**International Journal of Engineering and Technical Research (IJETR)**
**ISSN: 2321-0869 (O) 2454-4698 (P), Volume-7, Issue-4, April 2017**

# The best estimation for shift duration in tunnel excavation using stochastic simulation

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*Abstract*— **For the mining industry tunnels 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.**

**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 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.**

**Index Terms— Planning; tunnels; shift configuration; stochastic simulation; Monte Carlo.**

## I. 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 [1].

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.

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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 [2], 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. [3, 4, 5] 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. [3, 4, 5] 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).

**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 |

## II. 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 [1] 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).

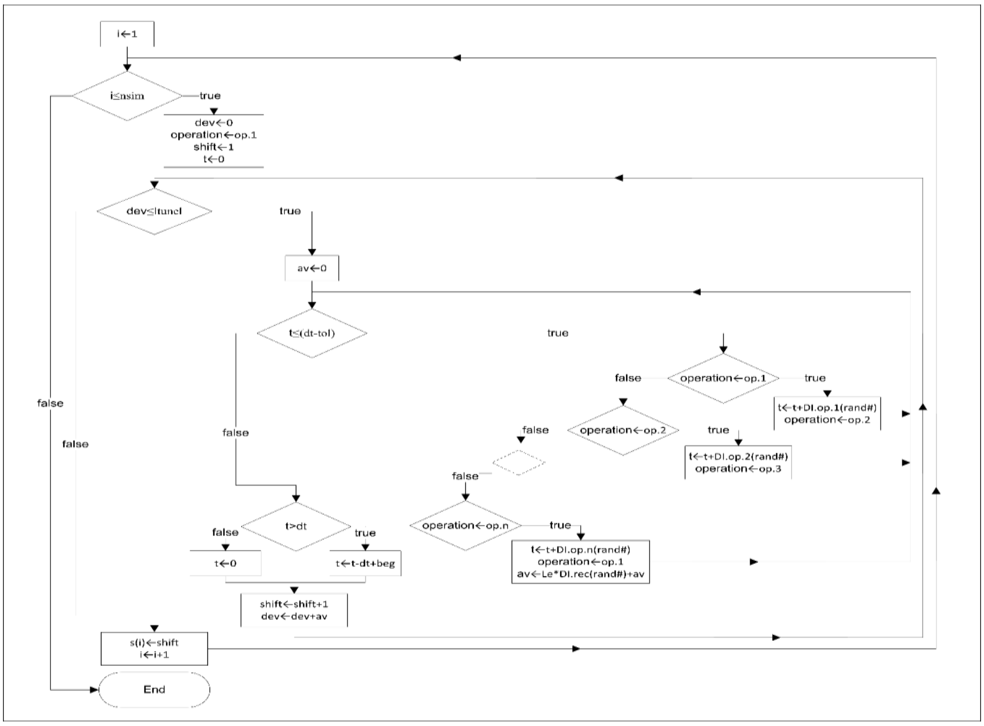


**Fig.1.** Scheme of the simulation algorithm of tunnel construction time

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, andtherefore 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. [3, 4, 5] 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.

## III. 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 [6], becoming one of the most common methods for carrying out this kind of analysis [7, 8, 9, 10, 11]. 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 [12]. 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.

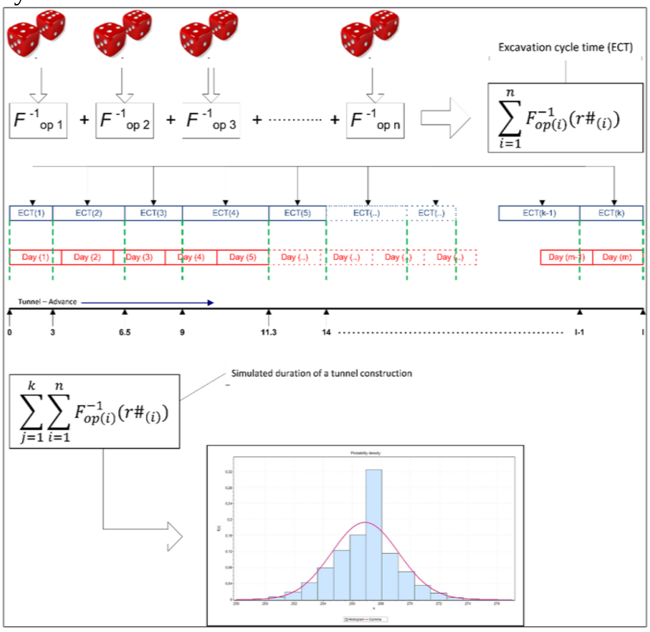


**Fig.2.** Scheme of the generation of simulated excavation cycle times and their interaction with the workdays and the tunnel advance

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 [3, 4, 5]. 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.

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.

**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 |

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.

## IV. 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 [13, 14]. This mine is an underground operation using the shrinkage exploitation method [15].

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 [2], 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. [3, 4, 5] 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.

| 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 |

## V. 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 [16]. 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.

## VI. 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

## ACKNOWLEDGEMENTS

This work was supported by DICYT/Universidad de Santiago de Chile, USACH (code 051515VN), PPGE3M Universidade Federal do Rio Grande do Sul.

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