SIMULATING DEVELOPMENT IN AN UNDERGROUND HARDROCK MINE

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ABSTRACT

System simulation is an increasingly popular technique for analyzing and improving existing as well as newly designed underground mining operations.

An engineering firm that specializes in simulation helped a major metals producer build a long-range planning model of an existing underground mine. Subsequently the team adapted this model to assess technology alternatives in the design of a new mine. The two models differ in the level of detail used for modeling the development process.

This paper discusses the differences in approach between the models along with the experiences gained and challenges faced during the construction and use of the models.

INTRODUCTION

In 1995 Inco Ltd. (Ontario Division), Mines Research formed a project team to study the production capacity and mine life for one of its existing mine sites located in Sudbury Basin (this mine is referred to in this paper as "CCSM"). The members of the team were mine engineers from Inco Ltd. and simulation consultants from Systemflow Simulations, Inc.

Simulation was chosen by the Company to help evaluate mine capacity planning decisions. The AutoMod simulation software was chosen for its programming language and three-dimensional dynamic output capabilities.

This was the first experience in modeling an underground mine for any members of the 1995 team. However, with the mining expertise of Inco personnel and the simulation and programming expertise of Systemflow Simulations, a successful model was developed.

Two models were built of CCSM. One model was a detailed model of the material handling of rock and ore from dump points to the surface. Individual vehicles and the skips were modeled and animated. This model was "a man-in-the-loop" model that required a model user to make various decisions. The human decision logic (for example, when to break balance) was not hard coded into the model, but left to user input during model execution. The useful modeling time frame of this model was limited to weeks or maybe months due to its interactive nature.

The 1995 team also built a less detailed, longer term model of CCSM. It had no material handling features or moving elements. This model, which became known as the "DP" model, contains logic for the development and production of an orebody upstream of the dump points. The DP model includes a three-dimensional representation of individual "material blocks" (whole stopes and drift segments). This representation is shown in Figure 1 (the picture is of a newer version, but the geometry animation is the same as in the original DP model). The model animates the mine's progress over simulated time using color changes to depict the current state of each material block.

In 1997 and 1998, the simulation project team of Inco Mines Research focused on improving the DP modeling and programming by breaking down the development and production processes to subprocess cycles and incorporating explicit long-term deployment and short-term assignment of equipment and crew resources into the process model. The mine site selected for the revised model was a test mine in the Sudbury basin. The purpose of the revised DP model was to support planning decisions made for design and technology changes.

The approach of the original and revised DP models to the representation of the development process is the subject of this paper.

MODEL LOGIC – ORIGINAL

The DP model logic has two components: development and production. Most of this discussion will focus on the development logic.

Development Logic in the Original DP Model

In the original model, development is modeled in a very simple way. A fixed number of "development resources" is deployed throughout the model. (For a definition of a simulation "resource" see Schriber 1998.) A development resource in this version is treated as a unit containing all crew and equipment needed to advance a single face.

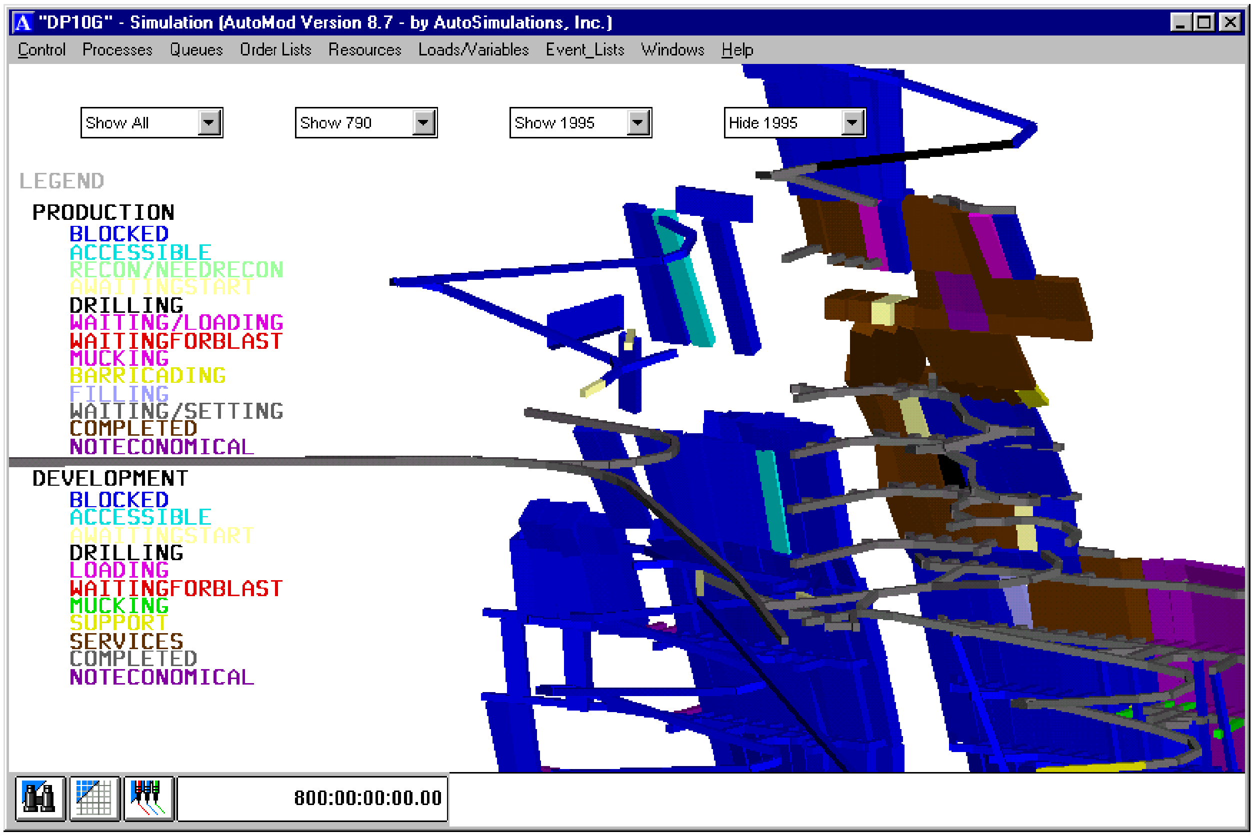

Figure 1. Mine geometry in the DP model.

Any face determined to be physically and logically accessible claims one of these resources or, if none is available, is added to a waiting list. Whenever a crew resource becomes available it scans the list for the highest ranking drift (see below for an explanation of drift ranking) to start next.

Once a drift segment has a development resource, development proceeds at a defined rate in feet per day. The rate can be adjusted to take into account shift scheduling inefficiencies and the long-term effect of short-duration scheduled and unscheduled downtimes, but are were no explicit random failures in the 1995 model.

In the original DP model there is a provision for each crew to have a different rate but there is no way to assign the crews to geographic regions or otherwise to influence which crew will work on which drift. Crew-specific region restrictions were added in an intermediate version of DP.

Also in the original DP model there is no provision for the increased efficiency that results from having a development resource simultaneously work on two or more faces that are close to one another in the mine instead of working on just one face. In an intermediate (1996) version of DP, once regions are defined, development resources are allowed to have up to three faces to work on and the rate depends on the number of faces in a nonlinear (user-specified) way.

Production Logic in the Original DP Model

In the original model, production is modeled using "crews" for each process that also represented the equipment, i.e., there was no separate modeling of equipment. Unlike development, for production each major equipment-using part of the process – drilling, loading, mucking, barricading, and sandfill, in the original DP model – has to claim a separate type of equipment. However, the type of equipment does not exactly correspond to the real equipment. Also production crew members are not modeled separately – they are assumed to be attached to the equipment.

There are some other interesting wrinkles in the production logic in the original DP model, such as adjacency restrictions (two nearby stopes can't simultaneously be active, where "nearby" is based on a user-specifiable distance threshold).

About Drift Ranking

Drift ranking is generally based on assigned stope sequence values. (Different strategies can be used in the original DP model to control the sequence in which stopes will be mined, but that is not the subject of this paper.) At the beginning of the model run every stope and possibly some drifts are initially assigned a ranking number (not necessarily unique) that is specified in the input data set as a sequence number. Rankings are propagated from stopes to drifts using predecessor relationships as described below.

Also at the beginning of the model run, predecessor relationships are defined throughout the model. This happens in three ways. First, a physical "tree structure" is established based on the physical geometry. In this tree structure every drift segment and stope has one or more physical predecessors unless it is tagged as "complete" or "already accessible" in the input data set. Second, all drift segments on a given level that are tagged as "infrastructure drifts" in the input data set are collected and made logical predecessors to every stope on the level. Third, additional logical predecessor relationships defined by the model user, if any, are read in from a data file. All of these relationships together form a single logical predecessor tree.

Before the mining starts in the model, the ranking values are copied from branch-to-root throughout the logical predecessor tree, as follows. Each material block calls a function that looks at its immediate predecessors one by one. If it has a higher (more urgent) ranking than the predecessor being examined, it copies its ranking value to the predecessor and calls the function recursively for that predecessor. (Actually in the model a lower-valued sequence or ranking number means more urgent, but we use the term "higher ranking" here to avoid confusion.) Because of the recursion this function is written in the C language in the model.

The result of this ranking scheme is that the development resource assignment rule will always choose faces that allow development to progress toward the highest ranking remaining stopes (or along or toward the highest ranking drifts, if rankings have been attached to drifts in the input data set).

For the purpose of this discussion of predecessors and ranking, a raise behaves like a drift segment. Raises were not in the original DP model but were added with limited detail in the intermediate and subsequent versions.

CAPTURING THE GEOMETRY

For proper operation of the original DP model, each material block (MB) must be identified and characterized by a number of properties. Among these properties are:

- Geometry
- Location and orientation
- Connectivity (which MB must be removed to access this MB – both physical and logical)
- Adjacency (which MBs must have no activity in order for work to begin on this MB)
- Grade vector (for ore)
- Orebody ID
- Level ID
  Workplace ID
- Type (for drifts) e.g. ramp, main, infrastructure access, ore access, etc.
- Rank and Sequence

The transition from mine plan geometry to model geometry is initially a time consuming one involving these steps for drifts:

- Develop a three-dimensional representation in AutoCAD for the drifts on each level
- Import the level geometry into AutoMod as a vehicle guidepath system (at this point we are using AutoMod only as a geometry data manager)
- Name each segment in AutoMod using a naming convention to incorporate certain drift properties (direction, orebody, level, workplace, and type)
- Repeat for each level
- Combine the geometry data into one file

A separate pre-processor program was developed to read the tagged geometry data for drifts and also a separately maintained spreadsheet containing a list of all stopes plus their geometries and other properties. The pre-processor generates connectivity and adjacency data and writes this information to textual data files used to run the model. The pre-processor also generates geometric descriptions that are grafted into the actual AutoMod simulation model to allow the mine operation to be animated.

As long as the underlying geometry does not change, the complete sequence of steps described above is required only once.

Some of the discussion of geometry capture applies equally to the revised DP model. The pre-processor code was recently redeveloped in support of the team's ongoing investigation of other more automated ways to get tagged drift and stope data into the DP model (based on AutoCAD, mine planning software such as DataMine, and/or other tools).

USEFULNESS OF THE ORIGINAL DP MODEL

With the major simplifications described above – for example, no separate concept of human resources and no accounting for the internal workings of a development crew – was the original DP model useful? The answer is yes.

We have to keep in mind the original goal of the DP model which was to assess the remaining mine life. In essence the original DP is a long-term planning model.

General Comments about Long Term Planning Models for Underground Mines

One of the fascinating things about modeling underground mines, from a simulation practitioner's perspective, is the multiple constraints on resource allocation and usage. For a given material block to make progress toward being removed, five absolute constraints must be met:

- Equipment must be available (for the next process step)
- Manpower must be available (for the next process step)
- The block must be accessible both physically (no material in the way) and logically (e.g. for a stope, any required level infrastructure must be complete)
- Restrictions on nearby simultaneous activity must be satisfied
- There must not be higher-priority blocks that meet the other constraints and are competing for the same resources

In a typical underground mine geometry, physical availability of faces drives the long-term development process up to a certain point. For a given mine plan there can be periods of time when there is a boundary on how fast development can proceed because only one crew at a time can work on each of the most critical faces. In the extreme case, if we consider a plan consisting only of one very long access drift leading to an orebody some distance away, deploying a second development crew in the early going will have zero effect.

The complex interactions among these factors make simulation an attractive choice for studying long term planning alternatives.

Conclusions from the Original DP Model

This paper is about development modeling in general, not about the CCSM models, so we will be brief in this section.

The team members believed that CCSM would suffer a shortage of accessible stopes within one to two years – in other words, the mine might be considered to be somewhat underdeveloped as of the time of the study (1995). The first runs of the original DP model were used to confirm this.

One of the interesting outputs from the DP model is a record of the number of accessible faces and the number of accessible stopes, both for the whole mine and for each orebody. The modeling environment can display this information as a line graph (blocks accessible versus time). See Figure 2 for an example. The overall graph provided quick visual confirmation: the number of accessible drifts was low for the first few years, leading to a drop in the number of accessible stopes two to three years out and corresponding reduced production. After this initial dip, things recovered for the remaining 7 to 10 years of mine life.

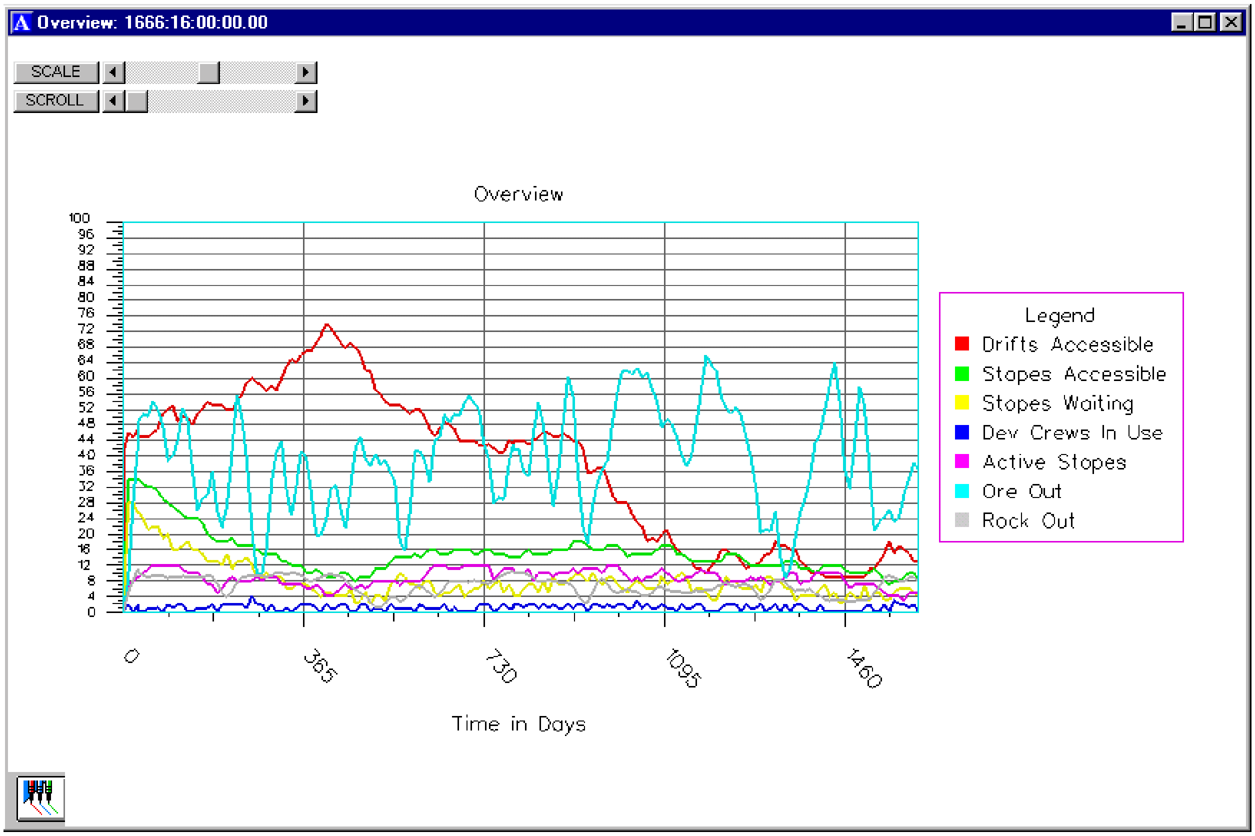

Figure 2. Sample time plot from the DP model.

The DP model allowed the team to run quick experiments with increasing the number of development resources deployed. It is possible to ask "what are the boundaries on production given unlimited development resources" or to deploy any number of development resources and compare the results. Later refinements allowed the resources to be deployed only in certain regions of the mine.

Could the predicted dip in production be reduced or eliminated by adding more development resources now, or is it too late? What would be the impact on the remaining mine life of changing the number or efficiency of development crews? The original DP model, while of limited absolute precision due to the many modeling assumptions made, could answer these questions in a relative way.

MODEL LOGIC – REVISED

Over time the DP model has been adapted for more detailed planning decision making. The general trend has been to add more detail to the existing framework and to increase the capability of the model to address more in-depth mine design and technology decisions.

There have been three major revisions. In the first (1996), detail was added to the original process flow. Geographic restrictions on equipment were implemented and multi-face development was added in an approximate way. In the second revision (1997), the development logic was totally rewritten to the point where it was more detailed than the production logic. In the third revision (1998), production logic was rewritten to match the development detail, and resource sharing (particularly of mucking resources) between development and production was added. Future planned revisions include incorporation of material handling constraints for outbound rock and ore and incorporation of additional mining methods.

With respect to development logic the model changes were significant. The development process was broken into the individual tasks of drilling, loading, mucking, support, and services installation. Individual crew members were separated out as resources that must be jointly allocated with appropriate specific equipment in order to perform a task. Input data sets were adjusted so that equipment could be defined and declared by type with possibly more than one type for a given task. Downtime detail was added so that failed equipment could be either repaired at the face or returned to the shop for repair or service depending on user-defined thresholds. Stochastic downtime of equipment is represented by Time Between Failures , Time to Repair, and Waiting for Repair probability distributions. (The Waiting for Repair distribution was used because repair resources and queuing rules for repair – potentially a major modeling effort in and of itself – are not implemented in DP as of this writing.)

A "foreman controller" was implemented to make crew and equipment allocation decisions both at the beginning of each shift and also when other state changes occur such as the freeing of a resource. Each development complex (region) has its own foreman controller. A "management controller" was implemented to direct the initial allocation and long-term movement of equipment among development complexes.

The revised model is being used to compare overall productivity and cost when different equipment data sets are provided and/or different mine plans (or mining methods) are proposed. Implementing the mine geometry for an alternative plan is still a thorny issue but progress is being made on generating the plans and the associated data using mine planning software and automating or semi-automating the conversion of this data into a format the model can use (a process which includes making adjustments to the model itself).

Conclusions from the Revised DP Model

The revised DP model has proven useful as a comparative tool. The Inco team has used the model to compare conventional and futuristic mine design and technology alternatives, various combinations of scenarios (plans, methods, equipment types, and staffing strategies). The outputs of the simulation are incorporated into separate economic evaluation models that aids the mine engineer in making the right method, technology and resource plan decisions. Due to crisis in the value of the metal produced, mining companies are pressed to look for more efficient ways of mining. These new ways, whether method, technology or both, need to be fully evaluated before any action is taken. Simulation, a powerful analytical tool, aids the miner to make the effective predictions. Inco is a good example for companies understanding this need. Simulation modeling has become extremely crucial and widely accepted throughout the Company.

The Team plans more model improvement in importing the design and geometry concepts as well as operational and tactical planning details. Despite the previously added process detail there are still many assumptions underlying the model results, so absolute answers are not always attainable. The models also demonstrate the lengthy modeling and coding involved with any mine simulation application resulting from the fact that no customized mine simulation package exists for immediate use in Underground Mining.

SUMMARY

From a simulation practitioner's standpoint the two different ways of modeling development are completely at odds. In the original model, the feet driven per day was known from historical data and plugged directly in as an input, so the overall progress of development was known to be reasonably close in the model to the actual pace of advancement in the field.

In the revised DP model, the feet driven per day input is replaced with the process cycle time input and became an output. This presents validation issues because it probably is not possible for this output to match the field-observed feet per day in a consistent way given the current level of geometry and drift/stope ranking detail (there are still many assumptions in the model). Overall times for drifting and stoping are used in the validation instead.

Does this potential discrepancy detract from the usefulness of the experiments run with the revised model? The authors think not. The model results should still be reasonably close and are being refined continuously at this writing. More importantly, in comparing two scenarios to determine which is best, it is not necessary for the output of such a conceptually complex model that still has important assumptions to be absolutely correct. What is important is for the relative strength or weakness of the scenarios being compared to be correctly assessed, and the latest version of the DP model does that well.

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