Universitat de Lleida

Planificación de construcciones subterráneas con métodos estocásticos

Juan Pablo Vargas Norambuena

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Universitat de Lleida

DEPARTAMENTO DE ADMINISTRACIÓN DE EMPRESAS Y GESTIÓN ECONÓMICA DE LOS RECURSOS NATURALES

Programa de Doctorado en Gestión Avanzada de Empresas en una Economía Globalizada

TESIS DOCTORAL

Planificación de Construcciones Subterráneas con Métodos Estocásticos

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UNIVERSITAT DE LLEIDA

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TESIS DOCTORAL

Planificación de Construcciones Subterráneas con Métodos Estocásticos

Tesis que presenta Juan Pablo Vargas Norambuena para optar al grado de Doctor por la Universidad de Lleida, bajo la dirección de los Drs. Alonso Alejandro Arellano Baeza y Francisco Juárez Rubio.

Firma del doctorando	Firma de los directores de las tesis
Juan Pablo Vargas Norambuena	Alonso Alejandro Arellano Baeza
	Francisco Juárez Rubio

Resum

A Xile, la mineria subterrània construeix més de 70.000 metres de labors horitzontals a l’any, la qual cosa significa una inversió superior als 70 milions de dòlars en el mateix període. Per altra banda, considerant la importància operativa que té aquest tipus d’infraestructures, atès que serveix d’accés als cossos mineralitzats i preparació de les unitats d’explotació, fa que la planificació prengui vital importància.

El present treball proposa una metodologia de simulació mitjançant el mètode de Monte Carlo i pretén ser un recolzament a la planificació, permetent d’obtenir una estimació més certa dels temps de construcció d’aquest tipus d’infraestructures, considerant la metodologia de construcció mitjançant perforació i voladura.

Per a l’ús del mètode de Monte Carlo, s’identifiquen les operacions unitàries que comprenen el cicle de construcció del túnel mitjançant perforació i voladura, i se’ls hi assignen distribucions de probabilitat, les que mitjançant la generació de nombres aleatoris fa possible simular el temps total de construcció.

Els resultats obtinguts mitjançant la metodologia plantejada es contrasten amb un cas real, on es pot observar que els terminis obtinguts per la simulació s’ajusten millor als temps reals de construcció del túnel que els planificats mitjançant mètodes convencionals.

A més, aquesta metodologia ha estat emprada per poder obtenir la millor configuració de la jornada de treball, segons allò permès per la legislació laboral xilena, amb la finalitat de minimitzar el temps de construcció del túnel.

Per últim, ha estat simulada la construcció dels túnels d’injecció 11 i 12 de la mina Chuquicamata Subterránea, aconseguint evidenciar les bondats del mètode en el moment de tenir una estimació de la finalització de la construcció de les obres.

Resumen

En Chile se construyen más de 70 km anuales de túneles mineros con una inversión superior a 270 millones de dólares. Dada la importancia que tiene este tipo de infraestructuras, ya que sirve de acceso al mineral, la planificación es vital.

El presente trabajo propone una metodología de simulación mediante el método de Monte Carlo que pretende servir de apoyo a la planificación, permitiendo obtener una estimación más certera de los tiempos de construcción de este tipo de infraestructuras.

Mediante el método de Monte Carlo se identifican las operaciones unitarias que comprenden el ciclo de construcción del túnel mediante perforación y tronadura, asignándoles distribuciones de probabilidad, para que mediante la generación de números aleatorios sea posible simular el tiempo total de construcción.

Los resultados obtenidos mediante se contrastan con un caso real, observando que los plazos obtenidos mediante la simulación se ajustan mejor a los tiempos reales de construcción del túnel que los planificados mediante métodos convencionales.

Se utilizó esta metodología para obtener la mejor configuración de la jornada de trabajo y su duración, según la legislación laboral de Chile.

Por último, se simuló la construcción de los túneles de inyección 11 y 12 de la mina Chuquicamata Subterránea, logrando evidenciar las bondades del método en el momento de tener una estimación de la finalización de las obras.

Abstract

Every year approximately 70,000 meters of tunnels with different sections are excavated in Chile for underground mining and civil works. The investments involve approximately 70 million dollars per year. In the mining industry this kind of infrastructure is very important as they serve to access the ore zones and prepare the ore excavation.

This work proposes a simulation algorithm based on Monte Carlo method that can provides the best estimation of the opening excavation times considering the classic method of drilling and blasting.

To use the Monte Carlo method, the unit operations involved in the underground excavation cycle is identified and is assigned to them probability distributions which, by means of the generation of random numbers, make it possible to simulate the total excavation time.

The results obtained by this method are compared with a real case where it can be seen that the times obtained by the simulation fit better the real tunnel construction times than those planned by means of conventional methods, and they also allow getting scenarios that can be important decision parameters at the time of planning a project of this kind.

Further used this methodology to obtain the best configuration of operational work shifts, as allowed by Chilean law, in order to minimize the time of tunnel excavation.

Finally, the excavations of the tunnels 11 and 12 of the Chuquicamata underground mine was simulated, showing evident the benefit of the method to obtain a estimation the ending of tunnel construction.

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Capítulo 1: Introducción y objetivos.

1.1.- Introducción.

La presente investigación tiene por objetivo desarrollar una metodología de planificación, basada en simulación de tipo estocástico, que sirva para estimar los tiempos requeridos para la construcción de túneles con una mayor cantidad de información que con la que se cuenta hasta ahora. Se trata de hacerla más precisa en el momento de tomar las decisiones, con el fin de tener una mayor certeza en el presupuesto de construcción de este tipo de obras.

Lo anterior tiene mucha importancia si se considera que la construcción de túneles es fundamental para un país minero como Chile, debido a que gran parte de la industria minería se desarrolla bajo el subsuelo.

Chile es el mayor productor de cobre del mundo (Cochilco, 2011) y gran parte de este elemento se obtiene por minería subterránea, entendiendo por esto como aquella extracción de recursos naturales no renovables que se desarrolla debajo de la superficie del suelo, en la corteza terrestre. La importancia de la minería subterránea queda demostrada cuando la Corporación Nacional del Cobre (Codelco) la considera como el pilar fundamental dentro de la producción del metal rojo (Codelco, 2012). Es posible pensar que, en el futuro, la minería subterránea será mayoritaria a escala mundial, ya que contamina menos que la minería de cielo abierto (Riveros, 2013).

Ahora bien, la importancia de la construcción de túneles en la minería subterránea, radica principalmente en que es la principal infraestructura de acceso desde la superficie hasta el subsuelo, donde se encuentran los yacimientos mineros rentables de extraer (Suorineni *et al.*, 2008), del cual una vez procesado se obtiene el elemento requerido, en el caso de Chile, el Cobre.

Codelco tiene proyectado realizar un total de 40 km de túneles por año, sin considerar el proyecto Chuquicamata Subterránea, lo que significaría una inversión de 180 millones de dólares por año (Revista Minería Chile, 2010). Para el proyecto de Chuquicamata Subterránea, que debería comenzar su explotación en 2020, se contempla desarrollar sobre 1.000 km de túneles en toda su vida útil, lo que podría alcanzar una inversión de 4.800 millones de dólares, y solo para el acceso y adecuación de la mina (Revista Minería Chilena, 2013).

Se puede ver la importancia que tiene la construcción de este tipo de infraestructura para la minería y, en consecuencia, para el país, por lo que investigar el desarrollo de una técnica de planificación que mejore o entregue más información a la hora de tomar decisiones para determinar los plazos de construcción y, por lo tanto, el presupuesto, será de gran utilidad para la industria minera.

En la actualidad la planificación se desarrolla con valores fijos, lo que genera un solo escenario de ocurrencia con una probabilidad de éxito de 100%. Esto difiere mucho de la realidad, ya que no se consideran combinaciones de eventos o sucesos que retrasan la ejecución de este tipo de obras de construcción, que si se tendrían en cuenta con este tipo de herramientas, que también permite hacer "Análisis de Riesgo".

1.1.1.- Generalidades en la Construcción de Túneles.

Se conoce como túnel, en el área de la ingeniería y arquitectura, aquella perforación que se hace en un terreno, de forma horizontal o sub-horizontal y lineal, siendo su objetivo comunicar dos puntos para realizar el transporte de materiales y personas, entre otras cosas. En minería subterránea, los túneles son fundamentales para generar los accesos a los cuerpos mineralizados para poder explotarlos, sirviendo como infraestructuras para el ingreso de materiales, personas y maquinaria, entre otras aplicaciones.

Existen varias formas de construir un túnel, pero para esta investigación se utilizará la construcción más usada, mediante perforación y tronadura (Suorineni *et al.* 2008), dejando de lado otras técnicas de construcción, como TBM "*Tunnel Boring Machine*" (Barthes *et al.,* 1994; Robbins, 2000, Yazdani-Chamzini & Yakhchali, 2012), que son más aplicadas en obras civiles (Fukuchi, 1991; Haraldsson 1992; Suorineni *et al.* 2008; Vanwalsum, 1991) para la construcción de túneles con extensiones superiores a 20 km y en línea recta (Marec, 1996).

El método de perforación y tronadura consiste en excavar la roca con el uso explosivos, siguiendo una secuencia de actividades cíclicas, conocidas como operaciones unitarias (Beall, 1973; Karlinski *et al.,* 2008; Suorineni *et al.* 2008; Zare & Bruland, 2006). Las actividades cíclicas consideradas para la construcción de un túnel son:

Perforación: consiste en la realización de tiros o barrenos en la cara del avance horizontal (ver Fig. 1 y Fig. 2), que posteriormente serán cargados con explosivos para generar la tronadura y quebrar la roca, con el fin de realizar el avance en la labor. El largo de la perforación efectuada será aproximadamente el largo del avance. Esta operación es una de las más sensibles dentro de la ejecución de labores horizontales, por la alta tasa de falla de los equipos y por la dispersión de tiempos en la ejecución de las perforaciones.

Carguío de explosivos y tronadura: consiste en cargar las perforaciones con explosivos para realizar la tronadura con el fin de quebrar la roca y lograr un avance en la frente de trabajo.

Ventilación: con posterioridad a la tronadura, se debe ventilar el lugar de trabajo debido principalmente a que se generan gases nitrosos. Este proceso se realiza con ventilación forzada.

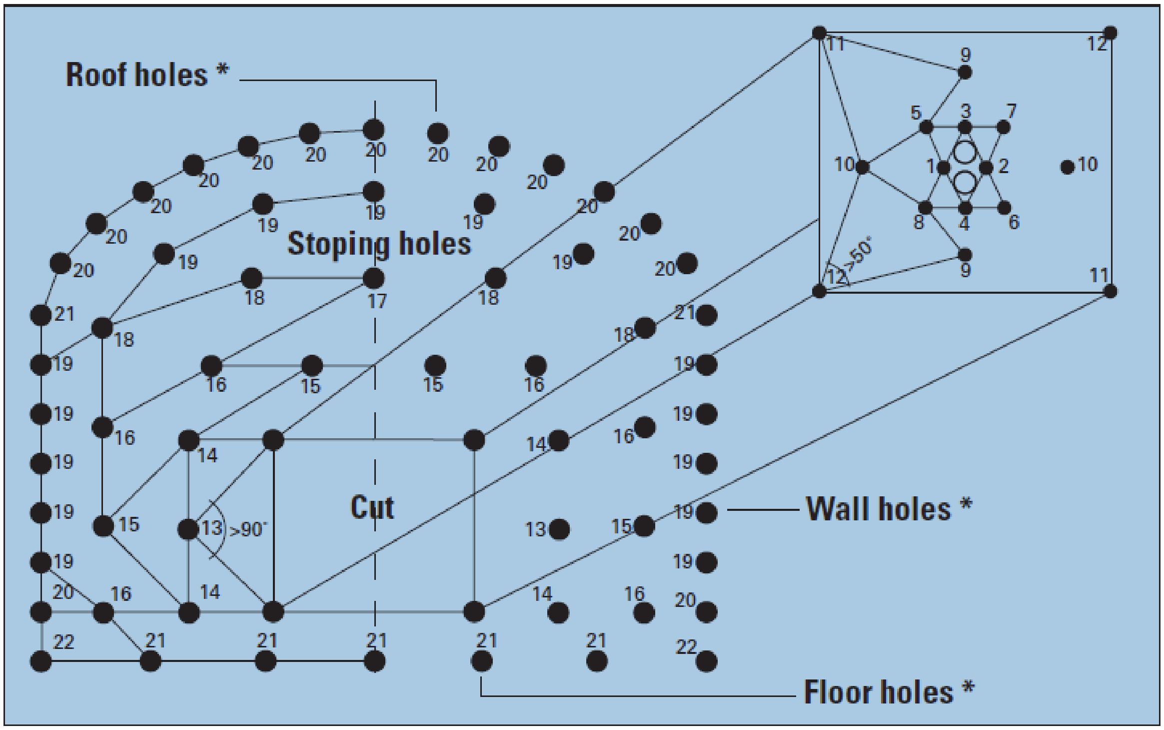

Figura 1. Diagrama de Perforación de Túneles.

Marina: este proceso contempla el retiro del material quebrado hasta un punto de acopio o un punto de carga. Cabe destacar que esta etapa, en conjunto con la perforación y carguío de explosivos, ocupa más del 70% del tiempo total de ciclo (Suorineni *et al.*, 2008).

Figura 2. Equipos de Perforación en Desarrollo de Túneles.

Acuñadura: contempla el desprendimiento de materiales "colgados" o en situación de riesgo por caída de altura. Este proceso se genera principalmente producto de la tronadura.

Fortificación: consiste en realizar trabajos de sostenimiento en la roca recién excavada, con el fin de asegurar los sectores tronados.

En la actualidad, al momento de planificar la construcción de un túnel, se consideran todas las actividades necesarias dentro de ciclo (ver Fig. 3), sabiendo que cada una de ellas tiene un tiempo de duración asociado. El tiempo de duración de ciclo será la suma de todos los tiempos.

Si se considera que el avance efectivo está relacionado con el largo de perforación, mencionado con anterioridad, se tendrá un avance por unidad de tiempo. Como se conoce el largo del túnel, se conocerá el tiempo de construcción del túnel, al que se le asociará el presupuesto de construcción.

Como se puede observar, tanto el tiempo de construcción como el presupuesto asociado, se realiza con un 100% de probabilidad de éxito, no representando la realidad al momento de construir.

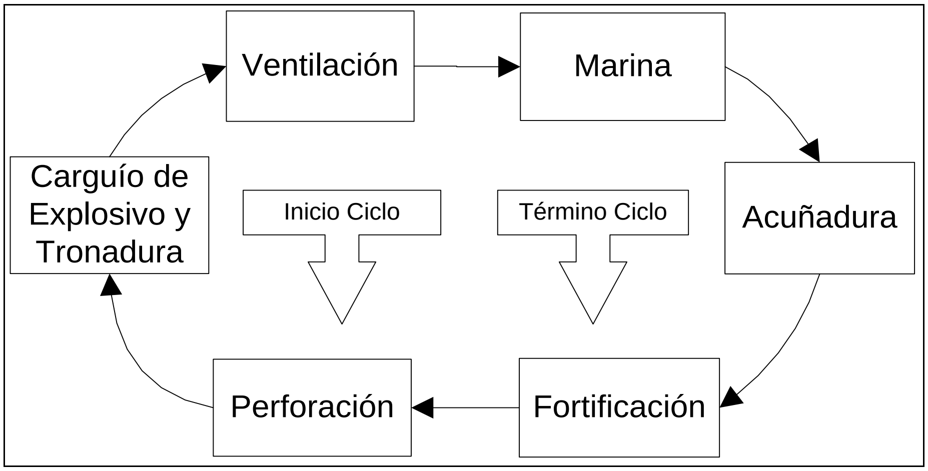

Figura 3. Ciclo de Construcción de un Túnel.

1.1.2.- Importancia de la Construcción de Túneles en la Minería Subterránea.

Un Yacimiento Geológico es una concentración anómala de minerales que, de tener valor económico, se conocerá como Yacimiento Minero y, si su extracción genera rentabilidad, se hablará de Mina (Minería).

La explotación o extracción de un recurso natural no renovable como un mineral económicamente rentable desde la corteza terrestre se puede hacer de dos formas: a cielo abierto (superficie) o de forma subterránea. Este último tipo tiene una estrecha relación con la construcción de túneles, puesto que el acceso a la corteza terrestre se debe hacer a través de este tipo de infraestructuras, para así poder acceder con personal, maquinaria y materiales para realizar los trabajos necesarios con el fin de extraer el mineral. En la Fig. 4

se muestra el ingreso a la Mina El Teniente, perteneciente a Codelco Chile, que es la mina subterránea más grande del mundo.

Existe una variada infraestructura en el interior de la mina, compuesta por túneles y chimeneas (labores verticales), necesarias para la explotación de cualquier mina subterránea. Este tipo de explotación se desarrolla por una variada gama de métodos subterráneos, los cuales dependen del movimiento de materiales, que se hace a través de los túneles dispuestos para esta función.

Durante la vida útil de una mina siempre se estará construyendo túneles, debido a que va cambiando la ubicación de la explotación de los minerales, por lo general profundizándose. Un ejemplo son los túneles del Nuevo Nivel Mina del Teniente (NNN), que se comenzaron a construir a fines de 2014 con el fin de acceder a las reservar más profundas de éste yacimiento minero. Esta infraestructura constará de dos túneles de 8 km largo y sección de 8 m de alto por 8 m de ancho, utilizando uno para la extracción del mineral (Túnel Conveyor) y el otro para el tránsito de personal, materiales y equipos (Túnel Personal) (Codelco, 2011).

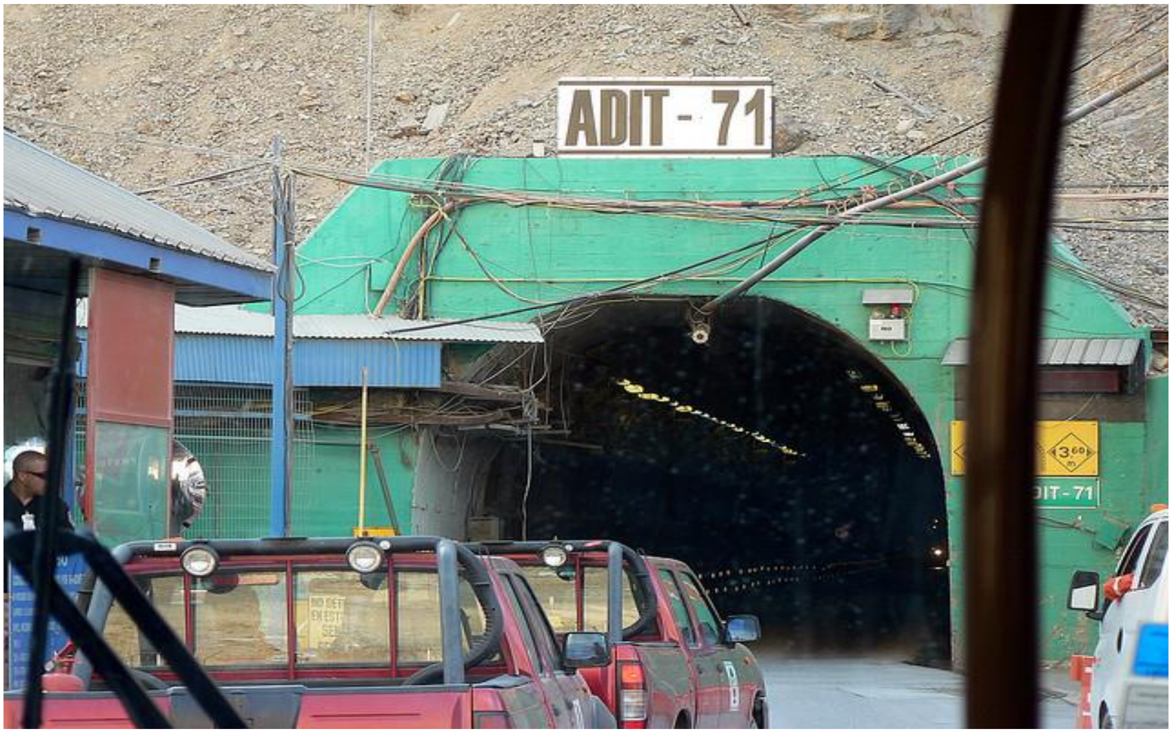

Figura 4. Ingreso Mina El Teniente (Adit 71), Codelco Chile División El Teniente.

1.2.- Problemática e Hipótesis.

Dada la importancia mostrada en la ejecución de este tipo de infraestructuras, es conveniente observar qué está ocurriendo en el momento de planificar su construcción y qué mejoras se introducirán con la metodología planteada en esta tesis.

Como se ha dicho anteriormente, la planificación de la construcción de un túnel se efectúa con valores fijos e invariables. Este hecho hace que el plazo de ejecución sea considerado como un valor fijo, que muchas veces no es real, sin dar la posibilidad de mostrar que sucedería si este tipo de construcción sufre desviaciones en los plazos de ejecución, que a la larga producen un descuadre presupuestario, y por consecuencia en los beneficios esperados.

Uno de los principales problemas que acontece al considerar valores fijos en la planificación es que se genera incertidumbre en torno a las decisiones al no poder cuantificar el riesgo. Se debe mencionar que al utilizar valores fijos no es posible considerar todas las posibles combinaciones de eventos en el transcurso de la construcción de un túnel. Si por el contrario se considera la variabilidad, se podría traducir la incertidumbre en riesgo ya que se puede cuantificar una decisión, indicando por ejemplo la probabilidad de éxito de ésta.

A modo de hipótesis, en este trabajo se desarrollará una metodología para la planificación de la construcción de túneles que incorpore la variabilidad propia de las operaciones unitarias. Para su realización se empleará la simulación estocástica, más específicamente el método de Monte Carlo (Metropolis & Ulam ,1949; Sobol, 1994), apoyada por la teoría de las Cadenas de Markov (Hillier & Liberman, 2006), con el fin de incorporar la variabilidad propia de las operaciones unitarias al proceso de estimación de tiempos de construcción de un túnel. Como producto de la metodología propuesta se muestran las posibles combinaciones de eventos que pueden ocurrir durante la construcción de un túnel.

1.3.- Estado del Arte.

En la actualidad la simulación por método de Monte Carlo se ha utilizado para determinar escenarios financieros o hacer estimaciones de costos en la industria, como se mencionó con anterioridad (du Plessis & Brent, 2009; Fuksa, 2009; Heuberger, 2005; Morley et al., 1999; Sabour & Wood, 2009; Simonsen & Perry, 1999).

También se ha utilizado en el área de geomecánica y diseño minero considerando la incertidumbre existente en la estimación de parámetros de diseño de ingeniería propios de la actividad (Khalokakaie *et al.*, 2000; Singh & Xavier 2005; Morin & Ficarazzo, 2006; Chiwaye & Stacey, 2010; Ghasemi *et al.*, 2010; Sari *et al.*, 2010).

Para el caso de la construcción de túneles, se observa evidencia de investigación utilizando el método de Monte Carlo (Fouladgar *et al.*, 2012; Spackova & Straub, 2013) desde una perspectiva de evaluación del riesgo considerando aspectos externos como condiciones climáticas y factores humanos que pueden incidir en este proceso (Spackova & Straub, 2013) o desde el gerenciamiento y administración de estos mismos (Fouladgar *et al.*, 2012).

Por todo ello, esta investigación es un aporte real a la administración de obras de tunelería, considerando el más amplio aspecto del término administración, siendo ésta la ciencia encargada de planificar, organizar, dirigir y controlar los recursos humanos, financieros materiales, tecnológicos y de conocimiento, entre otros.

1.4.- Objetivos.

El principal objetivo de este trabajo es desarrollar una metodología de planificación, basada en un algoritmo que utilizará el método de Monte Carlo, que pueda mejorar la planificación de la construcción de túneles al contar con mayor cantidad de información y así, por ejemplo, poder realizar presupuestos más precisos. Se ha escogido éste método de simulación estocástica debido a que se utiliza para hacer estimación de expresiones numéricas complejas o para modelar probabilísticamente procesos que de otra forma sería muy complejo y costoso evaluar.

1.4.1.- Objetivos Generales.

El objetivo de esta investigación radica en poder estimar de una manera fiable los plazos de ejecución de labores subterráneas horizontales (túneles) entregando las posibles variaciones que puedan ocurrir o mostrando los distintos escenarios a los cuales se enfrenta la construcción.

La principal contribución que se quiere hacer está ligada, principalmente, a la planificación de la construcción de galerías, las cuales podrán presentar probabilidades de éxito, fracaso u otro indicador, según sea el análisis que se requiera.

1.4.2.- Objetivos Específicos.

Generar una metodología de simulación mediante el método de Monte Carlo, con el fin de estimar la duración de la construcción de las labores subterráneas y así poder asociar la planificación de las obras a distintos escenarios de ocurrencia.

Con esta simulación se espera desarrollar una metodología de planificación que sea más certera a la hora de estimar la duración de la construcción de un túnel y se pueda tener mayor precisión en la elaboración de presupuestos de ejecución de las obras.

También se espera poder utilizar esta metodología para encontrar la mejor configuración para la jornada laboral ya que en Chile aún son variadas las jornadas utilizadas para este tipo de construcciones. Este punto estará siempre dentro del marco legal autorizado (Dirección del Trabajo, 2012)

1.3.- Alcances y Limitaciones.

Se utilizará el método de Monte Carlo, ampliamente utilizado para estudios de análisis de riesgo en distintas materias y disciplinas (du Plessis & Brent, 2009; Fuksa, 2009; Heuberger, 2005; Morley et al., 1999; Sabour & Wood, 2009; Simonsen & Perry, 1999). Este método funciona con la generación de números aleatorios que, al intervenir las funciones de distribución de probabilidad (FDP) representativas de los procesos que se quieren simular, generan escenarios de ocurrencia para estas operaciones, logrando representar la realidad. Este método se utiliza frecuentemente para simular procesos complejos, que de otra forma sería muy difícil representar.

Esta investigación se centrará exclusivamente en la planificación de construcción de túneles en minería por perforación y tronadura, no abarcando ninguna otra especialidad, como lo podrían ser túneles civil o túneles submarinos.

Aunque la definición de túnel, infraestructura que se utiliza para unir dos puntos en superficie mediante excavación subterránea que, debido a su topografía, sería imposible o económicamente inviable unirlos por otro medio, se debe mencionar que para este trabajo de minería subterránea, que se accede desde la superficie hasta el interior de la corteza terrestre para extraer los minerales, se empleará ya que el método constructivo es el mismo y la confección de presupuestos también.

1.7.- Contribuciones de la Tesis.

La metodología de esta tesis, basada en el método de Monte Carlo, será realizada con el software computacional Matlab®, que servirá como apoyo a la planificación de la construcción de túneles. Este programa generará información adicional a la ya disponible, con el fin de tomar una mejor decisión al momento de planificar.

Considerando los aspectos antes expuestos, se puede señalar que la metodología de planificación de la construcción de túneles propuesta será capaz de entregar los posibles escenarios, desde el punto de vista de duración de la construcción, a los que se verá enfrentado la ejecución de este tipo de infraestructura. Esto conlleva una mejora en la elaboración de los presupuestos de construcción debido a que se podrá tener más certeza en el momento de decidir el tiempo de duración de la obra.

Además, se pretende aplicar esta metodología para estimar la mejor configuración del turno de trabajo para construir este tipo de infraestructura, considerando la legislación laboral vigente y la mejor productividad frente al coste de construcción. Este hecho es de mucha importancia debido a que, en la actualidad, son muy variadas las configuraciones de turnos utilizadas, no existiendo estudios que sean capaces de mostrar cuál es el más adecuado. Se debe tener especial cuidado en la elección ya que los factores que influyen en la mejor configuración son muchos, como, por ejemplo, la sección del túnel, los equipos utilizados y, en consecuencia, las FDP obtenidas de cada una de operaciones unitarias necesarias para la construcción.

Capítulo 2: Metodología de la Investigación.

Como ya se ha mencionado, para poder representar de manera real la construcción de una galería mediante simulación estocástica, se necesita conocer las FDP y los factores que afectan el ciclo constructivo. Para este fin, se tomarán muestras de datos en una mina que realiza su explotación mediante minería subterránea, Compañía Minera San Pedro, ubicada en la Región Metropolitana, comuna de Til-Til, donde se realiza extracción de mineral de cobre. En esta operación se muestreará los tiempos de ciclos con el fin de generar las FDP necesarias para realizar la simulación de los ciclos constructivos.

En Compañía Minera San Pedro se tomarán datos de la operación que se realiza en Mina Esmeralda para, posteriormente, realizar la simulación de la construcción del nuevo proyecto Esmeralda II, que contempla el desarrollo de dos túneles, de 560 m cada uno, que servirán como acceso a la mina y extracción del mineral desde un cuerpo hidrotermal tipo veta, que se extraerá por el método de explotación Shrinkage (Chen, 1998). La simulación contempla el túnel para la extracción de mineral.

Cabe considerar que en Compañía Minera San Pedro no existen datos de tiempos de ciclos ni índices operacionales, por lo que se deberá hacer un levantamiento y ordenamiento de las operaciones existentes.

En paralelo con las mediciones que se realizarán en terreno, se elaborará un algoritmo, en la plataforma computacional Matlab®, que sea capaz de realizar la simulación desde un punto de vista dinámico considerando que todos los softwares que trabajan con el método de Monte Carlo tienen un trabajo estático de la información. Esto es fundamental, ya que es uno de los aportes de esta tesis, puesto que hasta ahora no se tienen indicios de que se haya desarrollado algo parecido.

Aunque este método no se ha utilizado para la simulación de construcción de galerías, se tiene una alta certeza de éxito dada su aplicación en otros ámbitos de similar naturaleza como, por ejemplo, el análisis de riesgo en el ámbito financiero o la estimación de parámetros de diseño ingenieril.

Se espera poder corroborar el algoritmo de estimación en al menos dos casos reales.

Capítulo 3: Artículos Publicados, Aceptados o en Curso

3.1.- Monte Carlo simulation as a tool for tunneling planning - Revista "Tunnelling and Underground Space Technology" (Publicado).

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Monte Carlo simulation as a tool for tunneling planning

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ABSTRACT

Underground mining involves development of shafts, ramps, drives or other types of excavation to gain access to mineralized zones and later to serve as the infrastructure for mining. Therefore, the time taken to access the excavation becomes a critical factor in mine planning. This work proposes a simulation algorithm based on stochastic probabilistic methods that can provide the best estimation for the opening excavation times when considering the classic methods of drilling and blasting.

The proposed methodology is based on stochastic numerical methods, specifically, the Monte Carlo simulation method, together with the technical conditions that affect the tunnel excavation cycle; the simulation is developed using a computational algorithm.

To use the Monte Carlo method, the unit operations involved in the underground excavation cycle are identified and assigned probability distributions that, by means of random number generation, make it possible to simulate the total excavation time.

The results obtained by this method are compared with a real case, where it can be seen that the times obtained by the simulation are a better fit with the real tunnel construction times than those planned by means of conventional methods. The simulation results generate different scenarios which contain important parameters to use in the decision making in the planning process.

1. Introduction

Ramps, shafts, drives or other development excavations are of great importance for the exploitation of underground mines, as they generate access to mineralized sectors and prepare exploitation units. Therefore, the construction time for the work becomes an important factor in the success or failure of a project of this kind.

This research proposes a method for the simulation of the excavation times of tunnels, which is presented as a decision-making tool in the planning stage of mining or civil engineering projects where it is necessary to develop this kind of infrastructure. There are several tunnel excavation methods. For our study, we will focus on excavation by drilling and blasting.

The difficulty in estimating the times of each of the unit operations in the tunnel excavation process is mainly because all the activities have variations that depend on unforeseen events, but they can be associated with probabilities of occurrence.

Due to associated costs, knowing the real excavation times becomes a priority in any mining project. Estimating the exact execution time is a complex task in which one runs the risk of getting it wrong, giving rise to increased problems with respect to planning and associated budgets.

Estimating a time and its probability of occurrence, or the possible time scenarios related to the excavation is a useful parameter for decision making. In this way, the proposed methodology will be a tool for reducing the risk associated with excavation time estimates in mine planning.

It is convenient to use the Monte Carlo method as a tool for predicting excavation times of development openings, keeping in mind that it is a stochastic simulation that allows analysis of complex systems with several degrees of freedom. This method is commonly used to solve complex mathematical problems by random sampling (Metropolis and Ulam, 1949; Sobol, 1994), making it one of the most commonly used for performing these kinds of analyses (Sari et al., 2010). It involves the generation of random or pseudo-random numbers that enter into an inverse probabiliy distribution, resulting in as many scenarios as the number of simulations made. The estimation will be more precise the more iterations that can be made.

At present, the Monte Carlo method has become a very efficient tool to determine financial scenarios or to estimate costs (Morley et al., 1999; Simonsen and Perry, 1999; Heuberger, 2005; Magda and Franik, 2008; du Plessis and Brent, 2009; Fuksa, 2009; Sabour and Wood, 2009). The vast majority of the studies made using

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Monte Carlo simulations consist of carrying out risk analysis from the standpoints of investment and profitability.

On the other hand, some studies have used Monte Carlo simulations in areas of mining engineering, such as geomechanics, resources estimation or mining design, mainly considering the uncertainty and complexity that there is in the estimation of design parameters belonging to this activity (Khalokakaie et al., 2000; Morin and Ficarazzo, 2006; Chiwaye and Stacey, 2010; Ghasemi et al., 2010; Sari et al., 2010), and it is in this area that the present research will be based.

The proposed methodology was applied to estimation of the excavation times of a tunnel for Compañía Minera San Pedro in a copper deposit in Chile.

2. Drilling and blasting excavation cycle

Excavation of underground structures by drilling and blasting consists of a cycle composed of different activities. Suorineni et al. (2008) detail the following sequence (see Fig. 1): drilling of the gallery surface, loading with explosives and blasting, ventilation (considered as an interference within the cycle), scaling and removing blasted material, and support installation (bolts, nets, shotcrete, among others). It must also be pointed out that these operations are performed during a shift or workday, which is a constant that also has an influence on the execution time of the construction cycle.

The general principle is to carry out drilling on the face of the excavation to load explosives which, when blasted, break up the rock, producing an opening that becomes the "tunnel" (Singh and Xavier, 2005). After breaking the rock, it is necessary to ventilate the place to eliminate the noxious gases that come from the blasting, an operation that is usually considered to interfere with the cycle (Suorineni et al., 2008). Then, the scaling operation is carried out, which consists of removing the loose rocks from the roof of the works that remain after the blasting, followed by the removal of the fragmented material. The cycle is finished by the supporting of the tunnel section that has been excavated to ensure the stability of the tunnel or gallery. Support of the underground excavation is a task that is done only if necessary, depending mainly on the quality of the rock.

Suorineni et al. (2008) present a breakdown of the percentage of time used for each stage of the process, identifying the importance of each. However, it must be considered that even having knowledge of the incidence of each operation in the cycle, it is very difficult to know the total duration of the cycle exactly, and therefore the time that will be needed to finish the excavation of the tunnel.

3. Determination of the excavation time of a tunnel using the Monte Carlo method

As described throughout this paper, tunnel excavation by drilling and blasting is a cyclical operation (see Fig. 1) Considering this fact, the main variables that govern this activity are the length advanced, usually in meters and the duration of the cycle, composed of the times involved in each of the operations that constitute the cycle. Using the model proposed by Suorineni et al. (2008), we can express the advance ratio as:

$$RA = Le/Tc \tag{1}$$

where "Le" is defined as the real advance after the blasting, or the drilling length times the efficiency of the blast (Le = drilling length × efficiency of the blast (%)), and Tc is the summation of the times of the activities considered in the development of the cycle.

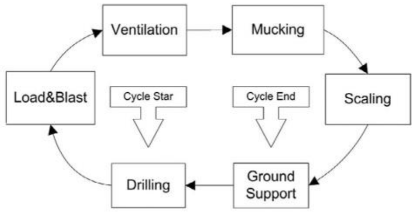


Fig. 1. Underground excavation cycle.

The activities considered in the cycle can vary according to the mining operation. For example, underground support may not be part of the cycle time, depending on the needs and requirements of the development of the excavation. A large part of the improvements in these kinds of operations is aimed at decreasing the excavation time of each of its component activities, in this way achieving increased advances over shorter times, consequently leading to a reduction of excavation costs (Suorineni et al., 2008).

In general, the estimation of excavation time (TD) is made by considering the advance ratio (RA) with respect to the length of the tunnel (LT), as expressed by:

$$TD = LT/RA \tag{2}$$

The formulation currently used has an excavation time as a result, which does not consider variability.

On the other hand, noncompliance with excavation times in these kinds of infrastructure project is certainly a problem in the case of mining that affects ore extraction, mainly because the planning is subject to access and preparation of the mineralized bodies.

The frequent noncompliance with the planned times occurs mainly because during the estimation of the excavation times for the underground openings, a fixed and unchanging value of advance per unit time in relation to the length of the tunnel is calculated, Eq. (2), which gives a fixed excavation time with 100% probability of success. However, it is well known that this is not the case, because as long as there is variability in carrying out the operations, the times can change.

Fig. 2 shows a diagram of a Monte Carlo simulation applied to the problem of tunneling planning, where the result is a probability distribution (PD) of the duration of the tunnel construction cycle. Unit operations PDs were obtained through the sampling of an adjacent tunnel.

In view of the variability of the operations, it is possible to establish the occurrence of pessimistic, probable, and optimistic scenarios, and to know the degree of certainty of the planning. Therefore, a methodology based on the Monte Carlo simulation is proposed to estimate operational time for the underground excavation. For this purpose, the excavation cycle model proposed by Suorineni et al. (2008) will be used as a basic structure, where each of the operations of the cycle will be assigned a PD with which the different scenarios will be simulated by the generation of random numbers (Sobol, 1994). These numbers will deliver the different times for each operation, and the sum of the simulated times per unit operation will give the cycle times that it is possible to obtain (see Fig. 2).

It can also be supposed that, in addition to the variability in the times of the operations that compose the cycle, there is also a variability in the efficiency or advancement measured in meters per blasting, Eq. (1), which adds one more component to the variability of the system.

The method used to simulate tunnel excavation time will be obtained from the tunnel effective advance over each cycle related to its duration, both items resulting from the generation of random

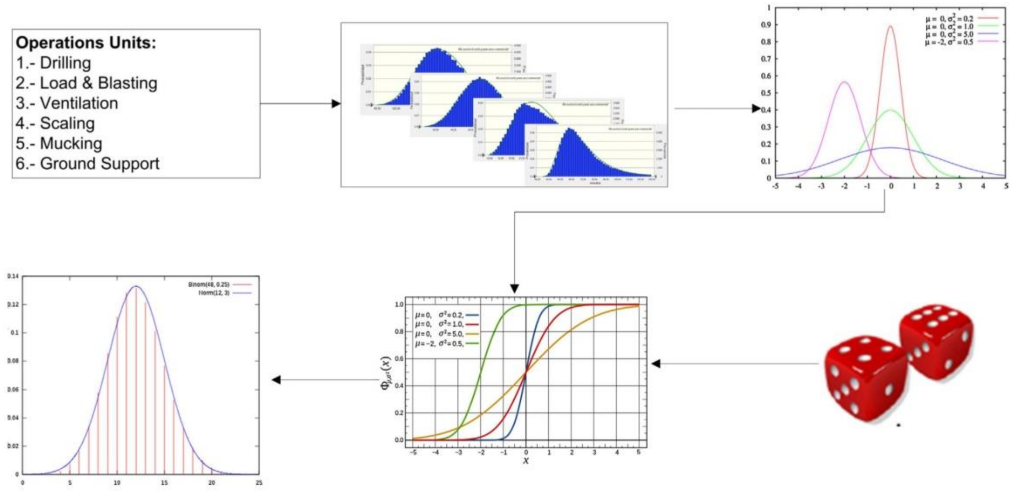


Fig. 2. Simulated times per unit operation.

numbers between 0 and 1, which act on the inverse PDs that represent the unit operations, in this way, obtaining an advance as a function of time. If this operation is carried out over the total length of the tunnel, it will have a time associated with the excavation, giving rise to a sample. Carrying out this operation as many times as necessary will produce simulations that can be fitted to a PD of the time associated with the construction of the tunnel.

Because of the need to make an iterative calculation of the order of thousands of cycles for the construction of the PD of the tunnel excavation time to solve the problem, the algorithm shown in Fig. 3 was developed.

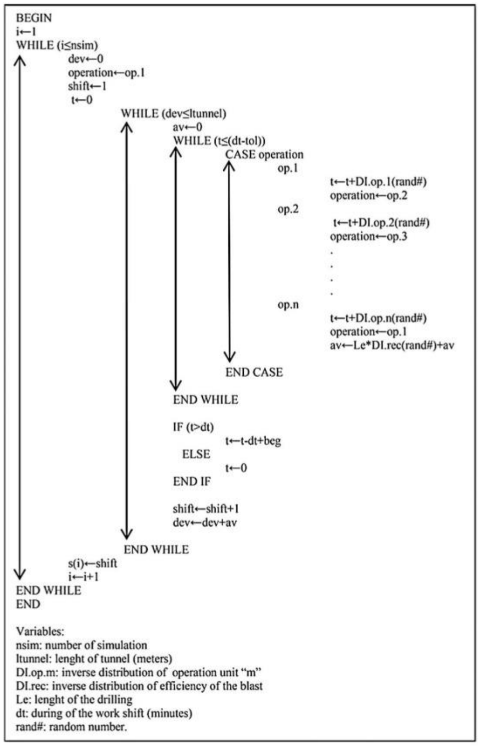
The algorithm is composed of three loops that control the required number of simulations, the tunnel length, and the relationship between the duration of the work shift and that of the tunnel excavation cycle. All these items are necessary to be able to simulate the total excavation time and, for clarity, they are shown schematically in the flow chart of Fig. 4.

The proposed scheme consists of three inclusive loops that are dependent on one another. The procedure is that the first loop, which contains the other two, controls the number of simulations required, knowing that each simulation will be the length of the tunnel construction.

The second loop provides the control that the excavation does not exceed the defined tunnel length, and every advance will be estimated by the PD of the efficiency of the blasting times and the length of the drilling, which has a fixed value. It will be added consecutively until the required tunnel length is achieved.

Finally, the third loop has the function of consecutively adding the times of the building operation cycle and verifies its relationship with the established work shift.

This last loop is the key to the simulation because it builds the cycle within the shift. This construction is carried out by means of the Monte Carlo simulation, where the statistical distributions associated with the execution times of each of the unit processes are applied to the excavation of the tunnel. The times obtained from this unit operation simulation are added, and then determined if the cycle will be finished during the operating shift. The details of the operation of each of the loops are given in the sequence.



```
BEGIN
i←1
WHILE (i≤nsim)
        dev←0
        operation←op.1
        shift←1
        t←0
                WHILE (dev≤ltunnel)
                        av←0
                        WHILE (t≤(dt-tol))
                                CASE operation
                                        op.1
                                                t←t+DI.op.1(rand#)
                                                operation←op.2
                                        op.2
                                                t←t+DI.op.2(rand#)
                                                operation←op.3
                                                .
                                                .
                                                .
                                                .
                                        op.n
                                                t←t+DI.op.n(rand#)
                                                operation←op.1
                                                av←Le*DI.rec(rand#)+av
                                END CASE
                        END WHILE
                        IF (t>dt)
                                t←t-dt+beg
                          ELSE
                                t←0
                        END IF
                        shift←shift+1
                        dev←dev+av
                END WHILE
        s(i)←shift
        i←i+1
END WHILE
END

Variables:
nsim: number of simulation
ltunnel: lenght of tunnel (meters)
DI.op.m: inverse distribution of  operation unit "m"
DI.rec: inverse distribution of efficiency of the blast
Le: lenght of the drilling
dt: during of the work shift (minutes)
rand#: random number.
```

Fig. 3. Algorithm to simulate the tunnel excavation time.

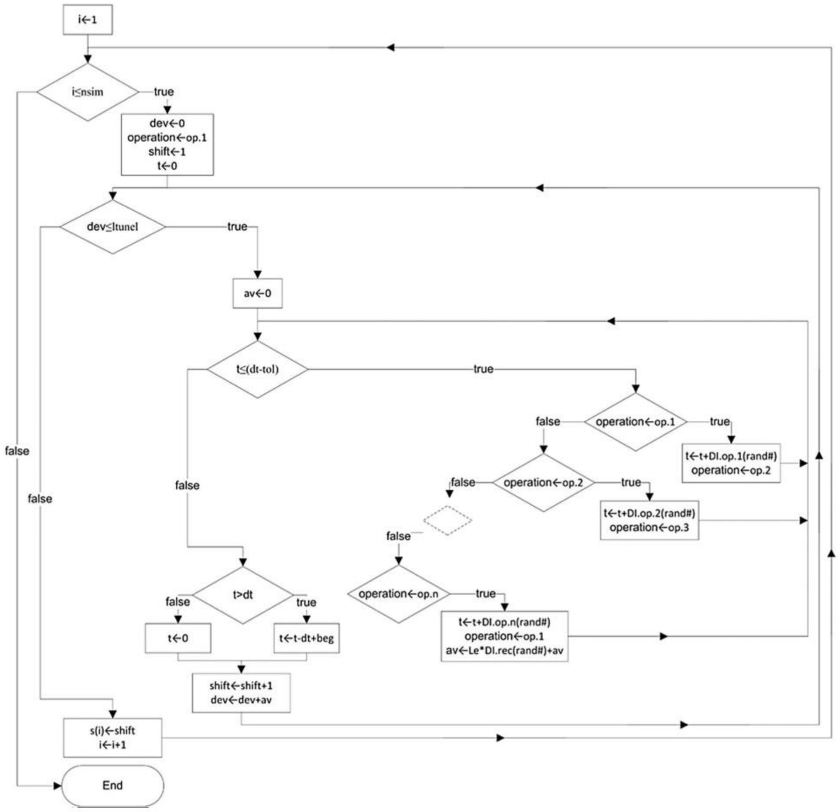


Fig. 4. Flow diagram of the total tunnel excavation time.

3.1. Control of the simulation numbers

As already mentioned, the function of the first loop is to control the required number of simulations, and it must be considered that each simulation involves the estimation of the time required to excavate a tunnel of the predefined length. Within this structure, the loop that contains the other two starts with the variable "*i*", which represents the number of the simulation currently under way, and it is given the starting value 1. The initial loop is "*WHILE* ($i \leqslant nsim$)", where "*nsim*" corresponds to the required number of simulations. Later, some variables are defined to begin the execution of the algorithm.

Variable "*dev*" is an auxiliary summand that is given the initial value 0 and increases in relation to the advance per blasting at the end of the second loop. The purpose of this variable is to control the simulation in relation to the length of tunnel excavation, executing the second loop until the desired length "*WHILE* ($dev \leqslant ltunnel$)" is reached, where "*ltunnel*" represents the length of the tunnel to be built.

The first loop also has the variable "*operation*", whose purpose is to identify the operation that will be performed in the third loop, which is adapted according to the operations of the construction cycle described by Suorineni et al. (2008). It should be mentioned that it is the only variable of the alphanumerical kind. The default value assigned in this location is "*op.1*", because it indicates the first operation of the cycle that is represented by the suffix 1. Every time it starts simulating the construction of the tunnel, it begins with the drilling, which is the first operation cycle.

The variable "*shift*" defines the work shifts required for the construction of the tunnel, and it is a counter that is modified at the end of the second loop, saving the data in a matrix "*S*" of dimensions equal to the number of required simulations, that will provide data for their later analysis.

Finally, variable "*t*", which is an auxiliary variable used to save the summation of times for the operations required to build the tunnel, is made equal to zero every time the construction of the tunnel begins, but it can also be initialized according to conditions that will be explained later, within the second loop.

3.2. Control of the advance of the simulated construction

The second loop controls that the advance of the simulated excavation does not exceed the proposed length, and to that end, the excavation is developed in the third loop, whose purpose is to control the duration of the cycle as a function of the duration of the work shift "*WHILE* ($t \leqslant (dt\text{-}tol)$)".

The verification expression is true as long as the summation of the duration of the operations cycle "*t*" is less than the duration of shift "*dt*" minus a tolerance time "*tol*", a variable which is an operational parameter that indicates if it is possible to continue with the following unit operation within the shift or if the operation goes to the following shift.

3.3. Calculation of the time of each unit operation

The duration of the cycle within the work shift is built successively through a "CASE" selection routine that attaches the time of each operation until the cycle is finished. Once a cycle ends, the following cycle can start within the same shift or can stop its execution to retake it at the following one. This depends on the operational tolerance "*tol*" estimated for the excavation of the tunnel, and at the time of applying the algorithm, will go deeper into this point.

The "CASE" routine included in the third loop has the function of arranging the operations so that they take place one after the other, at the same time that their time is evaluated according to the condition of the loop, in order to see if it is still within the duration of the chosen shift.

The time of each operation will belong to the PDs used to represent the process. In the present case, the variable "*DI.op.n*" will correspond to the inverse distribution of the operation mentioned in the suffix, in this case "*n*". This variable is a function of random numbers between 0 and 1.

The "*rand#*" variable, which represents random numbers between 0 and 1, generates the values of the operation, fitted to the distribution used according to what was pointed out by Sobol (1994). Once the operation has been executed, the variable "*operation*" will save the value of the following operation so that in the following iteration, produced by the "CASE", it keeps on advancing.

Once the third loop has ended, there is a routine condition that depends on whether the cycle ends together with the shift or is interrupted. This routine evaluates whether "*t*" is greater than "*dt*", which indicates to the algorithm if the other shift needs to add a restarting time for the activities "$t \leftarrow t\text{-}dt + beg$", where "*beg*" corresponds to the starting time, which is added as the shift ended by an interrupted activity meaning it was not included in any of the unit operations. The opposite case is that in which the activity ends within the shift, in which case it is not necessary to consider the restarting time. If appropriate, this restarting time must be added to the next sequence of the loop in the corresponding operation.

Also, at the end of the second loop, a work shift is added to the variable "*shift*", and the advance is added to the variable "*dev*", only if it has gone through the last operation in which the advance produced by the blasting "$av = Le * DI.rec(r\#) + av$" is found, where "$av$" reflects the meters of advance of the tunnel and "$DI.rec(r\#)$" is the inverse distribution of the percentage efficiency of the advance due to the blasting.

In this way, the successive simulations are built, delivering the time taken for the construction of each simulated tunnel, expressed in work shifts.

Given sufficient iterations, it will have a representative sample of the population from which the most probable duration for the construction of the tunnel can be inferred.

4. Application of the model at Compañía Minera San Pedro

Minera San Pedro Limitada (MSP) has several copper ore deposits in the Lohpan Alto district (Thomas, 1958; Thompson, 1992), located in the Coastal Range of Central Chile, in the Lo Prado and Veta Negra formations. One of these deposits is Mina Romero, in which the ore will be extracted by underground mining using the shrinkage exploitation method (Chen, 1998).

To gain access and prepare the mineralized body for its later exploitation, MSP has planned the construction of a 560 m horizontal access tunnel in a straight line, with a cross-section of approximately 3.5 m × 3.0 m.

To estimate the duration of the construction of this tunnel from experience of similar projects, MSP has considered that for every three work shifts of nine effective hours each, it would be able to carry out four cycles considering a hole depth of 1.8 m, which would mean a rate of advance of 2.4 m per shift, and considering two work shifts per day, an advance of 4.8 m/day would be achieved.

Considering the planed conditions, MSP has estimated that the project should take 117 days, even though previous experience in mines close to Mina Romero has shown that this planning is not quite precise because there are delays that are not always considered at the time of planning.

To apply the proposed methodology, obtaining data from zones of similar geological and operational characteristics as those of Mina Romero has been considered. For this purpose, there are some exploration tunnels made in the upper part of the deposit, with the same cross-section as the one that will be built and in rocks of similar characteristics to those of the access tunnel of Mina Romero.

For this purpose, the cycle has been divided into five activities: drilling, loading explosives and blasting, ventilation, scaling, and mucking. In MSP, there is no support installation because the rock is very strong. The Rock Mass Rating –RMR geomechanical classification of the rock mass (Bieniawski, 1976) carried out at the MSP indicates that the rock mass in the tunnel section is classified as very good rock (class 1) and no support is required.

The methodology for obtaining the times of the different activities of the excavation cycle in the exploration tunnels, was to measure each activity with chronometer by qualified personnel for three months. The quantity of used data for obtain the PD for each activity of the excavation cycle is 135 events, Table 1 shows the number of used data.

Table 1
Summary of statistical adjustment for operations units.

Unit operation	Used data	Parameters										Probability distribution
		Mean	Median	Mode	Standard deviation	Variance	Asymmetry	Kurtosis	Coefficient of Variability	Minimum	Maximum	
Drilling	137	195.45	193.89	190.23	38.08	1449.72	0.21	2.75	0.19	70.98	392.79	Beta
Load and blasting	133	56.09	55.76	54.98	11.64	135.58	0.14	2.72	0.20	14.77	113.51	Beta
Ventilation	136	90.00	90.00	90.00	1.00	1.00	–	–	–	–	–	Constant
Scaling	135	26.08	25.24	23.54	6.77	45.78	0.75	3.84	0.25	8.04	–	Lognormal
Mucking	135	70.03	65.66	58.33	20.22	408.77	1.69	8.48	0.28	30.95	–	Gamma

Table 2
Sensitivity analysis for iteration determination for the simulation.

No. iterations	Long tunnel (m)	Shifts duration (min)	Tolerance (min)	Reset (min)	Average (shifts)	Mode (shifts)	Standard deviation (shifts)	Minimum (shifts)	Maximum (shifts)
1.0E+05	560	540	60	30	266.89	267	2.31	257	277
2.0E+05	560	540	60	30	266.88	267	2.31	256	277
3.0E+05	560	540	60	30	266.89	267	2.31	256	278
4.0E+05	560	540	60	30	266.89	267	2.31	256	279
5.0E+05	560	540	60	30	266.89	267	2.31	256	277
1.0E+6	560	540	60	30	266.89	267	2.31	256	279

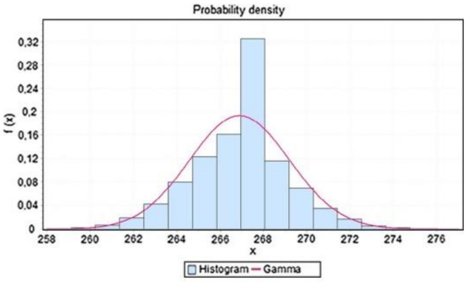


Fig. 5. Probability distribution for the simulation in Mine Romero.

After a period of measuring operational times in the exploratory work, each of the activities was characterized by means of statistical analysis that allows the determination of the PD that best fits the behavior of each activity. Table 1 shows a summary of the statistical analysis with the corresponding assigned PD. Ventilation was kept as constant in time.

Table 1 shows the results of the unit operations duration statistical analysis. The sampling was carried out in the field, and the data obtained for each operation was adjusted using the Anderson–Darling test in order to obtain their respective probability distribution function (PDF). All data expressed in minutes.

The distributions shown in Table 1 are those that were used to prepare the algorithm and will give rise to the simulated excavation times of the tunnel by means of the Monte Carlo method.

To carry out the simulation, making 10^5–10^6 iterations was considered. It was found that the variability between the first and the last simulation was not significant considering the mean and the mode of the results obtained.

Table 2 shows a sensitivity analysis for quantity of iterations in the simulation. It should be noted that above 10^5 iterations, the results stabilize, so the simulation was carried out using 10^5 iterations.

As stated in the simulation model, each simulated event consists of the construction of a tunnel of the given length, taking into account the duration of the shift and the tolerance to end the activities within the cycle. This means that if there is less time left than that specified for this item to finish the shift, the activities are suspended to be retaken on the following shift.

Finally, it is also necessary to consider the time for restarting the activities, which is the time required to redo the activities if the operation is interrupted by the end of the shift.

For the simulation, a section tunnel of 3.5 m × 3.0 m and a length of 560 m is considered, working with two shifts per day, each shift lasting 540 min, with a tolerance of 60 min, which represents the time between the end of one cycle and the end of the shift. If the tolerance time is less than 60 min, the activities end, and service activities or activities related to the operation such as cleaning are carried out.

Table 3
Summary of real data, planning data and simulation data.

Description	Cycles per shift	Advancement ratio (m/shift)	Daily advance rate (m/day)	Planned time (days)	Average shifts	% Error on real case
Planning	1.33	2.4	4.8	117	233	12.28%
Simulation	1.16	2.1	4.2	134	267	0.37%
Real	1.18	2.1	4.2	133	266	

Thirty minutes have been considered for restarting the activities, implying that if the cycle time lasts more than the shift time, this value is added to the cycle time because all the distributions presented in Table 1 consider the starting time of the activity, but not a restart due to the shift change. All the values considered correspond to experimental data from the experience of the operations area of MSP.

From the data presented in Table 1, and considering the simulation with 10^5 iterations, given that the difference compared to 10^6 iterations is negligible and it is easier for statistical software to handle, Fig. 5 shows the PD obtained.

Table 3 shows the real excavation time, the planning by MSP and the simulation, expressed in numbers of shifts. MSP used two shifts per day with a total 18 h effective working per day. It is possible to see how the data from the simulation is closer to reality than those obtained by conventional planning provided by MSP.

In contrast with the conventional planning method, which only determines one value for the required number of shifts, one of the advantages of the simulation method for the excavation time of tunnels presented in this study is that it makes it possible to get both pessimistic and optimistic scenarios with respect to the number of shifts needed to perform the job. These scenarios can be considered as the lower and upper limits of the confidence interval that describes the time for making the tunnel in shifts. In this case, the simulation gave an excavation time of 267 shifts, with a minimum value of 257 and a maximum value of 277 shifts (See Table 3).

Comparing the means of the simulation results, a 0.37% error was obtained, while the conventional planning method used by MSP gave 12.28% with respect to the actual excavation time. This difference is significant, because translated into days of execution it is seen that the conventional planning method used by MSP gives 16.5 days less than the time actually required, while the simulation gave a mean that differed from the actual excavation time by one day only.

5. Conclusions

A simulation methodology based on a Monte Carlo algorithm is presented that can estimate the time required for the excavation of a tunnel used in underground mining.

The data analysis obtained at MSP shows that this kind of stochastic simulation is a very effective tool for planning the excavation time of a tunnel.

Beside the accuracy of the means, the minima and maxima range obtained by the simulation is interesting because it delivers a practical parameter for setting planning criteria.

Based on the minimum and maximum range obtained by the simulation, optimistic and/or pessimistic scenarios can be presented that can serve as background for decision making in mining planning.

Because of the random nature of the excavation times of the activities involved in the mining works, it was determined that a planning methodology based on the Monte Carlo method fits reality much better than a conventional methodology, because operating by means of PDs incorporates the variability inherent to planning processes.

Through the incorporation of variability in mining planning it is possible to know with a greater degree of certainty the range over which the execution time of the work varies, and this makes it possible to decrease the financial risks associated with an error in the planning and at the same time maximize the utilization of the resources.

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References

Bieniawski, Z.R., 1976. Rock mass classification in rock engineering. In: Balkema, A.A. (Ed.), Proceedings of the Exploration for Rock Engineering, vol. 1. Cape Town, pp. 97–106.

Chen, X., 1998. Resuing shrinkage stoping. E&MJ-Engineering and Mining Journal 199 (10), 34–36.

Chiwaye, H.T., Stacey, T.R., 2010. A comparison of limit equilibrium and numerical modelling approaches to risk analysis for open pit mining. Journal of South African Institute of Mining and Metallurgy 110 (10), 571–580.

du Plessis, A., Brent, A.C., 2009. Development of a risk-based mine closure cost calculation model. Journal of the South African Institute of Mining and Metallurgy 106 (6), 443–450.

Fuksa, D., 2009. Managing cash for a mining company. Gospodarka Surowcami Mineralnymi-Mineral Resources Management 25 (1), 119–135.

Ghasemi, E., Shahriar, K., Sharifzadeh, M., Hashemolhosseini, H., 2010. Quantifying the uncertainty of pillar safety factor by monte carlo simulation – a case study. Archives of Mining Sciences 55 (3), 623–635.

Heuberger, R., 2005. Risk analysis in the mining industry. Journal of the African Institute of Mining and Metallurgy 105 (2), 75–79.

Khalokakaie, R., Dowd, P.A., Fowell, R.J., 2000. Incorporation of slope design into optimal pit design algorithms. Transactions of the Institution of Mining and Metallurgy Section A-Mining Technology 109, A70–A76.

Magda, R., Franik, T., 2008. Planning and design of rational parameters of longwall panels in underground hard coal mines. Gospodarka Surowcami Mineralnymi-Mineral Resources Management 24 (4), 107–117.

Metropolis, M., Ulam, S., 1949. The monte carlo method. Journal of the American Statistical Association 44 (247), 335–341.

Morin, M., Ficarazzo, F., 2006. Monte carlo simulation as a tool to predict blasting fragmentation based on the kuz-ram model. Computers & Geosciences 32 (3), 352–359.

Morley, C., Snowden, V., Day, D., 1999. Financial impact of resource/reserve uncertainty. Journal of the South African Institute of Mining and Metallurgy 99 (6), 293–301.

Sabour, S.A.A., Wood, G., 2009. Modelling financial risk in open pit mine project: Implications for strategic decision-making. Journal of the South African Institute of Mining and Metallurgy 109 (3), 169–175.

Sari, M., Karpuz, C., Ayday, C., 2010. Estimating rock mass properties using monte carlo simulation: Ankara andesites. Computers & Geosciences 36 (7), 959–969.

Simonsen, H., Perry, J., 1999. Risk identification, assessment and management in the mining and metallurgical industries. Journal of the African Institute of Mining and Metallurgy 99 (6), 321–329.

Singh, S.P., Xavier, P., 2005. Cause, impact and control of overbreak in underground excavation. Tunnelling and Underground Space Technology 20 (1), 63–71.

Sobol, I.M., 1994. A primer for the monte carlo method. CRC Press, Boca Raton, FL, pp. 107.

Suorineni, F.T., Kaiser, P.K., Henning, J.G., 2008. Safe rapid drifting-support selection. Tunnelling and Underground Space Technology 23 (6), 682–699.

Thomas, H., 1958. Geología de la cordillera de la costa entre el valle de la ligua y la cuesta barriga. Instituto de Investigaciones Geológicas, Santiago, Chile.

Thompson, D., 1992. The lohpan Project. Minera San Pedro, Santiago, Chile.

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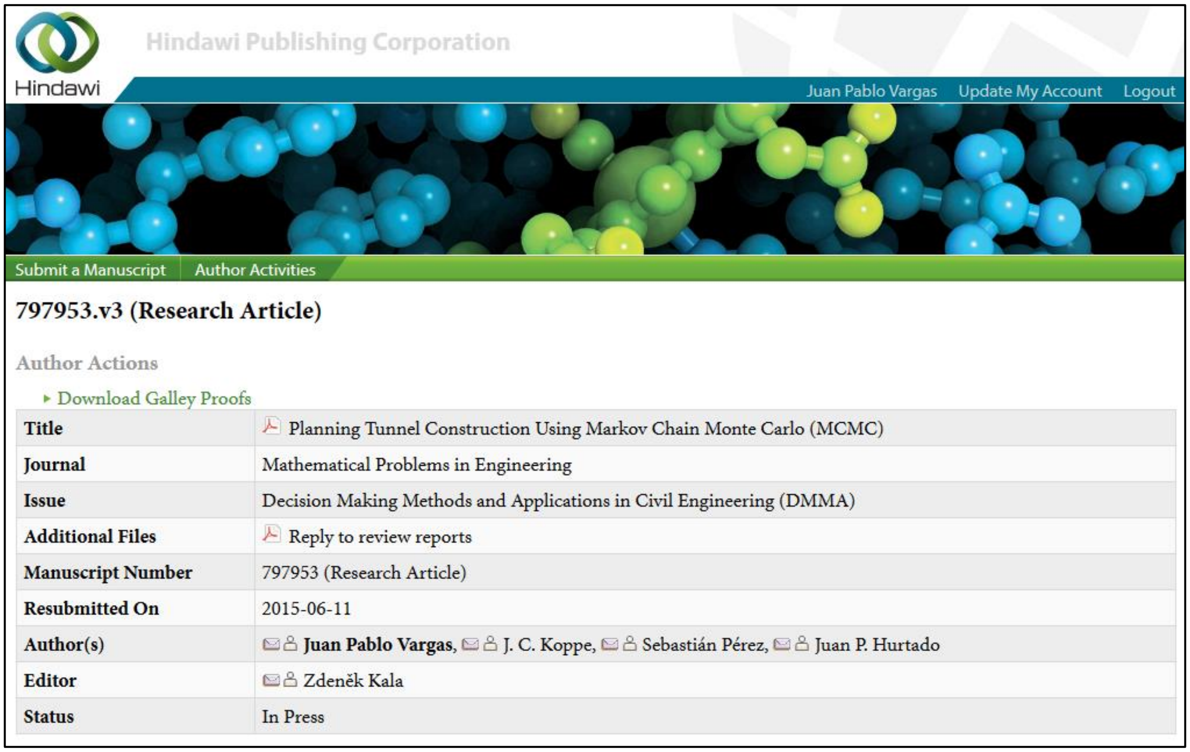

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Planning Tunnel Construction Using Markov Chain Monte Carlo (MCMC)

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Tunnels, drifts, drives, and other types of underground excavation are very common in mining as well as in the construction of roads, railways, dams, and other civil engineering projects. Planning is essential to the success of tunnel excavation, and construction time is one of the most important factors to be taken into account. This paper proposes a simulation algorithm based on a stochastic numerical method, the Markov chain Monte Carlo method, that can provide the best estimate of the opening excavation times for the classic method of drilling and blasting. Taking account of technical considerations that affect the tunnel excavation cycle, the simulation is developed through a computational algorithm. Using the Markov chain Monte Carlo method, the unit operations involved in the underground excavation cycle are identified and assigned probability distributions that, with random number input, make it possible to simulate the total excavation time. The results obtained with this method are compared with a real case of tunneling excavation. By incorporating variability in the planning, it is possible to determine with greater certainty the ranges over which the execution times of the unit operations fluctuate. In addition, the financial risks associated with planning errors can be reduced and the exploitation of resources maximized.

1. Introduction

Underground mining represents a fundamental pillar of ore production in Chile. It is assumed that in the coming years the proportion of underground mining compared with open-cast mining will increase as mineral resources accessible to surface exploitation become progressively exhausted.

One of the main activities involved in underground mining is tunnel construction, or, more generally, horizontal works, because this produces the infrastructure that provides access to the ore for extraction. Here, a "tunnel" should be understood as any underground excavation whose purpose is to join two points.

Given the importance of tunnels for mining, it is evident that there is a need to have a methodology that allows accurate planning of their excavation. To achieve this goal, the Markov chain Monte Carlo (MCMC) method is appropriate, since the construction of a tunnel is a cycle of activities consisting of unit operations, each of which exhibits a variability that can be represented in terms of a probability distribution function (PDF). Furthermore, the success or failure of the construction cycle is related to its actual duration compared with what was planned, which also depends on the time at which the cycle begins within the day's work shift. Thus, the construction cycle of a tunnel is dependent on the success or failure of the immediately preceding cycle, and therefore the event's probability of success is related to its predecessor, constituting an MCMC relation [1].

2. Tunnel Construction

There are several methods of tunnel excavation. This paper will focus on the construction of tunnels by drilling and blasting [2]. This technique involves an excavation or work cycle comprising a number of different activities. Suorineni et al. [3] mention the following unit operations: drilling of the tunnel surface, loading of explosives and blasting, ventilation (considered as an interference within the cycle), scaling and

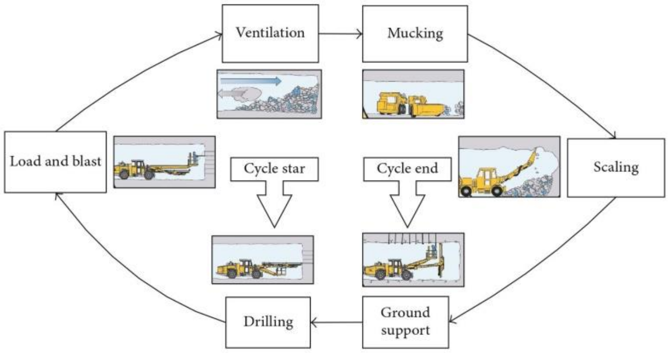

FIGURE 1: The drilling and blasting cycles in tunneling.

loading of the blasted material, and fortification (bolts, nets, and shotcrete, among others). Figure 1 illustrates the drilling and blasting cycles involved in tunneling.

The aim of the excavation cycle is to break up the rock with explosives, giving the required cross-sectional shape while the tunnel advances proportionally to the length of the drilling in the tunnel face. In this way, with successive cycles, the infrastructure is built gradually until the tunnel has been completed. However, even with knowledge of the number of unit operations in each cycle, and the time generally taken to perform each one, it is very difficult to determine exactly the total time required to complete the construction of the tunnel, mainly because all of the operations are subject to variations that depend on unforeseen events (although they can be associated with a probability of occurrence).

On the other hand, the work cycles, and therefore each of the unit operations, are executed within well-defined time periods (work shifts), which are framed within a 24-hour period. Usually, mining operates in continuous time periods without stoppages in production, and therefore tunnel construction proceeds in the same continuous manner. This is particularly important because the relation between the duration of the construction cycle and the period defined for the work shift will affect the efficiency of the cycle. Some of these inefficiencies result from changes in work shift that interfere with the working cycle. That is why Chilean law [4] specifies several types of work shifts, with various configurations as shown in Table 1. The choice among these is made on the basis of the estimated duration of the tunnel's construction cycle. For example, if the cycle time is estimated as less than 8 hours, the work shift that fits this best should be used, in this case T1 (Table 1), because this allows three cycles per day and thus a more rapid advance of the tunnel.

TABLE 1: Configuration of evaluated shifts.

Shift ID	Shifts per day	Hour per shift	Effective hours per day
T1	3	8	24
T2	2	10	20
T3	2	12	24

3. Planning of Tunnel Construction

Currently, to plan the construction of a tunnel, whatever its purpose, fixed values of the relevant parameters are used, giving consistent results. This is reflected in the following equation, which gives the construction speed of the tunnel in days related to the drilling length unit (RA) in terms of the drilling length (Lp), weighted by the effectiveness of the blasting (Ed), divided by the sum of the times for the unit operations in hours (Tp), and divided in turn by a factor that involves the unproductive times (Ti) in relation to the 24 hours of the day:

$$RA = \frac{Lp \times Ed}{\left[\left(\sum_{i=1}^{n} Tp_i\right) / \left(24 - \sum_{p=1}^{m} Ti_p\right)\right]}. \tag{1}$$

Then, with knowledge of the length of the tunnel (Lt), the execution time (D) is given by

$$D = \frac{Lt}{RA}. \tag{2}$$

The results obtained with this approach have until now always been used to plan this type of construction, but they can be improved by including the variability of each of the unit operations involved.

4. Monte Carlo Method and Tunnel Construction Planning

As already mentioned, tunnel construction involves excavation cycles consisting of unit operations that can be represented by PDFs, and it is clear that this process can be simulated using a Monte Carlo method [5]. With this approach, an excavation cycle (De) is simulated as follows:

$$\begin{aligned} De &= F^{-1}_{op(1)}\left(r\#_{(1)}\right) + F^{-1}_{op2}\left(r\#_{(2)}\right) + \cdots + F^{-1}_{op(n)}\left(r\#_{(n)}\right), \\ De &= \sum_{i=1}^{n} F^{-1}_{op(i)}\left(r\#_{(i)}\right), \end{aligned} \tag{3}$$

where F^{-1}_{op} is the inverse probability function of each of the n unit operations and $r\#$ is a pseudorandom number between 0 and 1.

Assuming that the number of excavation cycles required to construct the total length of the tunnel is known, since the advance achieved in each cycle is determined by the drilling length, which remains unchanged throughout the construction, the theoretical time taken for construction (Ds) is given by the following equation:

$$Ds = \sum_{j=1}^{k} \sum_{i=1}^{n} F^{-1}_{op(i)}\left(r\#_{(i)}\right), \tag{4}$$

where k is the number of cycles. For the model presented in (4) to represent reality, it is necessary to include in the construction of the PDFs the unproductive times and inefficiencies associated with each activity.

However, the duration of tunnel construction cannot be estimated using the Monte Carlo method alone, because this method does not take account of an aspect that is extremely important, namely, the fact that the probability of success of a cycle depends on the preceding cycle.

5. Application of Markov Chains

As already mentioned, the use of Markov chain theory is appropriate in this context, considering the characteristics of tunnel construction. Construction in mining takes place continuously 24 hours per day, and in general the working day is broken up into two or three periods (shifts), depending on the chosen workday (see Table 1) and as permitted by Chilean law [4]. Taken into account this work structure, tunnel construction in mining is faced with some particular problems that are mainly the result of inefficiencies due to changes of work teams and their transfer to the working areas.

In underground mining, owing to the specific characteristics of the work, excavation cycles are generally kept as multiples of working shifts, for a duration of less than 8 hours, for example, with preference being given to a T1 type of shift over T2 or T3 (Table 1), so that three cycles per day can be run.

It is possible that, owing to particular aspects of operational interference or inefficiency, an excavation cycle will not fit the established workday, increasing the duration of the cycle and affecting the next cycle. On the other hand, if success in the execution of an excavation cycle is represented by its completion within the established work shift or group of work shifts (with the cycle otherwise being considered a failure), then this condition in turn reduces the possibility of success of the following shift, because it takes time away from the latter and furthermore adds unproductive time due to activities interrupted as a result of the change of work. These situations can be considered as processes that can be modeled using Markov chain theory [1].

The algorithm presented in (4) cannot model such behavior, because it is unable to determine the simulation time of an excavation cycle as a function of the duration of the work shift. Therefore, to incorporate this behavior, it is necessary to have an algorithm for evaluating this simulation time.

6. Simulation Algorithm

To predict tunnel construction time, the Monte Carlo method appears to be an appropriate tool to use together with the Markov chain principle, given that it is a stochastic simulation that allows analysis of complex systems with several degrees of freedom. The Monte Carlo method [5] has become one of the most common ways to solve complex mathematical problems by random sampling [6–10]. It consists in generating random or pseudorandom numbers that are entered into an inverse distribution function, delivering as a result as many scenarios as the number of simulations performed [11]. The estimation will be the more precise the greater the number of iterations that can be done.

To use the Monte Carlo method, the unit operations are identified and each is assigned a PDF that depends on its nature and on the results of field sampling.

If the inverse functions of the PDFs of each unit operation of the excavation cycle are fed with random numbers, they will give as a result the duration of each operation. If the times thus obtained are added, this gives the total duration of the excavation cycle.

Once we know the duration of the excavation cycle, we must also consider another very important variable, namely, the distance advanced, or the real advance, after blasting (Le). This distance can also be described by a PDF, since it corresponds to the drilling distance (Lp) as affected by the blasting efficiency (Ed), as shown in (1). The drilling distance is a fixed value that depends on the characteristics of the drilling equipment, but the efficiency of the blast depends on the condition of the rock, variations in geological structure, and the characteristics of the explosive used, among other things, making this parameter vary from one blast to another.

Thus, if the durations of all the excavation cycles and the corresponding distances advanced are known, it is possible to determine the time taken for tunnel construction. Simulating this as many times as possible, a large number of scenarios are produced, generating a PDF of the time taken for tunnel construction.

The algorithm (see Algorithm 1) is composed of three loops, which control the number of simulations required, the required tunnel length, and the existing relation between the duration of the work shift and that of the tunnel excavation cycle. This point is fundamental for this work, being very important when it comes to choosing the best shift configuration to use. All these items are necessary to allow the simulation of the total construction time.

The proposed scheme consists of three inclusive loops dependent on each other. The operating form is that the first

```
BEGIN
$i \leftarrow 1$
WHILE ($i \leq$ nsim)
    $dev \leftarrow 0$
    $operation \leftarrow op.1$
    $shift \leftarrow 1$
    $t \leftarrow 0$
        WHILE ($dev \leq ltunnel$)
            $av \leftarrow 0$
            WHILE ($t \leq (dt - tol)$)
                CASE operation
                    op.1
                        $t \leftarrow t + DI.op.1(rand\#)$
                        $operation \leftarrow op.2$
                    op.2
                        $t \leftarrow t + DI.op.2(rand\#)$
                        $operation \leftarrow op.3$
                        ⋮
                    op.$n$
                        $t \leftarrow t + DI.op.n(rand\#)$
                        $operation \leftarrow op.1$
                        $av \leftarrow Le * DI.rec(rand\#) + av$
                END CASE
            END WHILE
            IF ($t > dt$)
                $t \leftarrow t - dt + beg$
              ELSE
                $t \leftarrow 0$
            END IF
            $shift \leftarrow shift + 1$
            $dev \leftarrow dev + av$
        END WHILE
    $s(i) \leftarrow shift$
    $i \leftarrow i + 1$
END WHILE
END
Variables:
nsim: number of simulation
ltunnel: lenght of tunnel (meters)
DI.op.m: inverse distribution of operation unit "m"
DI.rec: inverse distribution of efficiency of the blast
Le: lenght of the drilling
dt: during of the work shift (minutes)
rand#: random number.
```

ALGORITHM 1: Algorithm to simulate tunnel excavation time.

loop, which contains the other two, controls the number of required simulations, on the basis that each simulation is the construction of a tunnel with specified length.

The second loop imposes the condition that the construction does not exceed the defined tunnel length, with every advance being estimated by the PDF of the performance of the blast multiplied by the drilling length. The drilling length is a fixed value, and is added consecutively until the required tunnel length is achieved.

Finally, the third loop has the function of adding consecutively the times for the unit operations in each cycle and comparing this total time with the established work shift, a fundamental aspect of this work.

This last loop is the key to the simulation, because it constructs the cycle within the shift. This procedure is carried out using the Monte Carlo method, where the inverses of the PDFs associated with the execution times of the unit operations are applied. The times obtained from this simulation are added, and it is determined whether the cycle can finish during the operating shift.

The proposed simulation algorithm is detailed in the following section.

6.1. Control of the Number of Simulations. As already mentioned, the function of the first loop is to control the number of simulations required, taking into account that each simulation estimates the time required to build a tunnel with an already defined length. This loop, which contains the other two, starts with the variable "i," which represents the number of the simulation under way and is initially assigned the value 1. The first loop is "*WHILE* ($i \le nsim$)," where "*nsim*" corresponds to the number of required simulations.

Some variables are then defined to start the execution of the algorithm. The variable "*dev*" is an auxiliary adder that is assigned an initial value of 0 and is increased in relation to the advances per blasting at the end of the second loop. The purpose of this variable is to control the simulation in relation to the tunnel length built, executing the second loop until the desired length "*WHILE* ($dev \le ltunnel$)" is achieved, where "*ltunnel*" represents the length of the tunnel to be built.

In the first loop, there is the variable "*operation,*" whose purpose is to identify the operations that will be performed in the third loop and that are adapted according to the operations of the construction cycle described by Suorineni et al. [3]. It should be noted that this is the only alphanumeric variable. The value assigned by default in this location is "*op.1,*" since it indicates the first operation of the cycle, which is represented by the suffix 1. Every time that we begin simulating the construction of the tunnel, we will start with drilling, the first operation of the cycle.

On the other hand, the variable "*shift*" defines the work shifts required for the construction of the tunnel, and it is a counter that is modified at the end of the second loop, storing the data in a matrix "*S*" that is of dimension equal to the number of required simulations and that will provide the data for later analysis.

Finally, the variable "t," an auxiliary variable used for storing the sum of the times of the operations required for the tunnel construction, is set equal to zero every time the tunnel construction starts, but it can also be initialized, depending on conditions that will be explained later, within the second loop.

6.2. Control of the Simulated Construction Advance. The second loop imposes the condition that the simulated construction advance does not exceed the proposed length, and to that end the construction takes place in the third loop, whose purpose is to control the duration of the cycle in terms of the duration of the work shift "*WHILE* ($t \le (dt - tol)$)."

The verification expression is true as long as the sum of the times of the cycle's operations "t" is less than the duration of the shift "dt" minus a tolerance time "*tol*." This last variable is an operational parameter that indicates if it is possible to continue with the next unit operation within the shift or if the operation is to be passed to the following shift.

6.3. Calculation of the Time for Each of the Unit Operations. The cycle's duration in the work shift is built successively in a selection routine "CASE" that adds the time for each operation until the end of the cycle; then, the following cycle can start again within the same shift or stop the execution to retake it on the following shift, and this depends on the operational tolerance "*tol*" that is estimated for the execution of the tunnel. We will go into this point more deeply when we apply the algorithm.

The "CASE" routine in the third loop has the function of arranging the operations so they take place one after the other and also of evaluating the time taken under the loop's condition, in order to see if this is still within the duration of the chosen shift.

The times for each operation belong to the probability distributions used to represent the process. In our case, the variable "*DI.op.n*" corresponds to the inverse distribution of the operation specified in the suffix, in this case "n," and this variable is a function of random numbers between 0 and 1.

By means of the variable "*rand#,*" which represents random numbers between 0 and 1, the values of the operation are generated and fitted to the distribution used, as pointed out by Sobol [11]. Once the operation has been executed, the variable "*operation*" stores the value of the following operation so that, in the next iteration, as a result of "CASE," it keeps advancing.

At the end of the third loop, there is a conditioning routine depending on whether the cycle ends together with the shift or is interrupted. This routine evaluates whether "t" is greater than "dt," telling the algorithm whether the next shift should add an activity restarting time "$t \leftarrow t - dt + beg$," where "*beg*" corresponds to the restarting time, which is not included in any of the unit operations. If the shift ends cutting an activity, this restarting time is added. In the opposite case, where the activity ends within the shift, it is not necessary to add the restarting time. If appropriate, this restarting time will be added to the next sequence of the loop in the corresponding operation.

Also, at the end of the second loop, a work shift is added in the variable "*shift,*" and the advance is added in the variable "*dev*" only if it has gone through the last operation where the advance caused by the blasting, "$av = Le * DI.rec(r\#) + average$," is found, where "*av*" reflects the advance of the tunnel (in meters) and "*DI.rec(r#)*" is the inverse distribution of the percentage efficiency of the advance caused by the blast.

In this way, the successive simulations are constructed, delivering the time taken for each simulated tunnel, and accounted for in work shifts.

Taking in account the possibility of iterating as many times as necessary, we will have a representative sample of the population from which we can infer the most probable duration of the tunnel's construction.

7. Application of the Algorithm to Tunnel Construction

Minera San Pedro Limitada (MSP) has several copper ore deposits in the Lohpan Alto district, located in the Coastal Range of Central Chile. One of these deposits is Mina Romero, where the ore will be removed by underground mining [12].

To gain access and prepare the mineralized body for its exploitation, MSP has planned the construction of a 560 m access tunnel with no slope and in a straight line, with a cross section of approximately 3.5 m × 3.0 m.

The equipment used for drilling is an electrohydraulic drill of 45 mm diameter and the explosives are ammonium nitrate-fuel oil (ANFO) and Tronex (a derivative of dynamite), initiated by a nonelectrical shock tube detonator (NONEL). The mucking equipment is a load haul dump (LHD) of 6 yd^3.

To estimate the duration of construction of this tunnel, MSP, based on its experience in similar projects, has considered that, for every three work shifts with a duration of 9 actual hours each, it is able to carry out four cycles with a drilling length of 1.8 m, giving a rate of advance of 2.4 m per shift, so, with two work shifts per day, an advance of 4.8 m/day would be achieved.

Taking the above figures into account, MSP has estimated that the project should take 117 days, although previous experience in mines close to Mina Romero has shown that this estimate is not precise, because there are often delays that have not been considered at the time of planning.

To apply the proposed methodology, data from areas with similar geological and operational characteristics to those that will be faced in Mina Romero have been used. For that purpose, exploratory tunnels have been made in the upper part of the deposit, with the same cross section of the one that will be built and in rocks with similar characteristics to those of the Mina Romero access tunnel.

The cycle has been divided into five activities: drilling, loading and blasting, ventilation, scaling, and mucking. Support is not considered, because of the good quality of the rock. The rock mass rating (RMR) geomechanical classification of the rock mass [13] carried out by MSP indicates that the rock mass in the tunnel section can be classified as very good rock, with RMR over 85 points (class 1), and so no support is required.

After measurements had been made of the operational times of the cycle in the exploratory activities with characteristics similar to those that will be simulated, under the guidance of the Engineering Department of MSP, each of the activities was characterized in a statistical analysis that allowed determination of the probability distribution that best fitted the performance of each of the unit operations. Table 2 shows a summary of the statistical analysis, with the corresponding assigned PDFs.

Ventilation was kept constant in time, because MSP provides lunch for workers at the same time, and the duration of both lunch and ventilation is 90 min.

The distributions shown in Table 2 are those that were used to produce the algorithm and will be used in the Monte Carlo simulation of the tunnel construction time.

In general, the analysis presented in Table 2 is based on data obtained from field sampling, and the fitting was made by MSP, who are solely responsible for the data handling, but it should be noted that the fitting of the probability distribution curves was done by the Anderson-Darling method.

The simulation is involved between 10^5 and 10^6 iterations. It was found that the variability between the first and last simulations from this interval was not significant, considering the mean and the mode of the results (see Table 3), so it is believed that all the results delivered by simulation beyond 10^5 iterations are good.

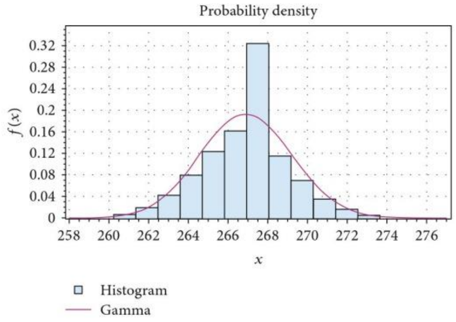

Figure 2: Probability distribution for the simulation in Mina Romero.

As stated in the model, every simulated event involves the construction of a tunnel with the specified length, taking into account the duration of the shift and the tolerance ("Tolerance" in Table 3) to ending the activities within the cycle. This means that less time is left rather than stipulated in this item to end the shift, so the activities are suspended and are taken up by the following shift.

Finally, it is also necessary to consider the restarting time ("Reset" in Table 3) of the activities, which corresponds to the time required to resume activities if the operation is interrupted by the end of the shift.

Both the tolerance and the restarting time can be modeled as Markov chain processes [1], because the success or failure of an event has an effect on the following one.

For the simulation, a tunnel of 3.5 m × 3.0 m with a length of 560 m is considered, with two work shifts per day, each of 540 min duration, with a tolerance of 60 min, which represents the time between the end of a cycle and the end of the shift. If the tolerance time is less than 60 min, the activities are finished and service or other activities related to the operation, such as cleaning, are carried out.

A 30 min time is considered for resumption of activities, implying that if the cycle time is longer than the shift time, this value is added to the cycle time, because all the distributions presented in Table 1 consider the starting time of the activity, but not a restart caused by a shift change. The considered values correspond to expert data coming from the experience of MSP in the operations area.

8. Analysis of the Results

According to the data presented in Table 3, and considering a simulation with 10^5 iterations (the difference compared with a simulation with 10^6 iterations is negligible and the shorter simulation is easier to handle with the available statistical software), Figure 2 shows the probability distribution obtained for the simulation in Mina Romero.

Table 2: Summary of statistical adjustment for unit operation.

Unit operation	Parameters								Probability Distribution
	Used data	Mean	Median	Mode	Standard deviation	Coefficient of variability	Minimum	Maximum	
Drilling	137	195.45	193.89	190.23	38.08	0.19	70.98	392.79	**Beta**
Load and blasting	133	56.09	55.76	54.98	11.64	0.20	14.77	113.51	**Beta**
Ventilation	136	90.00	90.00	90.00	0	—	—	—	**Constant**
Scaling	135	26.08	25.24	23.54	6.77	0.25	8.04	—	**Lognormal**
Mucking	135	70.03	65.66	58.33	20.22	0.28	30.95	—	**Gamma**

Table 3: Sensitivity analysis for iteration determination for the simulation.

Number of iterations	Tunnel length (m)	Shift duration (min)	Tolerance (min)	Reset (min)	Average (shifts)	Mode (shifts)	Standard deviation (shifts)	Min. (shifts)	Max. (shifts)
$1.0E+05$	560	540	60	30	266.89	267	2.31	257	277
$2.0E+05$	560	540	60	30	266.88	267	2.31	256	277
$3.0E+05$	560	540	60	30	266.89	267	2.31	256	278
$4.0E+05$	560	540	60	30	266.89	267	2.31	256	279
$5.0E+05$	560	540	60	30	266.89	267	2.31	256	277
$1.0E+6$	560	540	60	30	266.89	267	2.31	256	279

In contrast to the conventional planning method, which determines one value for the required number of shifts, one of the advantages offered by the simulation method presented here is that it is possible to have both pessimistic and optimistic scenarios with respect to the number of shifts required for carrying out the work. These scenarios can be considered as the lower and upper limits of the confidence interval that describes the construction time for the tunnel under study in shifts.

The simulation produces a histogram with a mean of 266.89 shifts, a mode of 267 shifts, a median of 267 shifts (with a minimum of 257 and a maximum of 277), and a standard deviation of 2.31, with a distribution that is symmetric in form. This histogram is fitted into a gamma distribution (Figure 2) with parameters $\alpha_1 = 7.4145$, $\alpha_2 = 8.4196$, $a = 257$ (minimum), and $b = 277$ (maximum). The curve was fitted using the Anderson-Darling method, as mentioned earlier.

For the case in question, 267 shifts, which is the value of the mean as well as the median and the mode, were considered. It was decided to use this value because it is a good representation of the simulated case and is the most repeated value. Figure 3 shows the probability distribution for the simulation in Mina Romero, and from this curve, it is possible to obtain the probability of success, in this case 0.6 (60%).

The gamma distribution is not of symmetrical type, but in this case is the best fit to the simulation data using the Anderson-Darling method—this is why the mean probability of success is 60% rather than 50%. Figure 2 shows that the mean is not in the middle of the curve, and this is confirmed by Figure 3.

Once the tunnel construction, which took 133 days, was finished, the means resulting from the simulation could be compared with the MSP plans and with the actual data (Table 4), revealing an error of 0.37% compared with the real time, while with the conventional planning method used by MSP the error was 12.28% with respect to the actual construction time. This difference is significant because, when it is translated into execution days, it can be seen that the conventional planning method used by MSP underestimated by 16.5 days the time required, whereas the simulation gave a mean differing by only one day from the real execution time. When the standard deviation is considered, we have a quite precise tool for planning, because the value considered is 267 ± 3 shifts.

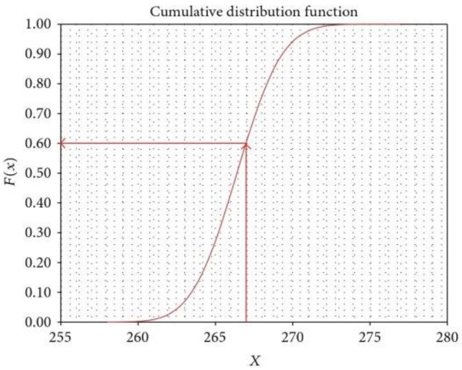

Figure 3: Cumulative distribution function of simulated data.

TABLE 4: Summary of real data, planned data, and simulation data.

Description	Cycles per shift	Advance rate [m/shift]	Daily advance rate [m/day]	Planned time [days]	Average shifts	% Error with real case
Planning	1.33	2.4	4.8	117	233	12.28%
Simulation	1.16	2.1	4.2	134	267	0.37%
Real	1.18	2.1	4.2	133	266	

It should be mentioned that the plan made by the Engineering Department of MSP is not represented in the histogram shown here. A more careful analysis would show that there is no event similar to what was planned and indeed that it would be very difficult for the event planned by the mining company to occur.

As can be seen, this simulation methodology based on the Monte Carlo method can estimate the time required for the construction of a tunnel used in underground mining.

9. Conclusions

The data analysis performed at MSP shows that this kind of stochastic simulation is a very effective tool for planning the construction time of a tunnel.

Beyond the accuracy of the means, the range of minima and maxima obtained by the simulation is interesting, because it delivers a potentially useful parameter for establishing planning criteria.

Based on the minimum and maximum values obtained from the simulation, optimistic and/or pessimistic scenarios can be proposed that they can serve as background information for making mine planning decisions.

Because of the random nature of the execution times of the operations involved in mining construction, it has been determined that a planning methodology based on the Monte Carlo method provides a better fit to real conditions than a conventional approach, because, with its use of probability distributions, it incorporates the variability inherent in the planning process.

By incorporating variability into planning, it is possible to determine with greater certainty the ranges over which the execution times of the different operations fluctuate. It is thereby possible to reduce the financial risks due to planning errors while maximizing the exploitation of resources.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] F. S. Hillier and G. Lieberman, "Markov chain," in *Introduction to Operations Research*, pp. 675–682, McGraw-Hill, 9th edition, 2010.

[2] S. P. Singh and P. Xavier, "Causes, impact and control of overbreak in underground excavations," *Tunnelling and Underground Space Technology*, vol. 20, no. 1, pp. 63–71, 2005.

[3] F. T. Suorineni, P. K. Kaiser, and J. G. Henning, "Safe rapid drifting—support selection," *Tunnelling and Underground Space Technology*, vol. 23, no. 6, pp. 682–699, 2008.

[4] Gobierno de Chile, *Código del Trabajo, Capítulo IV 'De la jornada de trabajo'*, Gobierno de Chile, 2012.

[5] N. Metropolis and S. Ulam, "The Monte Carlo method," *Journal of the American Statistical Association*, vol. 44, no. 247, pp. 335–341, 1949.

[6] H. T. Chiwaye and T. R. Stacey, "A comparison of limit equilibrium and numerical modelling approaches to risk analysis for open pit mining," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 110, no. 10, pp. 571–580, 2010.

[7] E. Ghasemi, K. Shahriar, M. Sharifzadeh, and H. Hashemolhosseini, "Quantifying the uncertainty of pillar safety factor by Monte Carlo simulation—a case study," *Archives of Mining Sciences*, vol. 55, no. 3, pp. 623–635, 2010.

[8] R. Khalokakaie, P. A. Dowd, and R. J. Fowell, "Incorporation of slope design into optimal pit design algorithms," *Transactions of the Institution of Mining and Metallurgy Section A: Mining Technology*, vol. 109, no. 2, pp. A70–A76, 2000.

[9] M. A. Morin and F. Ficarazzo, "Monte Carlo simulation as a tool to predict blasting fragmentation based on the Kuz-Ram model," *Computers & Geosciences*, vol. 32, no. 3, pp. 352–359, 2006.

[10] M. Sari, C. Karpuz, and C. Ayday, "Estimating rock mass properties using Monte Carlo simulation: ankara andesites," *Computers and Geosciences*, vol. 36, no. 7, pp. 959–969, 2010.

[11] I. M. Sobol, *A Primer for the Monte Carlo Method*, CRC Press, Boca Raton, Fla, USA, 1994.

[12] X. Chen, "Resuing shrinkage stoping," *Engineering & Mining Journal*, vol. 199, no. 10, pp. 34–36, 1998.

[13] Z. R. Bieniawski, "Rock mass classification in rock engineering," in *Proceedings of the Exploration for Rock Engineering*, pp. 97–106, A.A. Balkema, Cape Town, South Africa, 1976.

3.3.- Estimation of tunnel excavation time as a function of the configuration of operational shifts using stochastic simulation - Revista "Tunnelling and Underground Space Technology" (Presentado).

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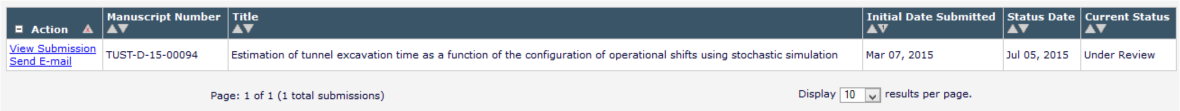

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Estimation of tunnel excavation time as a function of the configuration of operational shifts using stochastic simulation

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Keywords: Planning; tunnels; shift configuration; stochastic simulation; Monte Carlo.

Abstract

Considering only Chile, every year about 70,000 meters of tunnels of different sizes are developed for use in mining. The investments required for these infrastructure works are in the order of 70 million dollars per year.

For the mining industry this type of infrastructure is fundamental to allow access to the mineralized zones and prepare the exploitation units for the later extraction of the mineral.

Therefore, every aspect that improves the time required for the construction of these kinds of infrastructure would favor any mining project, and one of the most sensitive aspects for estimating the time taken for the construction of a tunnel is the configuration of the work shifts. This study deals with three types of shift configurations, which correspond to those used in Chile by the mining industry.

A stochastic simulation algorithm based on the Monte Carlo method and on Markov's Chain theory is proposed to find the shift configuration that improves the tunnel construction time.

The tunnel excavation cycle was characterized statistically considering a probability density function (PDF) for every unit operation, and through a simulation algorithm developed for that purpose it will represent the tunnel excavation time associated with a histogram of the process. After evaluating all the existing shift configurations, it is possible then to decide which one is the most favorable for tunnel construction.

The result obtained from the model is a histogram of the total tunnel excavation time that is directly related to the duration of the shifts. This model was applied in the San Pedro mine in Chile.

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1. Introduction

Development of ramps, tunnels, shaft, drives or other underground excavations is highly important especially in mining, because fulfilling production goals is strongly linked with the availability of works that allow access to the mineralized zones, and these accesses are built through tunnels (Suorineni *et al.*, 2008).

For the mining industry this type of infrastructure is fundamental to allow access to the mineralized zones and prepare the exploitation units for the later extraction of the mineral.

Therefore, every aspect that improves the time required for the construction of these kinds of infrastructure would favor any mining project, and one of the most sensitive aspects for estimating the time taken for the construction of a tunnel is the configuration of the work shifts.

Considering only Chile, every year about 70,000 meters of tunnels of different sizes are developed for use in mining. The investments required for these infrastructure works are in the order of 70 million dollars per year.

One of the most important components of tunnel construction cost is personnel and equipment, and this cost in turn is closely related to excavation time. Mining personnel usually work in shifts which vary in terms of hours per shift and number of continuous days of work. The shift combinations used in this study are those allowed by Chilean law (Gobierno de Chile, 2013), but this does not preclude applying this methodology to other shift systems not considered in this study.

The present research involves a sensitivity analysis of the various shift configurations carried out by Monte Carlo simulations that will make use of the algorithm proposed by Vargas *et al.* (2014) that is schematized in Figure 1. It will allow the determination of the tunnel's excavation time and the most favorable shift configuration for the development of the project considering construction speed.

The research made by Vargas et al. (2014) shown a relation with real data of the construction time versus the planning and simulation data. The result showed a best approach to reality by simulation data (error lower than 1%) than planning (error upper to 12%). In this case the work shift configuration used was T2 (Table 1).

2. Tunnel Excavation

To carry out these kinds of works there are several methods and the present study is focused on tunnel excavation by drilling and blasting. This technique consists of an excavation cycle composed of different activities (Suorineni *et al.*, 2008) that involve the following unit operations: drilling, loading explosives & blast, ventilation (considered as an interference within the cycle), scaling, mucking and ground support (bolts, mesh, shotcrete, among others).

Table 1. Configuration of evaluated shift.

Shift ID	Shifts per day	Hour per shift	Effective hours per day
T1	3	8	24
T2	2	10	20
T3	2	12	24

It is important to consider that even knowing the incidence of each of the unit operations in the excavation cycle, it is very difficult to know exactly the total time that it would take, and therefore the time that the tunnel's construction will take, because all the activities have variations that depend on unforeseen events that can however be associated with a probability of occurrence.

To carry out the present study the unit operations described and used by Vargas *et al.* (2014) have been considered. They are: drilling, loading explosives & blast, ventilation, scaling and mucking. Ground support was not included in this case study because the rock quality is good and doesn't require any kind of support during the tunnel excavation. We must consider that the duration of the cycle is the sum of all the unit operations mentioned above, and that is why there is direct incidence of shift duration in the planning of tunnel construction.

3. Simulation Algorithm

The excavation time was simulated using the Monte Carlo method as a tool for predicting the time needed for tunnel construction, keeping in mind that it is a stochastic simulation that allows analyzing complex systems with various degrees of freedom. This method is commonly used to solve complex mathematical problems by random sampling (Metropolis & Ulam, 1949), becoming one of the most common methods for carrying out this kind of analysis (Chiwaye *et al.*, 2010; Ghasemi *et al.*, 2010; Khalokakaie *et al.*, 200; Morin & Ficarazzo, 2006; Sari *et al.*, 2010). It consists in generating random or pseudo-random numbers that are entered in an inverse distribution function, giving as result as many scenarios as the number of simulations carried out (Sobol, 1994). The estimation will be the more precise the greater the number of iterations that can be made.

To use the Monte Carlo method the unit operations described previously were identified, and to them are assigned statistical distributions depending on the nature of the unit operation and the result of the field sampling.

Feeding the probability distribution functions (PDF) to each one of the excavation operations cycle with random numbers, the result will be the time taken by each unit operation. Adding the times results in the total duration of the excavation cycle.

Once the duration of the excavation cycle is known, another very important variable must be taken in account, the advance length or real advance after the blasting (Le). This length is also related to a PDF, because it corresponds to the drilling length (Lp) multiplied by the efficiency of the blasting (fd%) (Le = Lp × fd%). The drilling length is a fixed value that depends on the characteristics of the drilling equipment, but the efficiency of the blast depends on the conditions of the rock, the structures, explosives and the blast planning, among others, causing this parameter to vary from one blasting to another.

Then knowing the time taken by all the excavation cycles and their corresponding advance lengths, we can know the tunnel construction time. Performing this operation as many times as possible a large number of scenarios will be built, generating a PDF of the tunnel construction duration.

The algorithm (see Figure 1) consists of three loops that control the number of simulations required, the requested tunnel length, and the existing relation between the duration of the work shift and that of the tunnel excavation cycle (Vargas *et al.*, 2014). This point is fundamental for this analysis, because it will be very important at the time of choosing the best shift configuration to be used. All these items are the ones needed to simulate the total construction time.

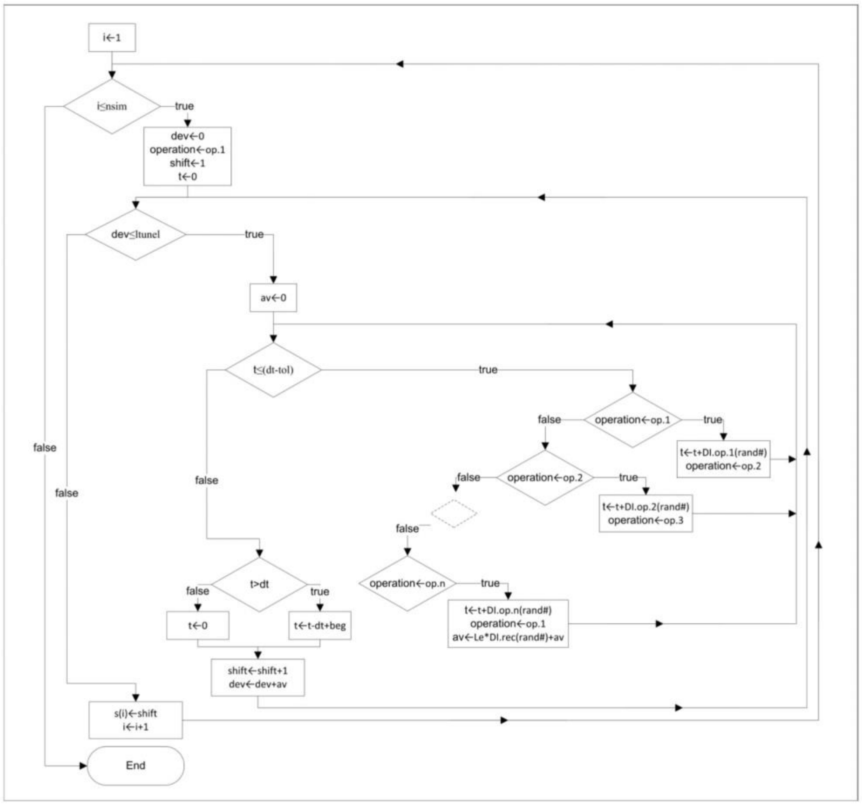

Fig.1. Scheme of the simulation algorithm of tunnel construction time.

The proposed scheme consists of three inclusive loops dependent on one another. The first loop, which contains the other two, controls the number of required simulations, knowing that each simulation will be the tunnel construction with the length to be studied.

The second loop controls the construction that will not exceed the defined tunnel length and every advance will be estimated by the PDF of the yield of the blast times and the length of the drilling, which is a fixed value that will be added consecutively until the required tunnel length is reached.

Finally, the third loop has the function of adding consecutively the times of the cycle's operations with the purpose of building it and seeing its relation with the work shift applied a fundamental aspect for this work.

This last loop is a key of the simulation because it builds the cycle within the shift. This construction is made by means of the Monte Carlo method, where the PDFs associated with the execution times of the unit operations used for the construction of the tunnel are applied. The times obtained from this simulation are added and, as appropriate, it is determined whether the cycle can be finished during the work shift.

As mentioned, the build of cycle of tunnel construction within the work shift, makes the succession of simulations show the work shift which adapting to simulated value of cycle, since the latter is a value that behaves according to PDF.

Figure 2 shows the construction of the excavation cycle PDF, from which the cycle times of the workdays are simulated. These cycle times may or may not agree with the workday.

The end of each excavation cycle implies an advance in the development of the tunnel (see Figure 2), and in turn this advance is also determined by the PDF of the blasting efficiency.

The modeled algorithm has as input parameter the total length of the tunnel, so construction cycles will be simulated until the specified length is achieved.

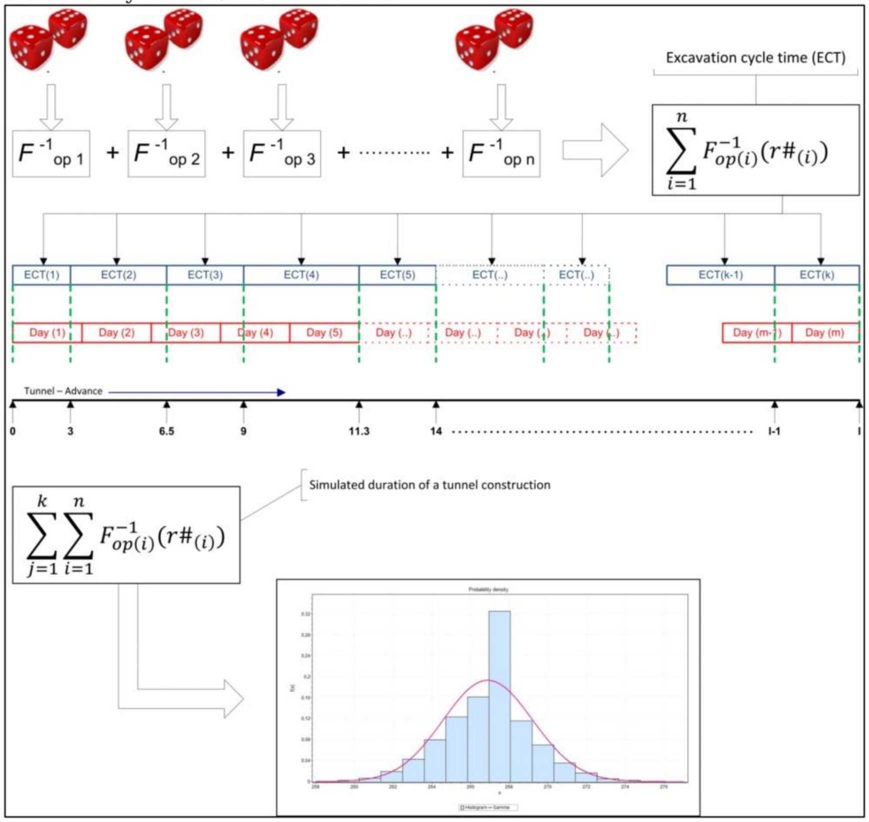

Fig.2. Scheme of the generation of simulated excavation cycle times and their interaction with the workdays and the tunnel advance.

4. Case study and problem definition

For this study, was applied the time database and the parameters used in the construction of the access tunnel of "Romero" mine belonging, Minera San Pedro's company. This area is represented by several cooper ore deposits of the Lo Prado and Veta Negra formations, located in the coastal range of central Chile. The most characteristically mineralization in this zone is bornite and chalcopyrite (Thomas, 1958; Thompson, 1992). This mine is an underground operation using the shrinkage exploitation method (Chen, 1998).

The analyzed problem corresponds to the construction of a 560-m long horizontal tunnel with a cross section of 3.5 × 3.0 m. This tunnel is excavated by drilling and blasting, with an average advance of 2.4 m per shift. The aim is to achieve the shortest tunnel construction time as a function of the configuration of the operating work shift.

The shift systems evaluated in the present study have the configuration proposed in Table 1. These shifts were chosen because they correspond to the configurations allowed by Chilean law (Gobierno de Chile, 2013), and the methodology is easily adaptable to other work shift configurations.

However, checking the different work shifts (Table 1) it's possible estimate that the best configuration is which one that shows the higher effective time, in this case T1 or T3. The T3 option is more efficient because have less interferences. Regardless of the results obtained in this study, it is necessary to interact with the duration of work shifts shown by Vargas *et al.* (2014) with a nominal time of each work shift. For example, if the operating shift duration is 8 hours the 12-hour work shift as the T3 will not be the most appropriate, in this case T1 and T2 shifts would be the most suitable.

The different shift configurations are illustrated in Tables 2-4, showing graphically the interaction between the working groups and the shifts, considering workdays (W) and rest days (R) for each working group.

Table 2. Work scheme for T1.

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Group																														
1	W	W	W	W	W	W	W	W	W	W	W	W	R	R	R	R	W	W	W	W	W	W	W	W	W	W	W	W	R	R
2	R	R	R	R	W	W	W	W	W	W	W	W	W	W	W	W	R	R	R	R	W	W	W	W	W	W	W	W	W	W
3	W	W	W	W	R	R	R	R	W	W	W	W	W	W	W	W	W	W	W	W	R	R	R	R	W	W	W	W	W	W
4	W	W	W	W	W	W	W	W	R	R	R	R	W	W	W	W	W	W	W	W	W	W	W	W	R	R	R	R	W	W

Table 3. Work scheme for T2.

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Group																														
1	W	W	W	W	W	W	W	W	W	W	R	R	R	R	R	W	W	W	W	W	W	W	W	W	W	R	R	R	R	R
2	W	W	W	W	W	R	R	R	R	R	W	W	W	W	W	W	W	W	W	W	R	R	R	R	R	W	W	W	W	W
3	R	R	R	R	R	W	W	W	W	W	W	W	W	W	W	R	R	R	R	R	W	W	W	W	W	W	W	W	W	W

Table 4. Work scheme for T3.

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Group																														
1	W	W	W	W	W	W	W	R	R	R	R	R	R	R	W	W	W	W	W	W	W	R	R	R	R	R	R	R	W	W
2	W	W	W	W	W	W	W	R	R	R	R	R	R	R	W	W	W	W	W	W	W	R	R	R	R	R	R	R	W	W
3	R	R	R	R	R	R	R	W	W	W	W	W	W	W	R	R	R	R	R	R	R	W	W	W	W	W	W	W	R	R
4	R	R	R	R	R	R	R	W	W	W	W	W	W	W	R	R	R	R	R	R	R	W	W	W	W	W	W	W	R	R

5. Results

The information used as input for the simulation in each of the shifts is shown in Table 5, considering a 560-m long horizontal tunnel and 10^5 iterations for each simulation. The data and PDF used in this algorithm is shown in Table 6.

"Tolerance" is an operational criterion that considers whether the next unit operation will continue, depending on the time remaining in the shift. In the case of the present simulation, by using 60 minutes one is considering that if one of the unit operations ends and less than 60 minutes of the shift are left, the cycle is stopped (assuming the loss of time) and it is restarted with the following shift.

The "restart" corresponds to the time that it takes to start an unfinished unit operation due to the end of shift.

Taking into account that the "tolerance" conditions the end of the excavation cycle within the shift or on the following one, the duration of the tunnel construction time increases as a result of the "restart" of the unit operations. This determines that the immediately consecutive excavation cycles have a dependence that can be explained by an adaptation of Markov's chain theory, since the event depends on the immediately preceding event (Hillier & Lieberman, 2010). All the shift configurations have feeding time deducted. Finally, the results obtained from the simulations correspond to those shown in Table 7.

For each configuration the number of shifts needed to complete the tunnel construction and consequently the project duration in days was obtained. It was used the mean value given by the simulation for purposes of analysis as this is similar to mode, consequently the value that is more repeated.

It should be noted that the standard deviation is quite small relative to the project's duration and in the worst case is 2.3 shifts or 1.15 days in the case of T2. For this study the most favorable shift configuration was the T3.

Table 5. Conditions to be simulated

Shift ID	Description [shift per day / hour per shift]	Work groups	Shift duration [min]	Tolerance [min]	Restart [min]
T1	3spd/8h	4	435	60	30
T2	2spd/10h	3	540	60	30
T3	2spd/12h	4	660	60	30

Table 6. Summary of statistical adjustment for operations units.

Unit Operation	Used Data	Parameters Mean [minute]	 Standard deviation [minute]	Probability distribution
Drilling	137	195.45	38.08	Beta
Load & Blasting	133	56.09	11.64	Beta
Ventilation	136	90.00	-	Constant
Scaling	135	26.08	6.77	Lognormal
Mucking	135	70.03	20.22	Gamma

Table 7. Results of the simulation.

Shift ID	Mean [shifts]	Mode [shifts]	Standard deviation [shifts]	Min. [shifts]	Max. [shifts]	Project duration [days]
T1	336.4	336	2.9	325	350	112
T2	266.9	267	2.3	257	277	133
T3	216.0	216	1.9	208	224	108

6. Conclusions

It is possible to simulate a tunnel excavation cycle by means of numerical methods and make a sensitivity study of the various shift systems of a tunnel construction project, and observe in what way they affect the development of the project from the standpoint of the construction deadlines and costs.

The study made it possible to determine by means of Monte Carlo simulations which of the different shift systems that were proposed is faster for tunnel construction, considering that parameters like these are of great importance in project planning, particularly in underground mining, where there is a dependence of production processes on the incorporation of tunnels.

Among the shifts that were studied it was concluded that T3 is the fastest in terms of construction speed.

Diagram of the algorithm nomenclature:

i:	Number of the simulation in progress
nsim:	Number of simulations
ltunnel:	Tunnel length (meters)
dev:	Auxiliary variable with initial value 0 that increases in relation to the advance per blasting
operation:	Operation identifier.
shift:	Variable that adds up the number of work shifts
av:	Variable that shows the tunnel advance in meters
t:	Auxiliary variable used to save the sum of the operation times
dt:	Shift duration (minutes)
beg:	Restarting time (minutes)
tol:	Tolerance to starting the next unit operation in the shift (minutes)
DI.op.n:	Inverse distribution of operation "n"
DI.op.rec:	Inverse distribution of the percent efficiency of the advance from the blasting
rand#:	Random number between 0 and 1
s(i):	Data matrix, number of shifts needed to build the tunnel

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References

Chen, X., 1998. Resuing shrinkage stoping, E&MJ-Engineering and Mining Journal 199 (10), 34-36.

Chiwaye, H. T., Stacey, T. R., 2010. A comparison of limit equilibrium and numerical modelling approaches to risk analysis for open pit mining. Journal of South African Institute of Mining and Metallurgy, 110(10), 571-580.

Ghasemi, E., Shahriar, K., Sharifzadeh, M., Hashemolhosseini, H., 2010. Quantifying the uncertainty of pillar safety factor by monte carlo simulation - A case study. Archives of Mining Sciences, 55(3), 623-635.

Gobierno de Chile, 2013. Título I "Del contrato individual de trabajo" – Capítulo IV "De la jornada de trabajo", in: Código del Trabajo, 26-34. Santiago, Chile.

Hillier, F.S., Lieberman, G., 2010. Markov Chain, in: Introduction to Operation Research 9th ed., McGraw-Hill, 675-682.

Khalokakaie, R., Dowd, P. A., & Fowell, R. J., 2000. Incorporation of slope design into optimal pit design algorithms. Transactions of the Institution of Mining and Metallurgy Section A-Mining Technology, 109, A70-A76.

Metropolis, M., & Ulam, S., 1949. The monte carlo method. Journal of the American Statistical Association, 44(247), 335-341.

Morin, M., & Ficarazzo, F., 2006. Monte carlo simulation as a tool to predict blasting fragmentation based on the kuz-ram model. Computers & Geosciences, 32(3), 352-359.

Sari, M., Karpuz, C., & Ayday, C., 2010. Estimating rock mass properties using monte carlo simulation: Ankara andesites. Computers & Geosciences, 36(7), 959-969.

Sobol, I. M., 1994. A primer for the monte carlo method, CRC Press, Boca Raton, FL, 107 pp.

Suorineni, F. T., Kaiser, P. K., & Henning, J. G., 2008. Safe rapid drifting-support selection. Tunnelling and Underground Space Technology, 23(6), 682-699.

Thomas, H., 1958. Geología de la cordillera de la costa entre el valle de La Ligua y la cuesta Barriga. Instituto de Investigaciones Geológicas, Santiago, Chile.

Thompson, D., 1992, The Lohpan Project. Minera San Pedro, Santiago, Chile.

Vargas, J.P., Koppe, J.C., Pérez, S., 2014. Monte Carlo simulation as a tool for tunneling planning. Tunnelling and Underground Space Technology, 40, 203-209

3.4.- Estimación del tiempo de construcción de los túneles 11 y 12 de inyección de aire del proyecto Chuquicamata Subterránea – Simposio de Ingeniería de Minas 2015, Universidad de Santiago de Chile.

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ESTIMACION DEL TIEMPO DE CONSTRUCCIÓN DE LOS TUNELES 11 Y 12 DE INYECCION DE AIRE DEL PROYECTO CHUQUICAMATA SUBTERRANEA

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RESUMEN

Este estudio tiene por objetivo estimar los tiempos de duración restantes en la construcción de los túneles de inyección 11 y 12 pertenecientes al complejo minero Chuquicamata Subterráneo.

Los tiempos de duración restantes se obtendrán mediante simulación estocástica, considerando el algoritmo planteado por Vargas *et al.* (2014).

El algoritmo será adaptado a cada tipo de roca, para así poder simular la construcción de ambos túneles. Las simulaciones no considerarán la construcción de los portales por tratarse de otra técnica de construcción, considerando además que son una certeza matemática, puesto que ya están construidos.

Los tiempos totales de construcción simulados fueron 1.013 y 1.004 días para el túnel de inyección 11 y 12 respectivamente. De lo anterior concluimos que quedan 184 y 161 días de construcción respectivamente.

INTRODUCCIÓN

La mina Chuquicamata, perteneciente a la Corporación Nacional del Cobre de Chile “Codelco Chile” es una de las explotaciones de cobre más grande a nivel mundial y se encuentra ubicada en la región de Antofagasta a 1.650 kilómetros al Norte de Santiago, Capital de la República de Chile.

La Mina Chuquicamata en la actualidad se encuentra en sus últimos días de explotación a cielo abierto, después de 100 años de explotación los costos han aumentado como consecuencia de las largas distancias de acarreo de material y aumento de la razón estéril/mineral, estos costos hacen en la actualidad de Chuquicamata una mina menos rentable.

Después de una serie de exploraciones que determinaron la presencia de una gran cantidad de recursos mineros remanentes (Codelco, 2011), denominados “Sulfuros Profundos de Chuquicamata” los que se encuentran por debajo de la operación a cielo abierto (Codelco, 2005), se definió realizar una explotación subterránea, cambiando radicalmente la forma de explotar este yacimiento. En este contexto es que actualmente se realizan diversas labores subterráneas, túneles de acceso y transporte, piques de extracción y túneles de inyección de aire.

Producto de lo anterior, el Consorcio Acciona-Ossa es la encargado de construir dos túneles de inyección de aire necesarios para una etapa pre-operacional o de preparación de la mina subterránea. Ambos túneles identificados como el túnel 11 y 12 son paralelos y con una longitud de 4.367 m y 4.349,8 m respectivamente, además pasarán por los mismos tipos de rocas, por lo cual se podrá considerar que presentan las mismas características litológicas al momento de efectuar las simulaciones..

Ambos túneles se construyen simultáneamente mediante perforación y tronadura (Suorineni *et al.*, 2008)

DESARROLLO

Producto de lo expuesto anteriormente, la importancia de los túneles que en la actualidad construye el Consorcio Acciona-Ossa es vital para el cumplimiento de los plazos planteados para este proyecto. De aquí podemos desprender la importancia de estimar el tiempo de construcción de los túneles 11 y 12 de inyección de aire, considerando que ya se encuentran construcción.

Para este fin, utilizaremos el algoritmo de estimación planteado por Vargas *et al.* (2014) en el cual se considera la estimación mediante un método estocástico basado en el método de Montecarlo (Metropolis & Ulam, 1949; Sobol, 1994)).

Metodología

La metodología del estudio se divide de la siguiente forma:

- Análisis de los datos entregados por el consorcio Acciona-Ossa.
- Selección y clasificación de datos según clase de roca.
- Determinación de las operaciones unitarias y largos de avance según clase de roca que se utilizaran en los algoritmos.
- Obtener distribuciones de probabilidad para los tiempos de las operaciones unitarias definidas.
- Obtener distribuciones de probabilidad para los largos de avance.
- Plantear los algoritmos necesarios para la simulación del tiempo de construcción de los túneles de inyección de aire, 11 y 12 a partir del algoritmo de construcción presentado.
- Obtener el tiempo simulado de construcción de los túneles de inyección de aire.

Descripción del Proyecto de Construcción de Túneles

Los portales o entradas a los túneles de inyección se encuentran a unos 6 km al este del actual rajo. Las obras de infraestructura permanente inicial consideran la ejecución de dos túneles de inyección de aire, actualmente en construcción por el Consorcio Acciona-Ossa, denominados 11 y 12.

Las dimensiones de los túneles después de fortificados, son de 10.74 m de ancho x 8.0 m de alto, con pendientes descendentes de 15% y longitudes individuales de 4.367 y 4.322 m para el túnel 11 y el 12 respectivamente, con orientación N80°W desde el portal y N80°E desde el rajo.

A continuación se presentan los principales alcances utilizados para la estimación de los tiempos de construcción de los túneles de inyección de aire.

- La jornada laboral comprende 2 turnos diarios de 12 horas cada uno con una jornada de trabajo que comprende 7 días de trabajo por 7 días de descanso, lo que en definitiva contempla 4 grupos de trabajo.
- Se determina la utilización de operaciones unitarias y largos de avance particulares para las distintas clases de roca CS2, CS3, CS4 y CS5, siendo esta última la de más mala calidad. Por lo tanto, se utilizaran algoritmos de estimación para las distintas clases de rocas presentes.
- El tiempo de construcción de los túneles de inyección está determinado por el número de turnos necesarios para completar el largo total del túnel.

Implementación Algoritmo de Simulación.

Para estimar el tiempo de construcción de los túneles de inyección de aire, se realizan dos modificaciones al algoritmo propuesto por Vargas *et al.* (2014), la primera modificación consiste en redefinir las operaciones unitarias del algoritmo original, ya que el algoritmo plantea cinco operaciones, las cuales son:

- Perforación,
- Carguío de explosivos y tronadura,
- Ventilación
- Marina
- Acuñadura

La modificación consiste en editar el algoritmo utilizando nuevas operaciones unitarias definidas por el ciclo de construcción de los túneles de inyección de aire, estas son las siguiente siete:

- Perforación
- Tronadura
- Ventilación (Valor constante por ley)
- Marina
- Acuñadura
- Fortificación

La segunda modificación es en el largo de avance, ya que en el algoritmo original considera un largo de avance fijo que se multiplica por un factor de corrección que al igual que las operaciones unitarias está definido en una distribución de probabilidad basada en largos de avance efectivos.

La modificación realizada consiste en que para simular el tiempo de construcción de los túneles de inyección de aire se utilizara como largo de avance una distribución de probabilidad obtenida a partir de largos de avance efectivos registrados.

Con estas modificaciones se obtiene el algoritmo de simulación de tiempo de construcción de los túneles de inyección de aire, para cada una de las clases de roca.

Los datos utilizados para este estudio fueron entregados por el Consorcio Acciona-Ossa y consisten en el registro diario de los túneles de inyección de aire. El periodo de los datos es desde septiembre del año 2012 hasta abril del año 2015.

Los datos consisten en tiempos registrados de las diferentes operaciones unitarias necesarias para la construcción de los túneles de inyección, estos datos son tomados por los capataces de ambos túneles y llevados a una base de datos computacional.

Para el estudio, estos datos son separados y procesados de manera independiente para las distintas clases de roca, determinándose así para el estudio solo las clases de rocas registradas en el proyecto, las cuales son CS2, CS3, CS4 y CS5. No existen registros de clase de roca CS1 y solo en cuatro ocasiones se registró clase de roca CS6, además esta última incluye tiempos de tronadura y por diseño el avance en esta clase de roca es mediante excavación mecánica, provocándose así una inconsistencia, por esta razón para el estudio, estos pocos datos son tomados como clase de roca CS5.

Para el estudio se procesan los datos de tiempos de ciclo registrados en la construcción de los túneles de inyección de aire hasta el día 5 de abril del 2015 (tabla 1) estos tiempos de ciclo permiten calcular el tiempo real de construcción por clase de roca de los túneles de inyección de aire hasta el avance real ejecutado. Cabe mencionar que en ambos casos no está considerado el largo del portal, ya que ese se efectúa con otra técnica de excavación, siendo 17,2 m para el túnel 11 y 18 m para el túnel 12, con una duración de construcción de 68 y 54 días respectivamente.

Para la obtención del tiempo de construcción de los túneles de inyección de aire mediante los algoritmos de simulación, se requieren de las operaciones unitarias y largos de avance ya definidos, además se requiere la distribución de probabilidad obtenida de los datos que componen las operaciones unitarias y largos de avance.

Tabla 1: Tiempos reales de construcción por clase de roca.

Clase de Roca		**Tiempo Real de Construcción**				
Túnel		**CS2**	**CS3**	**CS4**	**CS5**	**Total**
11	Avance (m)	73,60	1.153,30	1.075,40	1.258,30	3.560,60
	Días	13,20	250,90	226,80	338,00	828,90
12	Avance (m)	183,80	988,10	1.268,30	1.043,20	3.483,40
	Días	53,90	211,10	250,40	310,20	825,60

Tabla 2: Distribuciones operaciones unitarias.

Operación Unitaria	Clase Roca	Distribución	Media (min)	Desv. Est.
Perforación	CS2	Normal	246,56	64,57
	CS3	Lognormal	197,47	86,22
	CS4	Lognormal	144,16	50,87
	CS5	Normal	82,44	29,54
Tronadura	CS2	Lognormal	108,98	68,97
	CS3	Lognormal	121,83	61,29
	CS4	Lognormal	90,58	37,51
	CS5	Lognormal	68,01	21,82
Marina	CS2	Normal	201,92	68,65
	CS3	Lognormal	179,12	64,29
	CS4	Lognormal	161,29	48,69
	CS5	Lognormal	109,47	49,17
Acuñadura	CS2	Lognormal	78,98	48,93
	CS3	Lognormal	97,4	66,31
	CS4	Lognormal	94,79	50,16
	CS5	Lognormal	127,17	78,76
Fortificación	CS2	Lognormal	279,47	85,95
	CS3	Lognormal	391,53	177,7
	CS4	Lognormal	458,58	274,12
	CS5	Lognormal	483,46	222,96

Los datos de las distintas operaciones unitarias, se procesaron utilizando el algoritmo de Anderson-Darling, en la tabla 2 se muestran los datos obtenidos para ambos.

Las distribuciones obtenidas para ambos túneles son ingresadas en cada uno de los algoritmos modificados para cada clase de roca y se ejecutan las simulaciones, se hace la consideración que la ventilación es un tiempo constante, por lo tanto no se trabaja como una distribución.

Comprobación algoritmo de simulación

Para realizar la comprobación del correcto funcionamiento del algoritmo para ambos túneles, se procedió a simular las distancias reales ejecutadas de cada túnel con las distribuciones obtenidas.

Para el túnel de inyección 11 se tiene un tiempo de construcción de 829 días para 3.560 m, no incluye la construcción del portal. Al realizar la simulación para este túnel se obtuvo un resultado de 830 días, existiendo una diferencia despreciable.

Para el caso del túnel de inyección 12 donde se tiene un tiempo de construcción de 826 días para 3.483 m, no incluye la construcción del portal. La simulación arroja un valor para la misma distancia de 813 días siendo un error relativo de 1,6%.

En ambos casos se consideró 100.000 iteraciones.

Simulación túneles de inyección 11 y 12

Para realizar las simulaciones se consideró simular el total de los túneles, aunque ya estén construido gran parte de ellos. La razón de esta decisión es que no se tiene una estimación de las clases de roca que se espera en lo que queda de construcción y de esta forma se preservan los porcentajes de calidad de roca que ya se han sobrepasado.

Se realiza la ponderación de las clases de rocas ejecutadas para el largo total del túnel 11, el cual como ya se mostro es de 4.367 m, para realizar la ponderación se restó la distancia del portal, obteniendo así una distancia de 4.349,8 m (Tabla 3), esta es la distancia a simular para estimar el tiempo de construcción del túnel de inyección 11. Se realiza la ponderación de las clases de rocas ejecutadas para el largo total del túnel de inyección 12, el cual como ya se mencionó es de 4.322 m, para realizar la ponderación se restó la distancia del portal, obteniendo así una distancia de 4.304 m, esta es la distancia a simular para estimar el tiempo de construcción del túnel de inyección 12 (Tabla 4).

Tabla 3: Ponderación clase de roca túnel de inyección 11

Clase	Distancia Parcial (m)	%	Distancia Ponderada (m)
CS2	73,60	2,1%	89,90
CS3	1.153,30	32,4%	1.408,90
CS4	1.075,40	30,2%	1.313,80
CS5	1.258,30	35,3%	1.537,20
Total	**3.560,60**		**4.349,80**

Tabla 4: Ponderación clase de roca túnel de inyección 12

Clase	Distancia Parcial (m)	%	Distancia Ponderada (m)
CS2	183,80	5,2%	227,10
CS3	988,10	27,8%	1.220,90
CS4	1.268,30	35,6%	1.567,10
CS5	1.043,20	29,3%	1.289,00
Total	**3.483,40**		**4.304,10**

Los datos de entradas de los algoritmos son los siguientes según lo presentado por Vargas *et al.* (2014):

- N° de simulaciones: 100.000 y 200.000.
- Duración del turno: 12 horas → 720 minutos.
- Largo a simular: Distancia correspondiente a la clase de roca.

Los resultados obtenidos para las simulaciones de ambos túneles se muestran en las tablas 5 y 6.

De los resultados mostrados en las tablas 5 y 6, desprendemos que el valor utilizado para la planificación será el entregado por la media, el cual es muy similar a la moda, según lo señalado por Vargas *et al.* (2014). Lo anterior indica un valor de 1.013 días para el túneles de inyección 11 y 1.004 días para el túnel de inyección 12.

Tabla 5: Resultados simulación túnel de inyección 11.

Clase	N°Sim	Largo	Turno	Media	Desv.est.	Moda	Mínimo	Máximo
		(m)	(min)	(días)	(días)	(días)	(días)	(días)
CS2	10^5	89,9	720,0	13,4	1,4	14,0	10,5	16,5
CS3	10^5	1.408,9	720,0	290,0	9,3	290,0	272,0	311,0
CS4	10^5	1.313,8	720,0	274,4	9,6	275,0	254,0	296,0
CS5	10^5	1.537,2	720,0	435,4	12,0	436,0	405,5	416,0
Total				**1.013,2**		**1.015,0**	**942,0**	**1.039,5**

Tabla 6: Resultados simulación túnel de inyección 12.

Clase	N°Sim	Largo	Turno	Media	Desv.est	Moda	Min	Max
		(m)	(min)	(días)	(días)	(días)	(días)	(días)
CS2	10^5	227,10	720,00	60,58	3,52	61,00	47,00	79,00
CS3	10^5	1.220,87	720,00	251,35	4,32	252,00	229,50	269,50
CS4	10^5	1.567,08	720,00	327,22	5,26	327,00	307,00	351,50
CS5	10^5	1.288,95	720,00	365,09	5,48	366,00	341,00	388,50
Total				**1.004,2**		**1.006,0**	**924,5**	**1.088,5**

CONCLUSION

El buen comportamiento de estos algoritmos se comprobó en primera instancia simulando los túneles parcialmente ya ejecutados.

Por lo anterior podemos asumir que la simulación para ambos túneles tiene un grado de confianza alto 1.013 días parta el túnel de inyección 11 y 1.004 días para el túnel de inyección 12.

Los datos de simulación entregados no contemplan la construcción de los portales, esto principalmente porque no se desarrolla con perforación y tronadura, sino con excavación mecánica, que queda fuera de la metodología de simulación usada. Lo anterior no tiene relevancia si consideramos que la construcción de los portales, en relación a su tiempo de duración es una certeza matemática, puesto que fueron construidos y es de 68 días para el túnel de inyección 11 y 54 días para el túnel de inyección 12.

De lo anterior desprendemos que la duración de la construcción del túnel de inyección 11, incluido el portal es de 1.081 días (36 meses) y para el túnel de inyección 12 es de 1.058 días (35,3 meses). Considerando que los tiempos de construcción transcurridos son de 897 días para el túnel de inyección 11 y 880 para el túnel de inyección 12, se estima que ambos túneles terminarán dentro de 184 días y 161 días, considerando los avances realizados hasta la fecha.

REFERENCIAS

- Codelco. (2005). *Bases técnicas: Desarrollo de obras mineras proyecto de explotación de súlfuros profundos tercera etapa.* (Bases Técnicas Licitación No. DAP CP 050-05). Calama: Codelco.
- Codelco. (2011). *Minería subterránea: Pilar del futuro de codelco.* Retrieved 23/Enero, 2013, from http://www.codelco.com/mineria-subterranea-pilar-del-futuro-de-codelco/prontus_codelco/2011-05-19/170202.html
- Metropolis, M., & Ulam, S. (1949). The monte carlo method. *Journal of the American Statistical Association, 44*(247), 335-341.
- Suorineni, F.T., Kaiser, P.K., & Henning, J.G. (2008). Safe rapid drifting-support selection. *Tunnelling and Underground Space Technology, 23*(6), 682-699.
- Sobol, I. M. (1994). *A primer for the monte carlo method* (pp. 107). Boca Raton, FL: CRC Press.
- Vargas, J.P., Koppe, J.C., Pérez, S. (2014). Monte Carlo simulation as a tool for tunneling planning. *Tunnelling and Underground Space Technology,* 40, 203-209.

Capítulo 4: Discusión Global de los Resultados.

Dentro de la explotación de un yacimiento minero, la planificación de la producción es de gran importancia para el éxito del negocio, sustentado en que la velocidad de alimentación del mineral desde la mina a la planta de recuperación debe ser constante en cantidad y calidad para poder generar un producto homogéneo para la venta y que cumpla los estándares requeridos por los compradores. Para realizar la explotación requerida por la planificación se debe acceder a los yacimientos mineros por medio de túneles, y aquí radica la principal importancia en la estimación de tiempos de construcción de este tipo de infraestructura en minería subterránea, ya que siempre es parte de la ruta crítica en proyectos de estas características.

No se puede olvidar la importancia que actualmente tiene para la industria extractiva la minería subterránea ya que, a medida que la explotación avanza, ésta se va profundizando, lo que impide realizar una explotación de superficie y se debe mudar a una minería subterránea, como, por ejemplo, la División Codelco Norte de la Minera Estatal (Codelco, 2011).

De acuerdo con lo anterior, la construcción de túneles para dar acceso y posteriormente preparar los cuerpos mineralizados para su posterior explotación cobra gran importancia cuando hay que realizar una planificación y evaluación económica del negocio, ya que el inicio del proyecto y su continuidad estará limitada por su acceso.

Una de las metas principales de esta tesis fue plantear un método capaz de hacer más certera la planificación de la construcción de túneles por medio de la generación de información mediante simulación estocástica para tomar decisiones de calidad y disminuir los riesgos a que se enfrenta el negocio, con el fin de ser más precisos con los presupuestos de construcción.

Para responder a la hipótesis planteada en este trabajo se desarrolló un modelo numérico estocástico basado en el método de Monte Carlo para la planificación de la construcción de túneles. Una vez logrado el objetivo de dar más precisión a la planificación, también se pudo conciliar con los procesos de planificación e ingeniería.

El modelo desarrollado incorporó la variabilidad propia de las operaciones unitarias en el proceso de planificación, ajustando a la realidad los resultados de este proceso, y posibilitando la toma de decisiones con un mayor conocimiento de la realidad.

Hasta ahora la planificación de este tipo de trabajos se hace de forma lineal (Codelco, 2005), sin dejar espacio para las variabilidades propias de los procesos necesarios para construir un túnel. Por tanto, la metodología planteada en este trabajo supone un avance dentro del proceso de administración de la construcción de este tipo de infraestructura. Se puede mencionar que uno de los proyectos emblemáticos de la minera estatal, la construcción de los túneles de acceso al Nuevo Nivel Mina de División El Teniente, se encuentra con retraso ya que nunca se han alcanzado las velocidades de avance utilizadas para realizar la planificación, principalmente por problemas estratégicos asociados a esta construcción.

Una de las razones por las que no existen metodologías de planificación como la desarrollada en este trabajo es que los programas destinados a trabajar con el método de Monte Carlo, como @Risk o Crystal Ball, lo hacen en procesos estáticos, como lo sería una evaluación de proyectos o un flujo de caja, y para lograr una aplicación como la llevada a cabo en este trabajo es necesario realizar un modelo matemático y expresarlo en un algoritmo dinámico.

Además, se debe considerar que la planificación de obras está en un ámbito empresarial que, en algunos casos, está muy lejano a los modelos matemáticos. Muchas veces el actor empresarial no ve la necesidad o no conoce las posibilidades de aplicaciones matemáticas como éstas.

Una forma de mostrar la bondad que tiene utilizar una metodología como la propuesta es aplicarla a un desarrollo real. Para este fin se utilizó el complejo minero San Pedro y los túneles de inyección 11 y 12 de la mina subterránea Chuquicamata, donde se pudo evidenciar innumerables mejoras en torno a la planificación y administración de los recursos.

La metodología planteada puede servir para evidenciar posibles mejoras en la construcción de túneles como, por ejemplo, hacer una análisis estadístico de lo ocurrido en un turno y poder predecir lo que ocurrirá en el turno siguiente, teniendo en cuenta que existe una relación de cadenas de Markov, expresada en el segundo artículo presentado.

La relación antes descrita más la metodología presentada en esta tesis, es el primer paso de un sistema experto de toma de decisión.

Actualmente la industria minera subterránea no cuenta con sistemas expertos para la rápida toma de decisiones en la construcción de túneles, siendo una discusión que lleva varios años. Las empresas fabricantes de equipos para la minería llevan tiempo desarrollando sistemas que sean capaz de predecir la calidad de la roca o la capacidad de ser excavada, pero no han desarrollado una metodología que sea capaz de predecir, según eventos ya acontecidos, el desarrollo de las actividades futuras con la finalidad de hacer una óptima asignación de los recursos.

Además, con la metodología desarrollada en esta tesis, se puede predecir estadísticamente los que ocurrirá en las jornadas de trabajo futuras, pudiendo desarrollar sistemas expertos de toma de decisiones orientados a la asignación de recursos.

Esta tesis se puede considerar como un punto de partida de nuevas metodologías de planificación, debido a que, durante su desarrollo, se pudieron evidenciar algunos problemas como, por ejemplo, que la gran cantidad de datos que requiere el método de Monte Carlo expone al personal a riesgos físicos y ambientales. Para solucionar esto, es necesario explorar otras técnicas de simulación, como, por ejemplo, la simulación secuencial en espacio Gaussiano (SSG), cuya ventaja es que requiere menos datos que el método de Monte Carlo. Esto se debe a que los resultados obtenidos de la simulación SSG pasan a constituir parte de la base de datos como uno más de muestreo, utilizándose para generar una nueva simulación, y así de una cantidad reducida de datos se pueden lograr simulaciones que representen la realidad (Chiles & Delfiner, 1999).

Como se ha visto, el desarrollo de una metodología de planificación para este tipo de infraestructura abre un abanico de posibilidades a la industria, considerando que la industria minera tornará en un corto plazo de una minería a cielo abierto a una minería selectiva subterránea, cuya premisa principal es que hay que dar acceso, mediante túneles, a los cuerpos económicamente rentables de extraer.

Capítulo 5: Conclusiones finales.

Teniendo en cuenta los artículos presentados en esta tesis, se puede concluir que la metodología planteada se ajusta a los requerimientos de la industria minera, siendo capaz de simular el tiempo de construcción de un túnel mediante métodos estocásticos (Monte Carlo). Anteriormente era una herramienta invaluable al momento de planificar el desarrollo de este tipo de infraestructuras.

En el primer artículo "Monte Carlo simulation as a tool for tunneling planning" se presenta la metodología como un algoritmo computacional, con una aplicación de validación, donde se pudo comparar la efectividad del método al compararlo con la práctica actual de la industria. Un aspecto importante a considerar es que Minera San Pedro, en el momento de planificar la construcción de los túneles de acceso, consideró valores que no se encuentran dentro de las posibilidades de ocurrencia ya que se encuentra fuera del histograma de la simulación.

En el segundo artículo "Planning tunnel construction using Markov Chain Monte Carlo (MCMC)" se plantea la relación existente entre el éxito de un turno de trabajo con lo ocurrido en el evento anterior, para lo que se recurre a la teoría de las cadenas de Markov. Se puede ver que esta relación es, en gran medida, la responsable de generar dispersión en la planificación de este tipo de obras, dando origen a una aplicación de suma importancia en la industria minera Chilena, la cual se presenta en el tercer artículo "Estimation of tunnel excavation time as a function of the configuration of operational shifts using stochastic simulation". Esta aplicación es la relación de los trabajos ejecutados con la el tipo de jornada de trabajo escogido, de suma importancia ya que, para lograr una optimización en la construcción de un túnel, es necesario saber qué jornada se adapta de mejor forma.

Son innumerables los proyectos de construcción de este tipo de infraestructura que no se han desarrollado de manera óptima por varios factores, siendo uno de los principales trabajar con un turno no adecuado. Tal como se plantea en los artículos, al cortar los trabajos sin terminar el ciclo, se aumentan los tiempos de ejecución puesto que, el retomar actividades en desarrollo, se acumulan muchas ineficiencias propias de la lejanía de los lugares de trabajo en relación a los puntos de distribución del personal y equipos.

Se pudo ver que el modelo de simulación planteado en este trabajo es una poderosa herramienta en el momento decidir cómo afrontar los futuros trabajos, desde el punto de vista de la configuración de turno a escoger. En la construcción de túneles, esta elección se hace basándose en la experiencia de quienes están a cargo de los proyectos, siendo muchas veces errónea, por lo que se realizan cambios de configuración que requieren hacer modificaciones en los presupuesto, lo que podría afectar de forma negativa al proyecto de construcción.

Se pudo relacionar la eficiencia del turno o de la configuración del turno, gracias a la relación que existe entre el éxito de una jornada y su dependencia del éxito de la jornada anterior, que se relacionan mediante la teoría de cadenas de Markov.

Por último, en el cuarto artículo presentado se comprueba de forma práctica la efectividad del método en los túneles de inyección 11 y 12 de la mina subterránea Chuquicamata. La estimación precisa del término de una obra de construcción acarrea múltiples beneficios, además de una correcta asignación de los recursos necesarios como, por ejemplo, la llegada a obra de los ventiladores que suministrarán el aire al interior de la mina, lo cual traerá como consecuencia el inicio de las operaciones productivas de extracción.

Se puede ver a lo largo de esta tesis por artículos que hay un vacío que se pretende llenar con la creación de un método de predicción de tiempos de construcción de túneles cuya importancia radica en la introducción de una metodología de planificación teniendo en cuenta la variabilidad de los procesos, lo que hace más real la estimación al incorporar distintos escenarios de ocurrencia.

Otro aspecto innovador de esta metodología es que, a medida que el número de eventos simulados aumenta (en este trabajo caso 10^5) se tiende a encontrar todas las opciones a las que se ve enfrentada la construcción, por lo que el administrador toma una decisión basándose en probabilidades de ocurrencia, no de una muestra aislada sino de la población completa. Este punto da respuesta a la hipótesis planteada debido a que se puede mostrar las posibles combinaciones de eventos que se dan en el transcurso de la construcción de un túnel.

Por todo lo anterior, se puede decir que el modelo presentado en esta tesis es un aporte al estado del arte en esta materia, que se puede hacer extensivo a cualquier actividad cíclica de construcción que se desarrolle en minería y que se vea afectada por su interacción con la configuración de la jornada de trabajo.

Por último se debe mencionar que, en el desarrollo de esta tesis, se pudo ver la conveniencia de realizar las estimaciones considerando la variabilidad propia de los procesos, en esta tesis las operaciones unitarias, haciendo muy superior los resultados obtenidos respecto a los de una estimación de plazos con valores fijos e invariables.

Bibliografía

Barthes, H., Bordas, A., Bouillot, D., Buzon, M., Dumont, P., Fermin, J., et al. (1994). Tunnels - tunnel boring machines. *Proceedings of the Institution of Civil Engineers-Civil Engineering, 102*(1), 15-19.

Beall, J. V. (1973). Mining place and contribution. In G. Cummins (Ed.), *SME mining engineering handbook* (1st ed., pp. 1-13). NY: AIME.

Bravo, G., & Macgibbon, B. (1988). Improved estimation for the parameters of an inverse gaussian distribution. *Communications in Statistics - Theory and Methods, 17*(12), 4285-4299.

Chen, X. (1998). Resuing shrinkage stoping. *E&MJ-Engineering and Mining Journal, 199*(10), 34-36.

Chiles, J.P,& Delfiner, P. (1999). Conditional Simulations. In Wiley-Interscience Publication (Ed.), *Geostatistics: Modeling Spatial Uncertainty* (pp.449). Canada: John Wiley & Sons, Inc.

Chiwaye, H. T., & Stacey, T. R. (2010). A comparison of limit equilibrium and numerical modelling approaches to risk analysis for open pit mining. *Journal of South African Institute of Mining and Metallurgy, 110*(10), 571-580.

Cochilco. (2011). *Copper and other mineral statistics 1992-2011* (Yearbook No. 35). Santiago, Chile: Comisión Chilena del Cobre.

Codelco. (2005). *Bases técnicas: Desarrollo de obras mineras proyecto de explotación de súlfuros profundos tercera etapa.* (Bases Técnicas Licitación No. DAP CP 050-05). Calama: Codelco.

Codelco. (2011). *Minería subterránea: Pilar del futuro de codelco.* Retrieved 23/Enero, 2013, from http://www.codelco.com/mineria-subterranea-pilar-del-futuro-de-codelco/prontus_codelco/2011-05-19/170202.html

Gobierno de Chile, (2012) Código Del Trabajo, Dic 2012U.S.C. 25-34.

du Plessis, A., & Brent, A. C. (2009). Development of a risk-based mine closure cost calculation model. *Journal of the South African Institute of Mining and Metallurgy, 106*(6), 443-450.

Fouladgar, M. M., Yazdani-Chamzini, A., & Zavadskas, E. K. (2012). Risk evaluation of tunneling projects. *Archives of Civil and Mechanical Engineering, 12*(1), 1-12.

Fuksa, D. (2009). Managing cash for a mining company. *Gospodarka Surowcami Mineralnymi-Mineral Resources Management, 25*(1), 119-135.

Fukuchi, G. (1991). The present and future of mechanized tunnel works in soft ground. *Tunnelling and Underground Space Technology, 6*(2), 175-183.

Ghasemi, E., Shahriar, K., Sharifzadeh, M., & Hashemolhosseini, H. (2010). Quantifying the uncertainty of pillar safety factor by monte carlo simulation - A case study. *Archives of Mining Sciences, 55*(3), 623-635.

Código Del Trabajo, Capítulo IV "De la jornada de trabajo" (2012).

HARALDSSON, H. (1992). Road tunnels in iceland - present and future. *Tunnelling and Underground Space Technology, 7*(2), 149-156.

Heuberger, R. (2005). Risk analysis in the mining industry. *Journal of the African Institute of Mining and Metallurgy, 105*(2), 75-79.

Hillier, F. S., & Lieberman, G. (2006). Cadenas de markov. In I. McGraw-Hill (Ed.), *Investigación de operaciones* (8va ed., pp. 802). México D.F.: McGraw-Hill.

Karliński, J., Rusiński, E., & Lewandowski, T. (2008). New generation automated drilling machine for tunnelling and underground mining work. *Automation in Construction, 17*(3), 224-231.

Khalokakaie, R., Dowd, P. A., & Fowell, R. J. (2000). Incorporation of slope design into optimal pit design algorithms. *Transactions of the Institution of Mining and Metallurgy Section A-Mining Technology, 109,* A70-A76.

Marec, M. (1996). Major road tunnel projects — how far can we go? *Tunnelling and Underground Space Technology, 11*(1), 21-26.

Metropolis, M., & Ulam, S. (1949). The monte carlo method. *Journal of the American Statistical Association, 44*(247), 335-341.

Morin, M., & Ficarazzo, F. (2006). Monte carlo simulation as a tool to predict blasting fragmentation based on the kuz-ram model. *Computers & Geosciences, 32*(3), 352-359.

Morley, C., Snowden, V., & Day, D. (1999). Financial impact of resource/reserve uncertainty. *Journal of the South African Institute of Mining and Metallurgy, 99*(6), 293-301.

Revista Minería Chilena. (2010, Agosto 2012). Tunelería, negocios por US$ 200 millones. *Revista Minería Chilena, 350*, 223.

Revista Minería Chilena. (2013, Enero 2013). Avances en tunelería y fortificación minera. *Revista Minería Chilena, 379*, 91-93.

Ripley, B. D. (1987). Stochastic simulation. In John Wiley & Sons (Ed.), *Wiley series in probability and mathematical statistics* (pp. 237). USA:

Riveros, M. (2013, 07/01/2013). Minería subterránea, tendencia que crece en chile y el mundo. *El Mercurio: Economía y Negocios.,* pp. 1.

Robbins, R. (2000). Mechanization of underground mining: A quick look backward and forward. *International Journal of Rock Mechanics and Mining Sciences, 37*(1-2), 413-421.

Sabour, S. A. A., & Wood, G. (2009). Modelling financial risk in open pit mine project: Implications for strategic decision-making. *Journal of the South African Institute of Mining and Metallurgy, 109*(3), 169-175.

Sari, M., Karpuz, C., & Ayday, C. (2010). Estimating rock mass properties using monte carlo simulation: Ankara andesites. *Computers & Geosciences, 36*(7), 959-969.

Simonsen, H., & Perry, J. (1999). Risk identification, assessment and management in the mining and metallurgical industries. *Journal of the African Insitute of Mining and Metallurgy, 99*(6), 321-329.

Singh, S. P., & Xavier, P. (2005). Cause, impact and control of overbreak in underground excavation. *Tunnelling and Underground Space Technology, 20*(1), 63-71.

Sobol, I. M. (1994). *A primer for the monte carlo method* (pp. 107). Boca Raton, FL: CRC Press.

Spackova, O., & Straub, D. (2013). Dynamic bayesian network for probabilistic modeling of tunnel excavation processes. *Computer-AIDED Civil and Infraestructure Engineering*, *28*(1), 1-21.

Suorineni, F. T., Kaiser, P. K., & Henning, J. G. (2008). Safe rapid drifting-support selection. *Tunnelling and Underground Space Technology*, *23*(6), 682-699.

VANWALSUM, E. (1991). Mechanical pre-cutting, a rediscovered tunneling technique. *Rock Mechanics and Rock Engineering*, *24*(2), 65-79.

Yazdani-Chamzini, A., & Yakhchali, S. H. (2012). Tunnel boring machine (TBM) selection using fuzzy multicriteria decision making methods. *Tunnelling and Underground Space Technology*, *30*, 194-204.

Zare, S., & Bruland, A. (2006). Comparison of tunnel blast design models. *Tunnelling and Underground Space Technology*, *21*(5), 533-541.