum discharge rate in the same proportion as the bunker level to the bunker capacity. Finally, the third policy guarantees that there is no shortfall from the conveyor belt capacity and that the bunker levels are not exceeded (i.e. fallen into negative terms) when they discharge at the maximum rates.

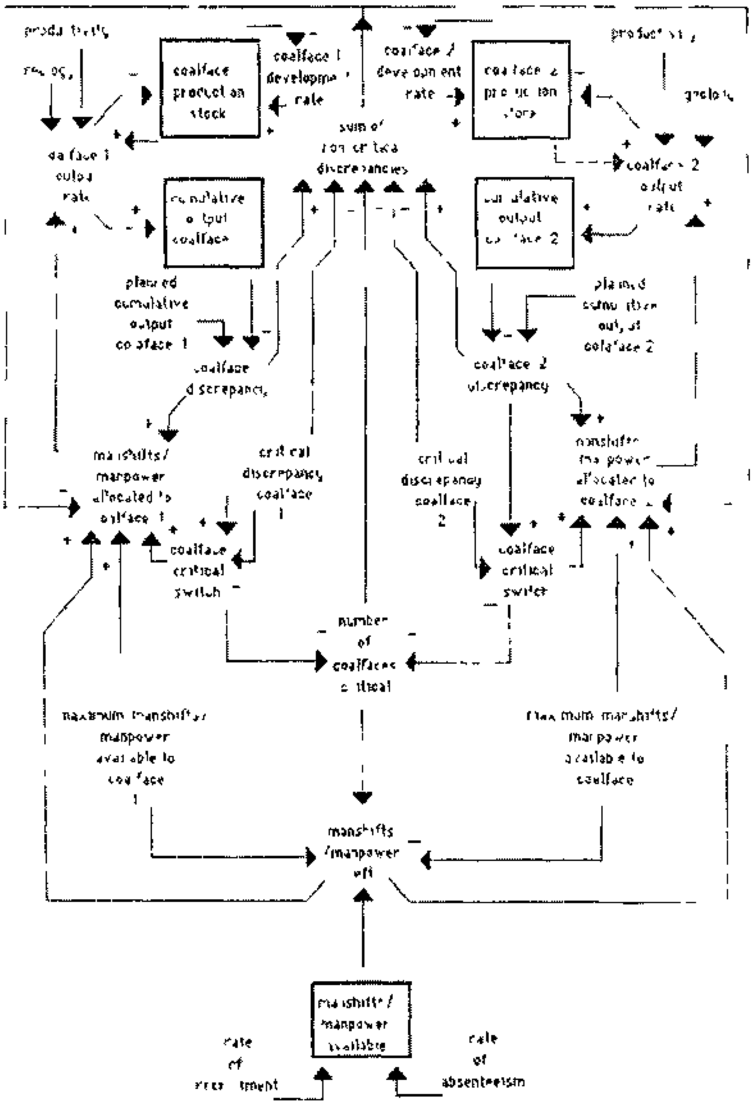
The model experiments, simulated with STELLA software tor these three different policies, determines the efficiency of the system when all determinants of the system, namely the coal production rate, bunker capacity and conveyor belt capacity are changed, and among the three policies, third is observed to be the most efficient.

The influence diagram for the underground mine of concern is shown in Ficure 2.

4 CONCLUSION

System dynamics is not a widely used technique in mining industry. Despite this fact, the relationships between the variables of a mine is mostly nonlinear and dynamic, and such a description of the system not only allows better understanding of the shortfalls of the system but also facilities the simulation of operating policies.

The two research work described in this paper, suggest that, a mine can be described as a dynamic feedback system. The description of the mine in such a manner helps identifying the relationships and interactions between the variables of the mine, and therefore such a representation allows a better understanding of the system behavior than conventional techniques.



Figuie 2 Influence diagram of the ııdeıgıound coal mine (WoKtenholme 1990)

Anotheı advantage of the methodology ıs that, it allows simulation ot vaııous policies on the model, and the lesults of different policies under different conditions can be observed easily In this sense, the constructed models act as manaaeual decision tools

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