Application of System Dynamics Principles to Surface Mining Problems

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This paper explores how to apply system dynamics principles to surface mining problems towards understanding the consequences of mining efficiencies. Some simulation examples related to machine and people performance have been used to demonstrate systems engineering concepts to mining engineers. The simulation tool used is Vensim, which is widely used in industrial engineering applicable to systems thinking, and systems dynamics. The science and mathematics behind the system dynamics as well as benefits and typical challenges are discussed to explore the applicability to mining problems. The benefit of having one less drill is easily quantifiable with the developed model which is one of many other measurable benefits, using the developed model. Some of the benefits of the improved quality of drill holes are not fully quantified as this depends on the mine specific inputs. There are examples of quantifying this in the other industries using system dynamics tools.

Keywords: Systems thinking, systems dynamics, automation, drilling, modelling, quantification, simulation.

INTRODUCTION

A mine can be described as a multitude of systems that need to work in tandem to achieve a certain production rate. This production rate normally is planned way ahead of actual mining operation, based on many assumptions. This includes factors such as market demand, costs, and exchange rates. One of the drawbacks in a mining project to achieving the set targets is the variability. One can imagine that a manufacturing factory's variables are measurable, and predictable due to the known nature of the machines in the given production environment. In mining, variability exists at many levels due to natural variability of the rock itself in the first place, i.e., ore body definition and qualities. Mining processes are prone to human error, system errors and performance of sub-processes such as drilling and blasting, performance of loading and hauling, and performance of recoveries at the plant, based on the earlier planned production and grades. In all this complexity the mines need to measure and manage when a new process is injected into an existing system.

Since mining is very dynamic in nature, how to measure the impact of any change in the system that is very complex and interactive? This question then leads to the objective of building a model of a mine, using system dynamic tools towards the justification of an initial objective for measuring the change.

The dynamic nature of mining can be expressed in mathematical expressions and statistical behaviours. The complex mathematics of causality relationships built in Excel based models are difficult to follow and comprehend. System dynamics are seen as a possible tool to model mining processes to see the changes introduced into the dynamic mining environment, irrespective of the magnitude. Sometimes change in diameter of a drill hole may have a major impact in the final profile of the mining process. This paper will demonstrate how to apply principles of system dynamics to observe consequences of these actions.

WHAT IS SYSTEM DYNAMICS

System dynamics stems from control theory, and the modern theory of nonlinear dynamics. Mathematics behind system dynamics is elegant, and is based on industrial engineering concepts such as strategic thinking, operations management, etc. Most managers do not think in mathematical terms such as nonlinear differential equations or even calculus or have forgotten about it. Furthermore, there is high diversity of technical managers and their approach to problem solving. Sterman (2000) states that we should not fear such mathematics since system dynamics have tools developed that use high mathematics in the background, but in the foreground, all seems logical and causality is traceable with visual tools used to define the environment being modelled to seek various solutions for industrial problems. There are three modelling methodologies used to solve problems, which are System Dynamics Modelling, (SD), Discrete Event Modelling (DE) and Agent Based Modelling. SD and DE were developed by Jay Forester. They are methods that take a top-down approach. Agent-based modelling focuses on individual behaviour and is therefore considered a bottom-up approach (Sontamino, 2014). A comparison of these three methods is found in a simulation software manual by Any Logic (Borshchev, 2013, pg 37.) as can be seen in *Figure 1* .

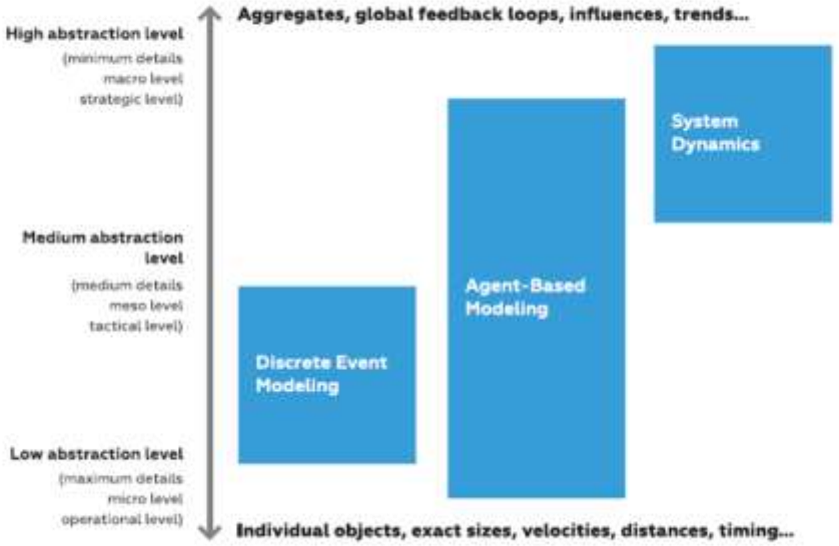
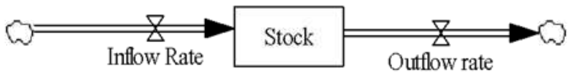


Figure 1. Comparison of discrete event modelling, agent-based modelling and system dynamics modelling (Borshchev, 2013).

A simplified diagram as shown in *Figure 2* is a typical example of how system dynamics is modelled, and the type of mathematics that is seen behind the simulation environment - called a stock flow diagram.



$$\frac{d(Stock)}{dt} = Inflow\ (t) - Outflow\ (t)$$

$$d(Stock) = \int_{t_0}^{t} (Inflow(t) - Outflow(t)dt + Stock(t_0)$$

Figure 2. Stock-flow diagram of a system dynamics modelling with the formulae.

Any dynamic movement can be expressed in rates and stocks according to systems theory. In mining for example, reserves are a stock, and the reserves are depleted at a certain rate - what we call mining rate. The mined-out ore is then collected in a stockpile which then flows out in the form of sales. The rate at which the product is shipped defines the outflow rate. A system dynamics model can be modelled at a simple to remarkably detailed level of sub-processes. The unit processes in mining are cyclic and the time it takes to drill and blast a block of ground should in principle be equal in time for loading, hauling, crushing, etc.

MINE VALUE CHAIN

A quotation from two renowned researchers is mentioned in terms of the importance of this research:

- "Total quality management and business process re-engineering are initiatives that were often not measured in terms of balanced financial and other economic and operational indicators, nor linked directly to the resource strategies of organisations." (Stevenson & Wolstenholme, 1999, pg. 4).

In summary, value thinking means developing a broad understanding of how future cash flow is impacted by operational and management strategies. Therefore, value thinking means thinking systemically and dynamically. (Stevenson & Wolstenholme, 1999). This statement stresses further on the importance of the term "value chain" in a mining environment. Although the bottom line is about cost per ton, but there are other gains that are not so easily quantified.

A typical mine has long- medium- or short-term goals based on the mine's resources. The mine stock is divided into equal parts to be mined per unit time. And each chunk of mine stock goes through a few processes, for example surveying of the block, drilling, blasting, loading, hauling, crushing/processing as individual processes. A block of ground will end up at the stockpile after the journey from in-situ or block to the level of crushed pile at the processing plant as a final product. This whole train of processes are treated as six stages of delays. Let us call it the sixth order delay, as it would be called in the system dynamics terminology. Initially during the first stage of the mine, mining blocks will be ramping up to a steady state of production levels later in the life of the mine. Then the inflow and outflow will stabilise due to the continuous rate of mining. If this is a perfect system, then the graphics representing the process would look like the one seen in *Figure 3*.

The mining process looks simple in this diagram if all processes are treated at the same mean time for each block for the respective processes. Matters get complicated when there is a delay in one of the processes. This may then create variabilities and instabilities in the mining environment.

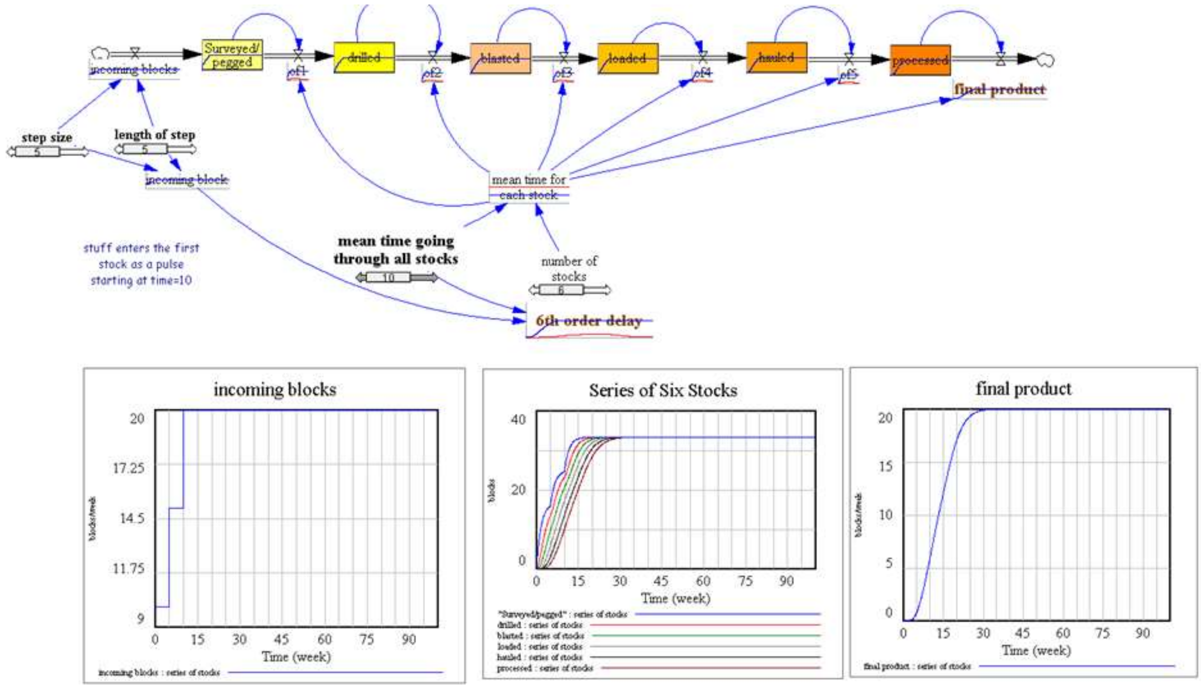


Figure 3. Ideal mining cycle with fixed delays between sub-processes.

In an ideal world, the delays will be only for the initial weeks, and thereafter due to continuous production it will not matter anymore as seen in the model. In this graph the delay between each process is exaggerated to make it visible in the graph for demonstration of the concept.

The next example will explain how instabilities are created in mining due to process times not matching because of either diminished capacity or delays, such as machine breakdowns etc.

The first complication in mining is that production is not continuous but discrete, due to the discrete number of blocks drilled-blasted-loaded-hauled. Each block once drilled needs to be handed over to the blasting personnel. In between there are various quality checks, and a handover process. If there were not enough number of blocks available for each unit, they would be waiting for the next one in line. If the blasting team does not approve the quality of drilled holes, they may request a re-drill of certain holes, etc. This causes delays in the handover process of the block to the loading crew. The quality of the blastholes is assessed, in case they are collapsed, drilled short or too long, or deviated from an X-Y location. The correct drilling of each block is therefore an essential process.

The quality of loading and hauling is similarly important, and the mining team needs to ensure that the handover of a quality blocks requires some form of quality checks. If not managed well it may delay the next round of drilling and blasting. The loading team takes over the blasting block to be loaded after some quality checks and site preparation is conducted. Tidying up the site with a dozer is a critical step in ensuring that loading and hauling is not affected by the loose rocks on the floor. The muckpile profile of the block after being blasted is another concern to the loader - such as too high, too low or scattered. The muckpile shape is shown to have a large impact on loaders, and the shape is very much dependent on the quality of blasting, and therefore quality of drilling. If there are toes, the excavator may not be able to handle those areas. Toes sometimes need to be blasted to make the loading process smoother. In addition, there may exist large boulders that need to be handled separately, i.e., put aside to be blasted later or a hydraulic pecker may be used to further fragment the boulders. These types of inefficiencies and delays impact on the cycle of unit processes that are dependent on each other, and cause variabilities and instabilities.

A simple model is built to demonstrate how variability is created in a mining environment using a system dynamics modelling tool called Vensim.

For example, we have one mining block that will be staked by a surveyor, then drilled, then blasted and loaded onto the trucks to be dumped either to a crusher or stockpiles, and waste dumped to waste dumps.

The first process in the mining cycle is staking of the blastholes, and modelling of this process will be demonstrated for only one blasting block. Resources and block processing time can be estimated. It is a simple process; it will be demonstrated that variability results in complexity. The block to be surveyed is queued in the system which is a ‘stock’ in Vensim modelling terms. The block arrival rate depends on production scheduling and planning of the blocks. The simple model as shown in Figure 4 assumes that every day one block will be released to be staked by a surveying team that can finish surveying the block in one day. Please note that these are not realistic numbers and are used for demonstration of how Vensim will be used to build a detailed model from simple steps towards complexity.

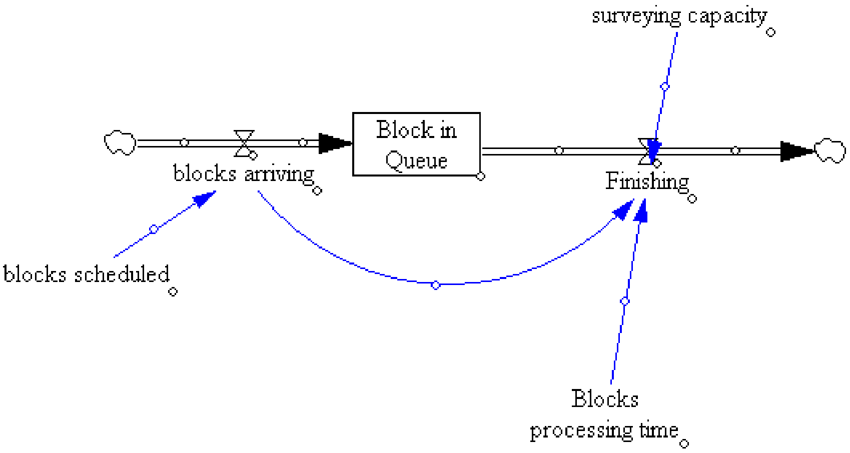


Figure 4. Simple capacity planning function for analysis of variability.

This model uses DELAY BATCH function and set as below for determination of finishing rate of the staking process. Similarly, all other unit processes are modelled with the same type of delay batch formula. For a stable cyclic mining, the delays introduced into block processing time for surveying will cause instabilities in the next process.

DELAY BATCH (blocks arriving, surveying capacity, blocks processing time, 0, 0, 0) [1]

A series of minute simulation model was generated with a combination of input variations for which the scenarios are listed in *Table 1* below to show the resultant variability graphs. Scenarios are run in very small numbers to demonstrate the pronounced effect of the relationship between inflow and outflow rates

The model is tested with various scenarios as listed in Table 1.

Table 1. Schedule-capacity-processing time scenarios for simulations from Figure 5 to Figure 9

Figure Reference	Blocks Arriving		Surveying Capacity	Block processing time
Figure 5	1 per day		1 per day	1 per day
Figure 6	2 per day		1 per day	1 per day
Figure 7	1 per day		2 per day	1 per day
Figure 8	1 per day		2 per day	2 per day
Figure 9	1 per day		1 per day	2 per day

The model is built to run for the duration of 14 days to be able to see the work queued in detail. The objective is not to have an accumulation of blocks in the queue. It is acceptable to have some variation in the stock but on average it should be horizontal. If stock keeps increasing this means there is a delay in the downstream processes, either due to capacity or processing time. The accumulation results in increased production stress on the crew and may lead to further errors due to fatigue. Each process needs to be as stable as possible due to demand from the downstream processes.

In Figure 5 the model is stable and shows a blanced steady state flow with capacity, and processing time matching the scheduled flow.

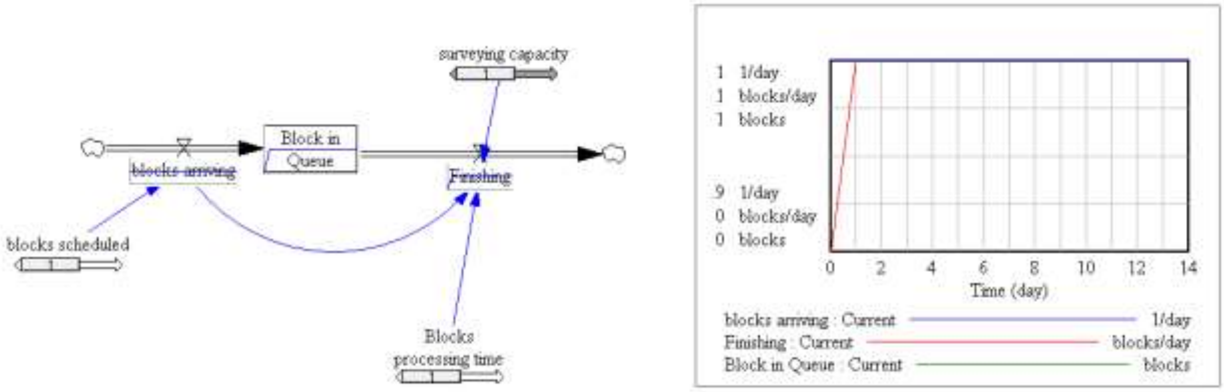


Figure 5. Schedule-capacity-processing time Scenario 1.

In *Figure 8*, the scenario now changes to less work assigned to the team but processing time doubles together with capacity. The two teams now finish work every second day. The input and output stay one block per day. The system is stable but there is variability in queued work flow; but on average the output is one block per day.

In Scenario 5, only block processing time is doubled (Figure 9). This again causes variability in the work finished and causes lists of 'work to do' increasing at a steady state. This setup is useful to analyse delays in production due to delays in processing time, such as cycle times.

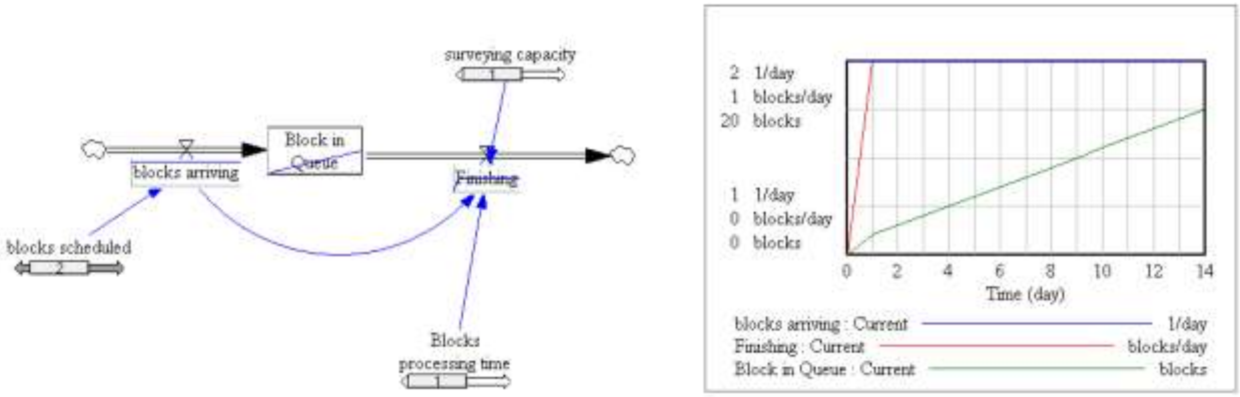


Figure 6. Schedule-capacity-processing time - scenario 2.

Figure 6 demonstrates the outcome when the work requirement is doubled, and capacity and processing time is kept fixed, this then causes a steady increase in the work lined up or queued.

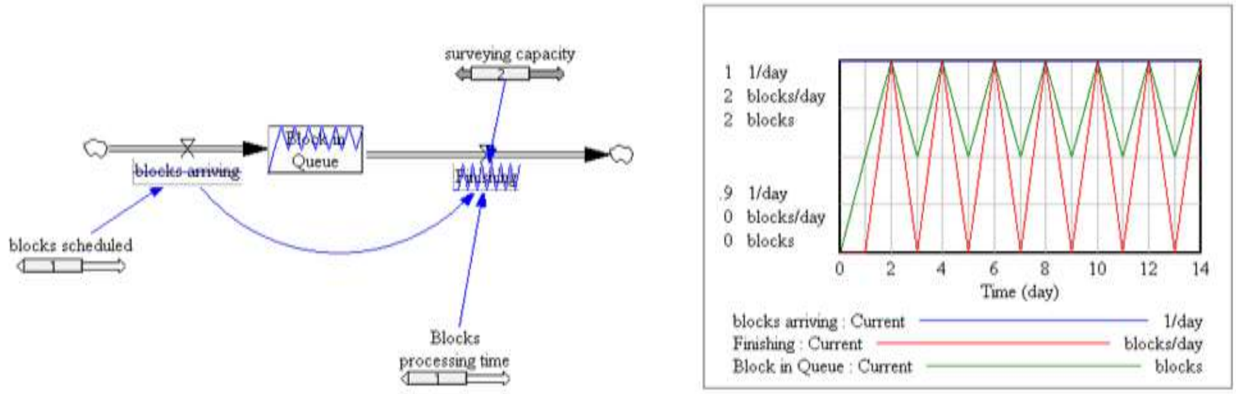


Figure 7. Schedule-capacity-processing time scenario 3.

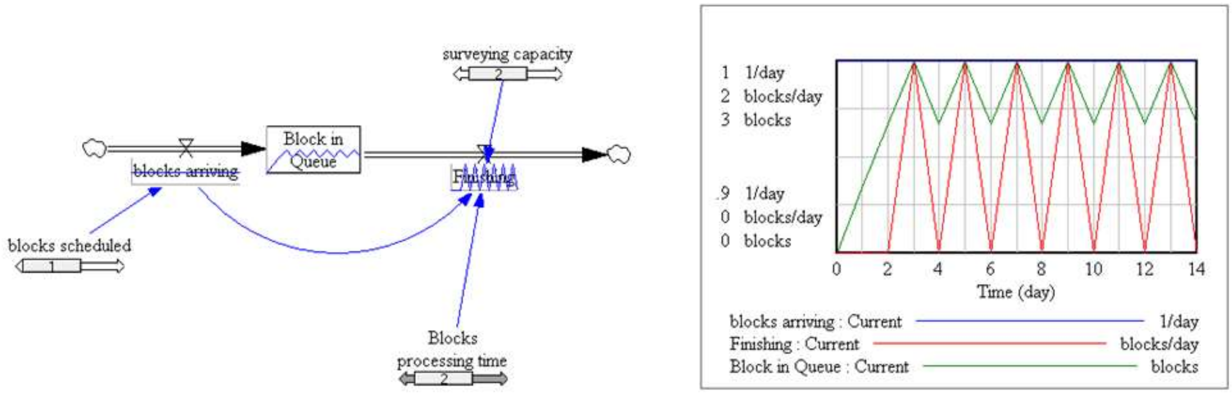


Figure 8. Schedule-capacity-processing time scenario 4.

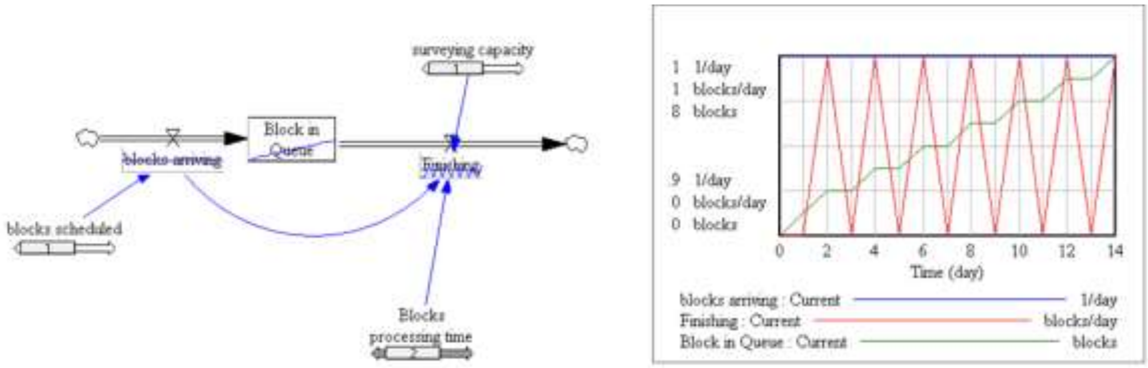


Figure 9 Schedule-capacity-processing time Scenario 5

Finally, the doubling of the block processing time results in work accumulating in the stock of scheduled blocks in Figure 9. The formula for this variable as used in Vensim application is:

DELAY BATCH (blocks arriving, surveying capacity, blocks processing time, 0,0,0) [2]

This exercise helps us to understand the significance of correct planning, scheduling, and resource planning for a balanced and stable process. If the tasks are allocated to the capability for which they are designed, then the system is mature and stable. If a process becomes erratic the rest of the processes will experience it in the form of pronounced variations or fluctuations.

Finally, all processes that precede each other are connected in a larger model as in *Figure 10*. In this small model the drilling blasting loading and hauling workloads within a 14-day period are sequenced, and the variability is evident from the minor changes. The purpose of this demonstration is to show that delay in the drilling process will create variability on the blasting, loading and hauling work schedule.

As can be seen in the simple simulation models, cyclical mining processes need to be as efficient as running a factory. Delays in any one of the processes will create stress in the working environment to keep up with the demand from the next process.

The next step in modelling is to establish the base model, based on expectations of an organisation, i.e., planned output and resource allocation for each cyclic mining unit process.

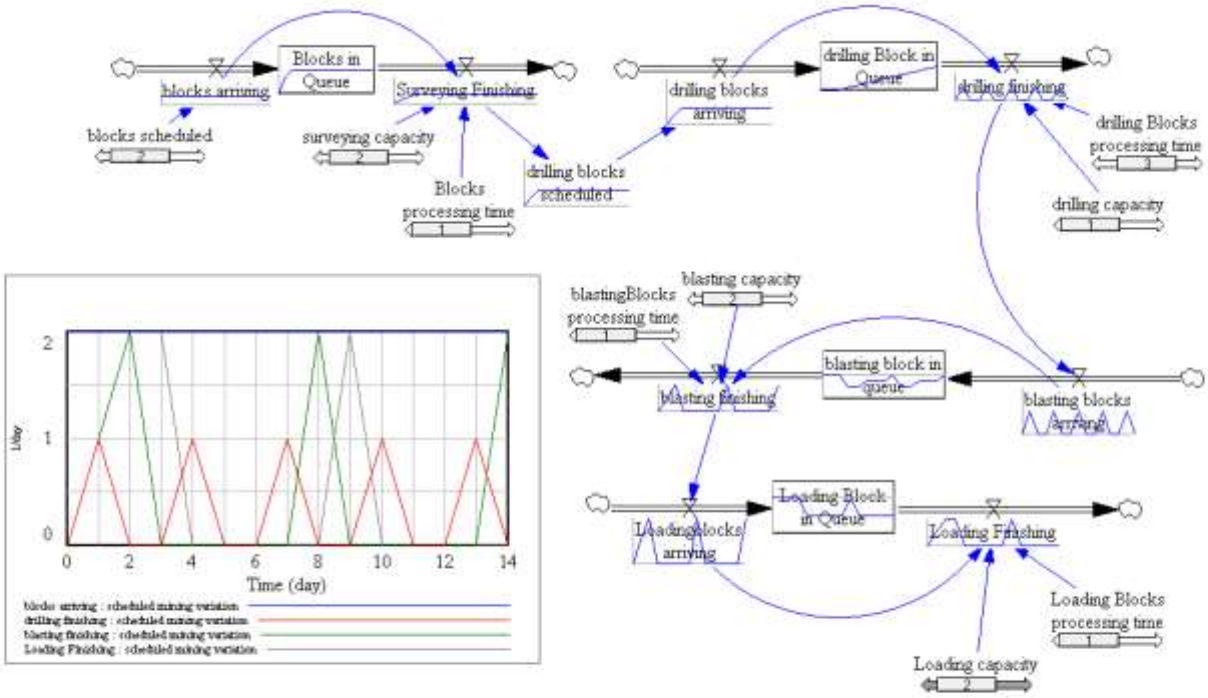


Figure 10. Cyclical mining unit processes and dependencies.

A VENSIM MODEL BUILT AROUND AN IRON ORE MINE

It is easier to perceive and grasp as well as visualise the concept discussed in the previous section in a real mining setup with real variables such as production demand, capacity, and matching blast design parameters. Screen captures of the step-by-step process of the model built will be presented in this section.

Production Environment Setup

The production environment for a predetermined mining rate was to be built first which also sets the economic parameters of mining.

The objective behind this model was to demonstrate the impact of cycle time efficiencies mainly due to automated drilling. The research aimed to demonstrate whether the claimed benefits associated with automated drilling are in fact true for a realistic mining environment setup. Some of the claims for the improved drill and blast can be seen in *Figure 11*. Not all these claims can be linked to automation. Some are easily quantifiable, and some need careful analysis; as the objective is to be able to measure the benefit in various what-if scenarios with the clutter of detail omitted, which clouds our understanding of causality.

It is not possible to isolate a section for repeated similar conditions experimentation in a mine, but it is in simulations. The impact of a process change in a similar condition, setting up a dynamic simulation is most likely the best option, instead of having endless scenarios tested.

Some of the anticipated causalities of improved drilling quality are shown in *Figure 11*.

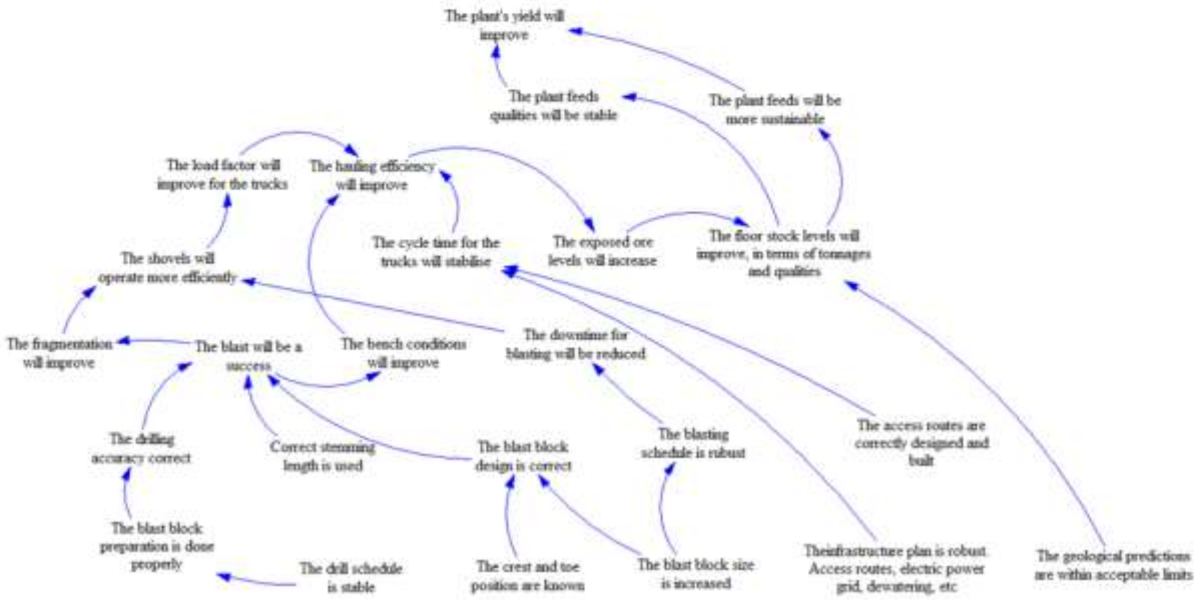


Figure 11. Cause and effect relationship of improved drilling and blasting.

The direct benefit of automation is envisioned as a reduced number of drill rigs required for production demand in the mining environment. The production demand for a specific mine is built into the model, based on the monthly production rates for both ore drilling and waste drilling.

Hauling is the highest cost component in the mining operation; therefore, it is necessary to breakdown each cost component, and relationship between these attributes. Since the biggest cost item is loading, the concept must also have a linked causality for savings that will be achieved due to reduced cycle times of the loading and hauling process.

Improved fragmentation is a direct result of better-quality drilling and blasting. This is partially built into the model based on the P80 size distribution, as per research which measured P80 based loading and hauling efficiencies. The Kuzram fragmentation model had to be incorporated into the larger mine model to be able to determine P80 value.

Blast fragmentation has two major effects on loading and hauling performance in mining operation due to the digging time, and bucket payload which is the ratio of void and fill factor. Improved fragmentation may cut down the time taken to haul by preventing unnecessary queues at the shovel. If the time losses at the shovel location can be prevented, loading equipment will not be idle at the production face. Energy losses while trucks are waiting is another loss that can be linked to bad fragmentation. The presence of boulders in the muck pile will cause further time delays. This may cause loaders as well as haulers to wait idle until the boulder is removed from the production face. There seems to be a direct relationship between smaller fragmentation and increased tonnage, and individual dipper and hauler cycle.

The digging time against mean fragment size relationship can vary from one operation to the other. A relationship obtained at a quarry where a digging time study was conducted by Jethro (2016) was used to link fragmentation size distribution to digging time. He mentions that decreasing mean fragment size by 10 cm means gaining two seconds of loading time at each pass of the excavator.

Excavator and truck matching is a critical factor to be incorporated into the larger simulation model. Therefore, Table 2 has been used to create an automatic loading parameter selection of a truck matched to the correct payload simulation. This relationship is necessary for determining loading cycle times.

Table 2. Analysis of effects of excavator/truck matching on load and haul costs (Gregory, 2003 cited in Hardy 2007)

Operating weight of loaders	**100**			**400**			**650**		
Bucket capacity (cubic meters)	6.5			20			34		
Truck payload (tons)	Number of passes	Load Time (mins	Cost Index (%)	Number of passes	Load Time (mins	Cost Index (%)	Number of passes	Load Time (mins	Cost Index (%)
49	4	2.13	200						
91	7	3.48	144	2	1.25	125	2	1.25	135
146	12	5.73	130	3	1.72	114	3	1.72	115
187	15	7.08	126	4	2.18	104	3	1.72	102
230	18	8.43	134	5	2.65	101	4	2.18	100
353				6	4.05	110	6	3.12	106

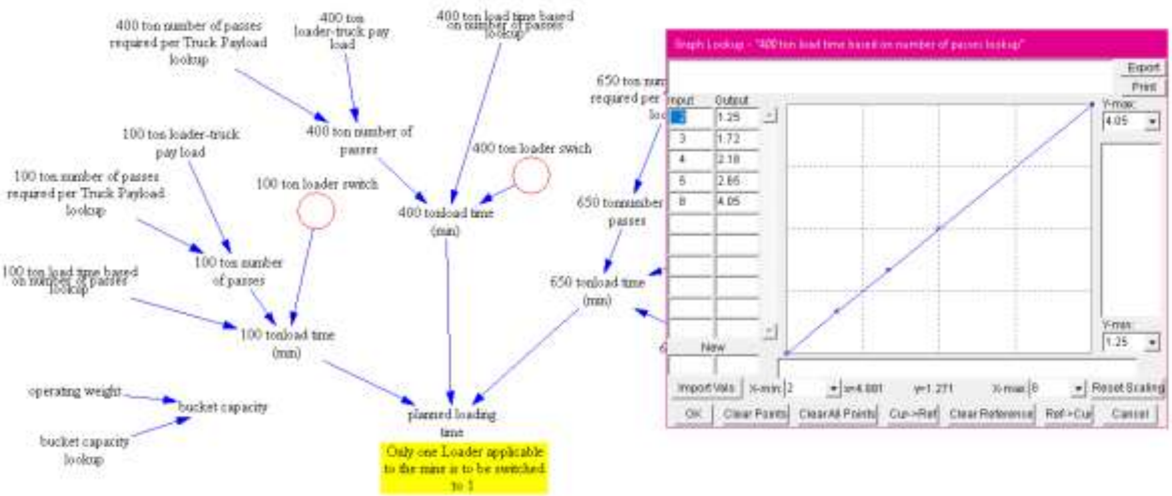


Figure 12. Truck matching model for correct loader type based on the data presented in Table 2.

P80 determination is done in another part of the simulation setup using Kuzram Prediction Formulae in *Figure 13*. This relationship is then incorporated into the model as seen in *Figure 14*.

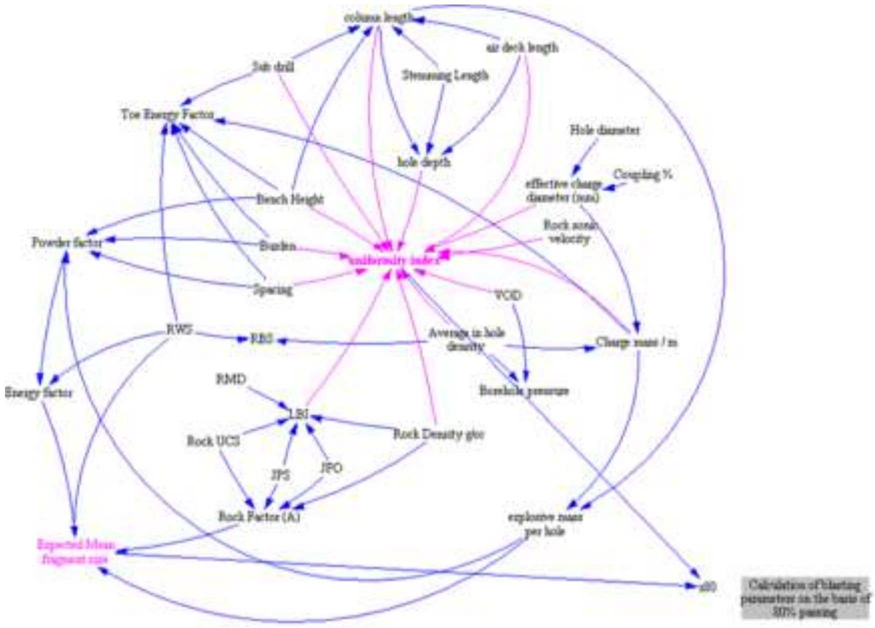


Figure 13. Fragmentation model to determine characteristic size at 80% passing (P80).

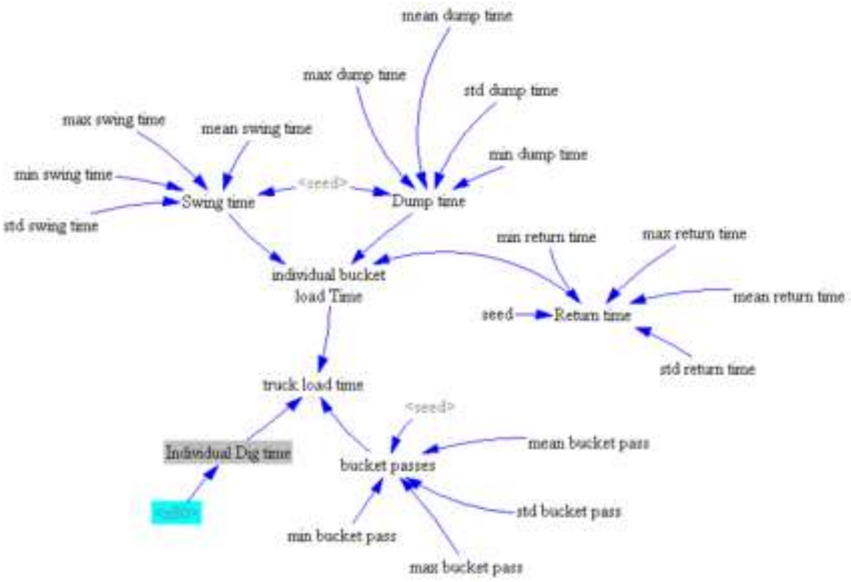


Figure 14. Determination of individual dig time based on P80 fragmentation size of the muckpile.

In the simulation setup a switch function was built in for a quick change introduced to the system, in this case it was a drill automation switch. In addition, sliders are used to change some of the input values for a more interactive experience of the consequences of change in the parameters.

The switch function comes in handy for setting up the machinery correctly matched within the model. Certain loaders in mining serve certain sizes of trucks. The weight of the loader is used as the criteria of the selection of the correct hauler in this case. The literature cited in Hardy (2007) lists the excavator-truck matching criteria as well as the important detail on the number of passes required to load the truck and the cycle times, as listed in Table 2. This data was used to build the switch function for excavator selection. Using the switch function, the model can be setup easily with the correct excavator or loader type matched for the specific mine. The following formulae was used towards building the switch function together with a look up table attached to that function for the number of 'passes'.

IF THEN ELSE("400 ton loader swich"=1 , "400 ton load time based on number of passes lookup"("400 ton number of passes"),0).

Figure 12 includes the lookup table setup within the switch function for one of the loaders.

It was demonstrated by Brunton *et al*., (2003) that at P80 passing size for a Liebherr 994 excavator demonstrates the best correlation. In conclusion the following relationship was found to be true for average dig time versus P80 fragmentation:

Average dig time (sec) = 12.36+0.0072 X P_{80} (mm) [3]

PARTIAL SIMULATION DEMONSTRATING THE BENEFIT OF HAVING AUTOMATED DRILLS

The objective of building such a big model was to realise major changes to an existing system in terms of cycle times, cost benefits and productivity, almost to the level of a gaming like setup.

The simulation setup has an automation switch function built into variables that are believed to be directly affected due to automation. By switching this to 'on' the results of the simulation change. For example, the required number of drill rigs for the set production environment is a value changing over time and calculated as in the range of 7-14 without an automation option.

Due to improved cycle times the combined number of drill rigs required is calculated as 10 for both ore and waste drilling. The reduction in the number of rigs was purely due to reduced variability. Both graphs are screen captures and presented here with the automation switch off and on respectively in *Figure 15*.

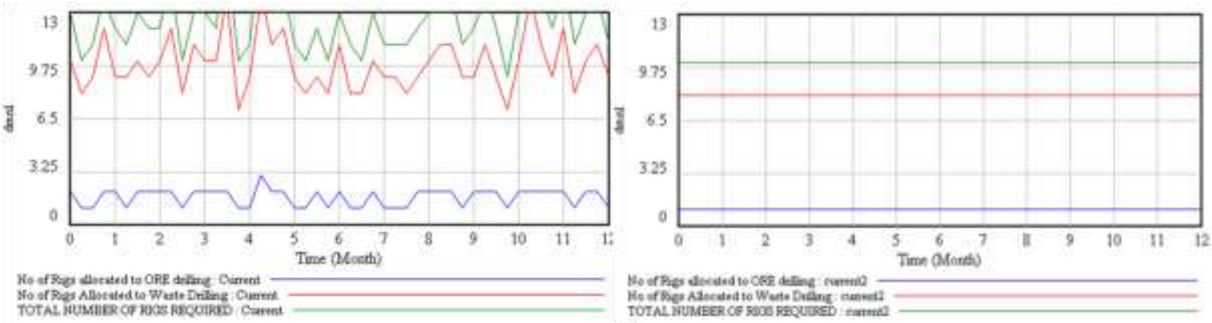


Figure 15. Number of rigs required with automation off (graph on left) and on (graph on right).

The simulation will be able to calculate financial implications of having automated systems on drills, and the cost benefit of improved drilling on the eliminated rework or re-drill due to incorrectly drilled or collapsed blastholes. The influence of only one type of variation is significant in terms of number of rigs required as an example, The more variability introduced into the model the more complex the output becomes. This is the benefit of having simulation based total system studies where one can choose which area needs to be studied by switching off the other variations such as rock properties. A skilful system dynamic modeller will include these kinds of switches within the model to control the degree of variability within the complete system. In this research rock properties were kept constant to isolate the problem to only the drill position-related errors.

CHALLENGES OF SYSTEM DYNAMICS MODELLING

There are some challenges to systemic approach to mining as discussed by Claassen (2012). A systemic approach based on flow principles is required to design, operate, manage and improve mining value chains otherwise result in only local optimisation. This will destabilise the system and make it unpredictable over the long term. Synchronisation, alignment and integration of capacities in the mining value chain supports a mechanistic approach to mining that increases complexity whereas the synchronisation, alignment, and integration of flow and flow attributes result in the simplification of complex mining flow systems. Management, improvement, and operations methodologies in mining must consider the variability in ore and ore body morphology within a flow context to simplify complex geological environments, and to optimise ore utilisation and system performance. Improvement initiatives that do not consider this important aspect of mining are doomed to failure as it will introduce more variability, and dependencies that will destabilise the system and make it less predictable. A mining methodology, such as Mineral Resource Throughput Management that focuses on all key drivers (internal and external) within a flow context as part of the methodology enables the identification of constraints, dependencies, and inter-dependencies in the mining value chain. It also assists with establishing management and control rules, processes and activities based on flow principles and ensure the stability of the mining value chain over the long term.

The advantage of having such a model helps management to have quick answers even with the smallest change in the design and production parameters, as well as having an insight on cost implications.

There are some statements that are made in the mining industry, such as: “As the drill diameter increases the drill tempo decreases”, “As the ground becomes harder the drill tempo decreases”, “As the ground elasticity increases the rock becomes tougher, therefore drill rate decreases”, “As the ground becomes blocky the drill rate will be slower and the drill steel might bend, leading to bit stuck, or drill deviation occurs”.

Now with the model created, these statements can be turned into actionable formulations with stocks rates and auxiliaries. The impact is then easily observable on all other processes with a simple sliding action on the input variable created.

When processes do not achieve targets planned, the impact can be nonlinear due to the dependencies; therefore, the sub-model presented as a conceptual stock and flow diagram for quantifying the impact of each process. It is an example of a nonlinear relationship that may exist in a cyclic environment.

The challenge in system dynamics however is to have the correct input updated live as a daily management tool. The input data can be linked to the latest excel database type of inputs so that it can be used to strategize when a change is required in the mine.

CONCLUSIONS

A system dynamics model of an iron mine to quantify the changes introduced to the mining environment has been discussed as a case study to justify the choice of system dynamics as a solution tool for mining problems. This alternative tool which is less known in the mining world has promising potential to understand the dynamics of the mining environment. The simulation of the mining environment from planning the mine to the management of mining is possible. The benefit of automation was partially calculated showing that due to cycle time reductions, the number of drill rigs required reduces considerably. This result could have been calculated with a spread sheet type of application; however, the result is only one of many that can be obtained using the same SD simulation model. The benefit of having one less drill is easily quantifiable. However, the impact of the improved quality of drill holes has not yet been quantified as this depends on the mine-specific inputs. The author has seen methods of quantifying this in the other industries, using system dynamics tools. The tool has the potential of presenting the mining setup with good visuals, in terms of demonstrating causality and calculating in the background, using strong mathematical relationships.

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