# Probabilistic performance assessment for crushing system. A case study for a mining process.

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**Abstract:** The productive performance of a system is mainly determined by its design specifications such as volume, capacity and processing speed; however, it is also conditioned on the reliability of its equipment, the logic be-hind the operation of the process and the availability of its overall system. In this viewpoint, these features are relevant to estimate the throughput, and need to be given due account in proper dimensioning and management.

Significant modelling complexities can arise when accounting for realistic conditions for multi-production, storage flexibility, recirculation, setups, and random times of operations and repairs. Within an integrated, systemic view of the production process and related productivity performance, these issues must be treated by fusing the methods of reliability and availability analyses with those of production process engineering.

This article propose an integrated probabilistic modelling to analyze, evaluate and compare the performance of a Crushing line under specific operational criteria, considering the characteristics of its equipment and the systemic setting in which they are embedded. The resilience characteristic is an important real factor of this kind of process, so will be analyzed in detail.

According to, the software RelPro® will be used to model the Crushing System (mining process in Chile). This software was developed in Java language, based on Monte Carlo simulation (simulation by event). This modelling creates the flexibility needed to model the complex behaviour of high-dimensional systems.

**Keywords:** System Modelling, Performance Simulation, Simulation by event, Resilience restriction, Primary Crushing Process.

## 1. INTRODUCTION

In current literature, there are several investigations whose objective is to identify the principal factors that directly affect the maximization of throughput and economic benefit, those that converge at empirical consideration of reliability, maintainability, and availability indicators (RAM). The traditional reliability analyses based on a logical and probabilistic modelling contributes to improve key performance indicators (KPIs) of a system [1], a direct influence in determining optimal operation designs [2]. In this line, there are many alter-natives available for reliability analysis of systems employing analytical techniques, like Markov Models [3], Poisson [4], and other techniques [5]. The systematic study are usually based on techniques like Reliability Block Diagrams (RBDs) [6, 7], Fault Trees (FTs) [8], Reliability Graphics (RGs) [9], Petri Nets (PNs) [10], among others; which allow for the logical relationships that underlie the behaviour or dynamics of the process. In some applications, specifically when complex and dynamic systems are involved, these techniques must be adapted or extended with further considerations. An excellent example for this is the adaptation of de classic RBD to measure the effects of the buffer inventory level on the performances of the production line [11].

In practice, the performance of a production line is limited by intrinsic characteristic of each one of the equipment that contributes to the overall functioning, the most important are:

- ✓ Nominal Capacity of the machinery/stations/production equipments.
- ✓ Reliability and Maintainability behaviour

- ✓ Maintenance Planning
- ✓ Operational Restrictions
- ✓ Setting or structure of the system

Their corresponding limitations can create bottlenecks in the production which must be accurately evaluated and effectively corrected [12, 13]. Then, the operational reliability and productivity of a system must be analyzed in a combined fashion to allow optimal exploitation of resources to achieve the set production goals [3]. This requires that a number of characteristics of the production processes be given due account, such as the last mentioned.

In this line, the primary concern of this proposal is to build a model to analyze and project the system performance (mining process) involving realistic criteria last mentioned. This proposal directly derives from industrial requirements in the context of design evaluation.

Monte Carlo simulation is used as the modelling framework to capture the realistic aspects of equipment and system behaviour [15, 16]. This approach creates the flexibility needed to model the complex behaviour of high-dimensional systems.

The most important motivation for using Monte Carlo simulation comes from the possibility of building a realistic (probabilistic) model of a system's (stochastic) behaviour, which allows the creation of realistic system production life representations by sampling the occurrence of discrete random events from their characteristic probability distribution functions. This method is commonly used to solve complex problems by random sampling [17, 18]. It involves the generation of random or pseudo-random numbers that enter into an inverse probability distribution, resulting in as many scenarios as the number of simulations made [19]. The results of this process being far more informative than what can be inferred from a few designed scenarios, e.g. generated for 'what if' type analyses.

In this paper a Monte Carlo simulation-based analysis procedure is used to analyze a real-world case study from mining engineering. The simulation model will be implemented in the RelPro environment [20], estimating the expected behaviour of performance of each piece of equipment and of the system as a whole, and generates related confidence bounds that account for the statistical variability in behaviour.

RelPro is an analysis and simulation tool that can be used to model continuous and discrete production systems, such as conveyors, transfer lines, mass production lines, fleets, and others. RelPro allows the reproduction of randomized replications of a system model using highly complex logic and it provide innovative and efficient algorithms to analyze and evaluate different scenarios, supporting making decision process related to design and operational conditions, aiding of course the business result.

The motivation of this work is to build an integral probabilistic modelling for a mining process (Crushing line), which constitutes a systematic procedure to model, simulate and sensitize the selected production process, all under innovative algorithms and friendly RelPro environment.

According to the aims, this article is organized as follows: in section ''System Description,'' the application is presented in detail; in sections ''Modelling of the system'' the process is modeled under RelPro environment and briefly summarized according to the general methodology; in section ''Data Analysis,'' will be explained the importance of the data and reliability and maintainability analysis with RelPro.

Finally, case study is solved in section "Simulation Model" and some concluding remarks are given in section ''Conclusion''. .

## 2. SYSTEM DESCRIPTION

In the context of mining industry, this paper presents and analyses a real case study developed in a cooper Open pit mine, specifically for the primary crushing (PC) (Fig. 1), which normally is the first stage in a comminution process [1]. Crushing is normally carried out on 'run-of mine' ore, and the objective is to reduce the size of the material from the mine, which is then transported by some conveyor belts to a stockpile.

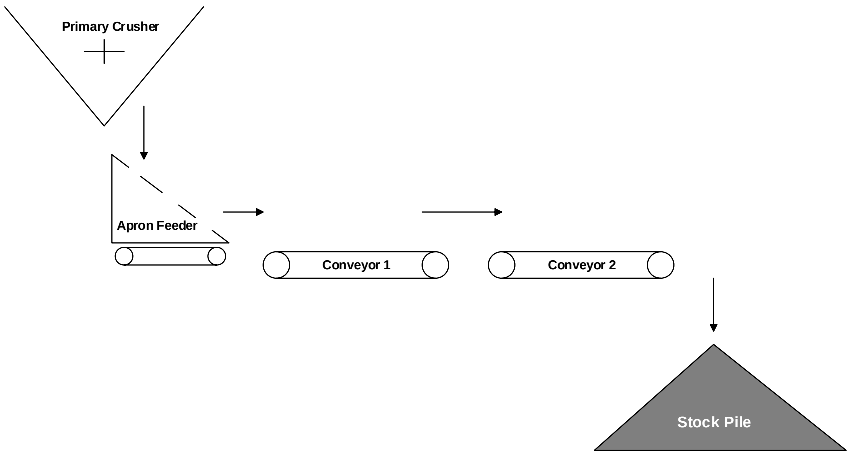


**Fig. 1 Process diagram for the primary crushing process**

As a brief description of the process involved, after a mining company has removed overburden, extraction of the mineral ore begins using specialized heavy equipment and machinery, such as loaders, haulers, and dump trucks, which transport the ore to processing facilities using haul roads. After, the ore is dumped into the primary crusher; then an apron feeder is connected controlling the gravity flow of bulk solids, providing an uniform feedrate to the next receiving belt conveyor. Two next belt conveyors are connected to the apron feeder, to finally feed the stockpile.
The main characteristics of the primary crushing process shown in Fig. 1 are listed in Table 2.

**Table 1. Primary crushing process information**

| Equipment | ID | Basic Fucntion |
|---|---|---|
| **Primary Crusher** | CH_001 | Mineral size reduction |
| **Apron Feeder** | FEED_001 | Control of the gravity flow of bulk solids, providing an uniform feedrate to the next receiving belt conveyor |
| **Conveyor Belt 1** | CONV_001 | Transport the crushed mineral to the next conveyor |
| **Conveyor Belt 2** | CONV_002 | Transport the crushed mineral to the stock pile |

## 2. MODELLING OF THE SYSTEM

The logic behind the operation (functional dependency) of the process can be understood by using a simple question What' if? It means that it is necessary to recognize the effect of some random or planned state change of any production equipment/machinery of the process over the system, that involve the effect in terms of functioning and work load capacity over the others machineries, subsystems and overall system. Normally, there are two possible states, degradation (normal established functioning) and not degradation (failure state, preventive intervention or operational detention) [21].
The four components of the process are connected in a simple serial setting, which implies that any single failure will cause the entire system to fail. A major operational criteria that benefits the outcome (second scenario to model and sensitive) is the resilience of the process when the primary crusher or the apron feeder fails. When one fails, or both simultaneously, the downstream process will continue to work for the next 40 minutes. This operational feature is equivalent to if both machineries have the ability to accumulate material during normal operation, been capable to supply 30 to 40 minutes of downstream operation
The resilience scenario leads to a cold standby system [22], which satisfies the usual conditions (i.i.d. random variables, perfect repair, instantaneous and perfect switch, queueing). It is important to consider tree important features:

- ✓ To model it, it is necessary to create a "virtual" stand by equipment, with specific parameters of failure and repair.
- ✓ As preliminary criteria, the failure distribution must be a Uniform Distribution with parameter of life equal to range of the resilience time estimated (30 – 40 minutes).
- ✓ As preliminary criteria, the repair time distribution of the "virtual" equipment must be equivalent to the repair time distribution of the main equipment. It is a conservative scenario.

The Fault tree diagrams are developed (Fig. 2 and 3) to support the understanding and representation of the both process scenarios.

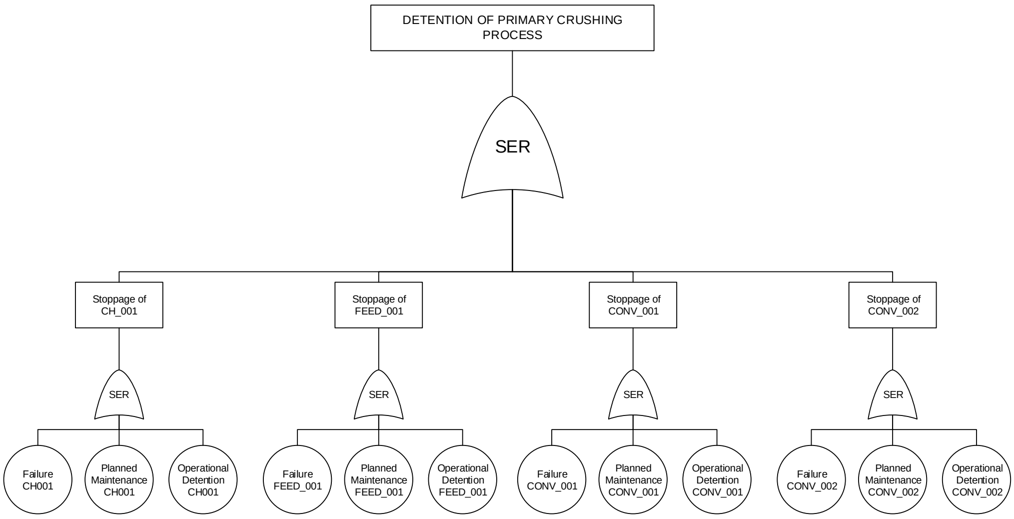


**Fig. 2 FT representation of the primary crushing process - immediate effect**

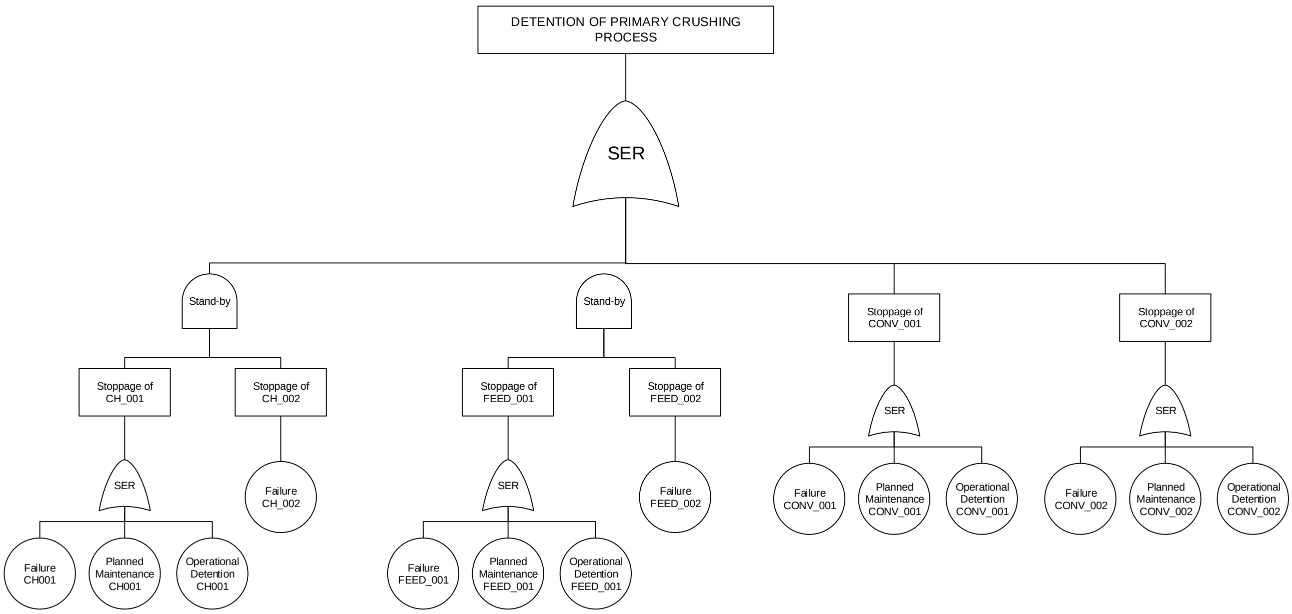


**Fig. 3 FT representation of the primary crushing process – resilience approximation**

So, process modelling in software RelPro must consider the traditional scenario (immediate effect of detention) and the constraint scenario (resilience approximation). With this, the analysis results will be enriched.

As was indicated at the beginning of the paper, the motivation of this work is to build an integral probabilistic modelling, so the next section will explain and analyze the statistical data related to: Times To Failure (TTF) associated to reliability and Time To Repair (TTR) related to maintainability.

The simulation will not include parameters linked to operational stoppages nor planned maintenance. This consideration just simplified the analysis in terms quantity of analysis, but not in terms of quality or methodology, since these considerations can be modelled and integrated just like a serial setting as was graphically represented by the FT diagrams (Fig. 2 and 3).

## 3. DATA PARAMETERIZATION

The definition of the probability distributions is commonly used to describe the failure and repair processes of the equipment. Different types of statistical distributions are examined and their parameters are estimated by using, as mentioned before, the RelPro Application. The software fits several distribution models based on the historical data, and it is possible to choose and use a preferred model, or accept the distribution recommended by the software (Weibull 2 parameters, Exponential, Lognormal, Normal, Dirac Delta and Uniform).
The following step in data management is to determine the nature of the equipment involved in the process, so the distributions must be selected under relevant stochastic models, according to the behaviour of the data in terms of trend and independence.
Analyzing the historical data of the equipment involved, independence and trend indicators are calculated. In the first instance, this feature is observed graphically. For this, some graphics of cumulative time to failure (TTF) observe the behaviour of trends and then dispersion charts of successive lives to observe the degree of correlation of variables or independence. Also, the Laplace test was applied. Due to space limitations, these are not included.
The Software RelPro allowed to estimate all the parameters for each probability density function (TTF and TTR), and no trend was identified. As an example, Fig. 4 shows the parameterization for the primary crusher, specifically for times to failures (TTF).

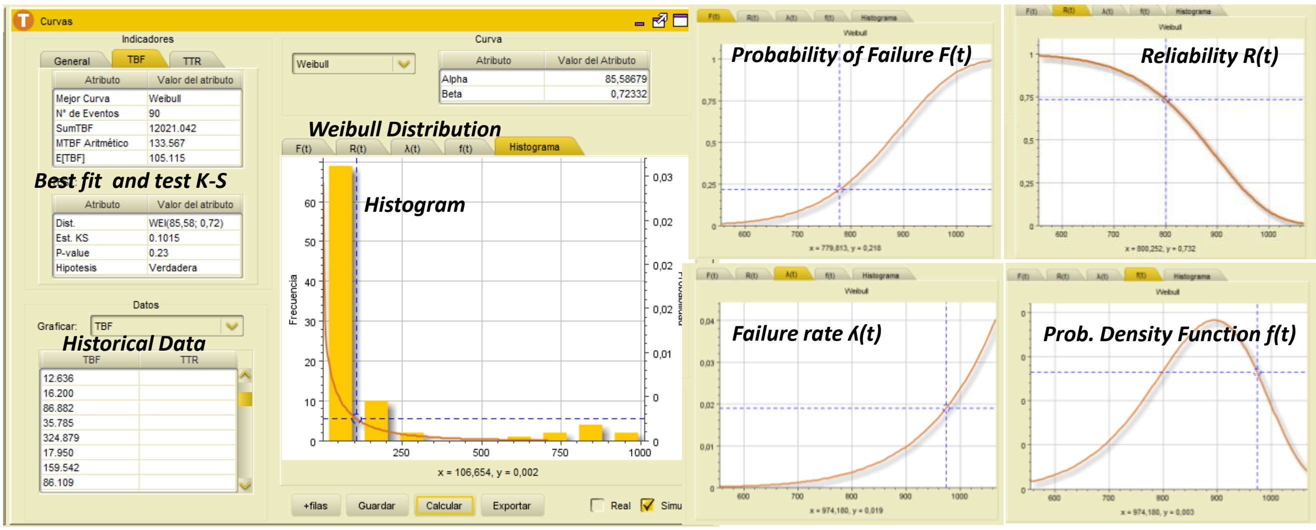

**Fig. 4 Probability density function for primary crusher**

Fig. 4 summarize the information about: histogram of failure, Accumulated probability of failure F(t), reliability R(t), failure rate ʎ(t), probability density function of failures f(t) and the relevant information about the Kolmogorov–Smirnov tests [23] (statistical goodness-of-fit test selected in RelPro).
Table 2 summarizes main parameters and key indicator related to reliability and maintainability.

**Table 2. Reliability and maintainability information**

| Equipment | Time To failure Parameterization | | | | Time To Repair Parameterization | | | |
|---|---|---|---|---|---|---|---|---|
| | Best fit Distribution | Parameter 1 | Parameter 2 | MTBFi | Best fit Distribution | Parameter 1 | Parameter 2 | MTTRi |
| CH_001 | Weibull | α=85,72 | β=0,72 | 106 | Normal | μ=4,1 | σ=1,12 | 4,10 |
| FEED_001 | Weibull | α=82,01 | β=0,87 | 88 | Normal | μ=3,9 | σ=1,31 | 3,90 |
| CONV_001 | Exponential | λ=0,054 | | 19 | Normal | μ=1,2 | σ=0,60 | 1,20 |
| CONV_002 | Weibull | α=15,84 | β=0,65 | 22 | Exponential | λ=0,76 | | 1,32 |

## 4. SIMULATION MODEL

To model and simulate the process, it is necessary to consider all the specific operating conditions and all realistic restrictions that exist and are physically respected by the real process. The main characteristics of each piece of equipment to be considered in the simulation model are listed in Table 2, and the restriction related to the logical and functional dependency were explained in detail in the section: Modelling of the system. The FT for both main scenarios helps to build the model in RelPro environment.

The simulation must consider an overall production rate, which is similar for all equipment according to the serial setting explained. Each piece of equipment must be able to produce at the rate required by the process, this being totally or partially as demanded by the system.

For this specific case, the rate considered is 3000 ton per hour, and it assumes that the ore input is equivalent to the ore rate output demanded by the process. This means that in any case the system will stop for lack of supply or for capacity problem after the second conveyor belt (feeding the stockpile).

The graphical models (base for the simulation) developed in RelPro are presented and discussed next.

### 4.1. About RelPro

Processing systems depends in part on the operating logic established, for this RelPro has efficient algorithms dedicated exclusively to the representation and analysis of these logics. Most of continuous simulators, or discrete but with continuous control and monitoring variables, perform the calculation of indicators and identification of states through monitoring at certain intervals of time (usually very small), this procedure is slightly efficient when it is compared to vision oriented just to the state change of components of the system. That means that the monitoring and consultation is performed only when something in the system changes state, either random or planned condition. For this, a continuing evaluation of the state of each system element is required. So, in the field of simulation, RelPro is a simulator based on discrete-event occurrence, in contrast with continuous simulation in which the simulation continuously tracks the system dynamics over time. The impact generated depends exclusively on the established functional dependencies and diagrammed in RelPro environment.

The main elements of the modeling are: Tree of components representing the hierarchical structure in the systems, and the flow chart includes:

- ✓ Actionable nodes representing systems, subsystems or equipment, logic-nodes configuration (method by which distributed or flow conditions over the subsequent process) input and output nodes (clarifies the input and output of material processed).
- ✓ Bows, correspond graphically to arrows, represent the transfer of flux.

The graphical models (base for the simulation) developed in RelPro are presented and discussed next

### 4.2. Simulation Modelling and Analysis in RelPro environment

Now, as was mentioned at the end of the section “Modelling of the System” RelPro will consider the traditional scenario (immediate effect of detention) and the constraint scenario (resilience approximation). With this, the simulation modelling is:

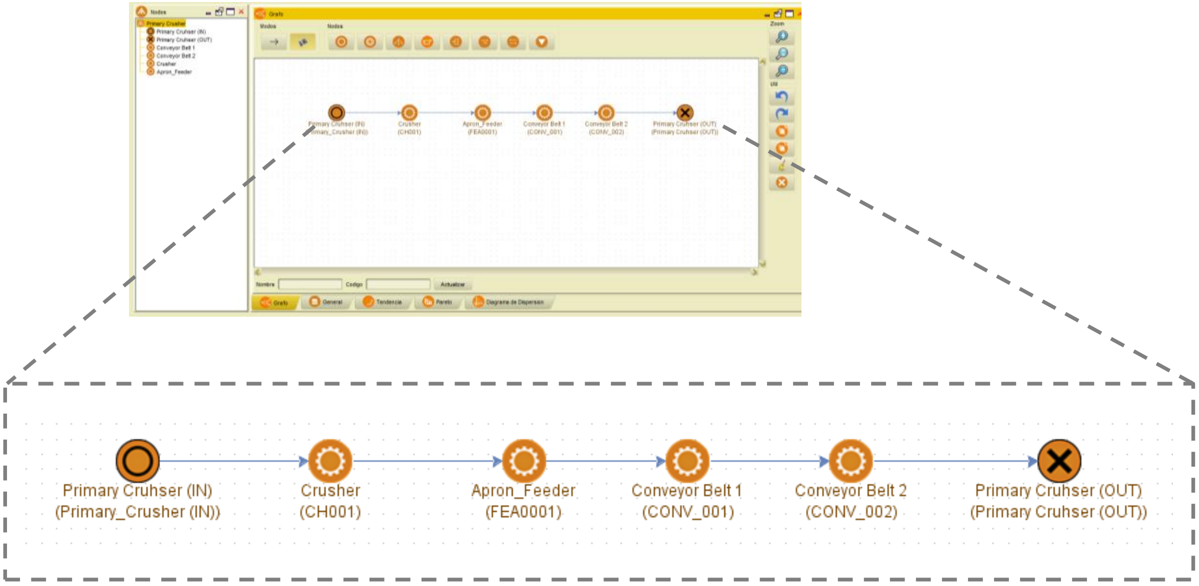


**Fig. 5 Graphical representation of modelling in RelPro environment – Immediate effect scenario**

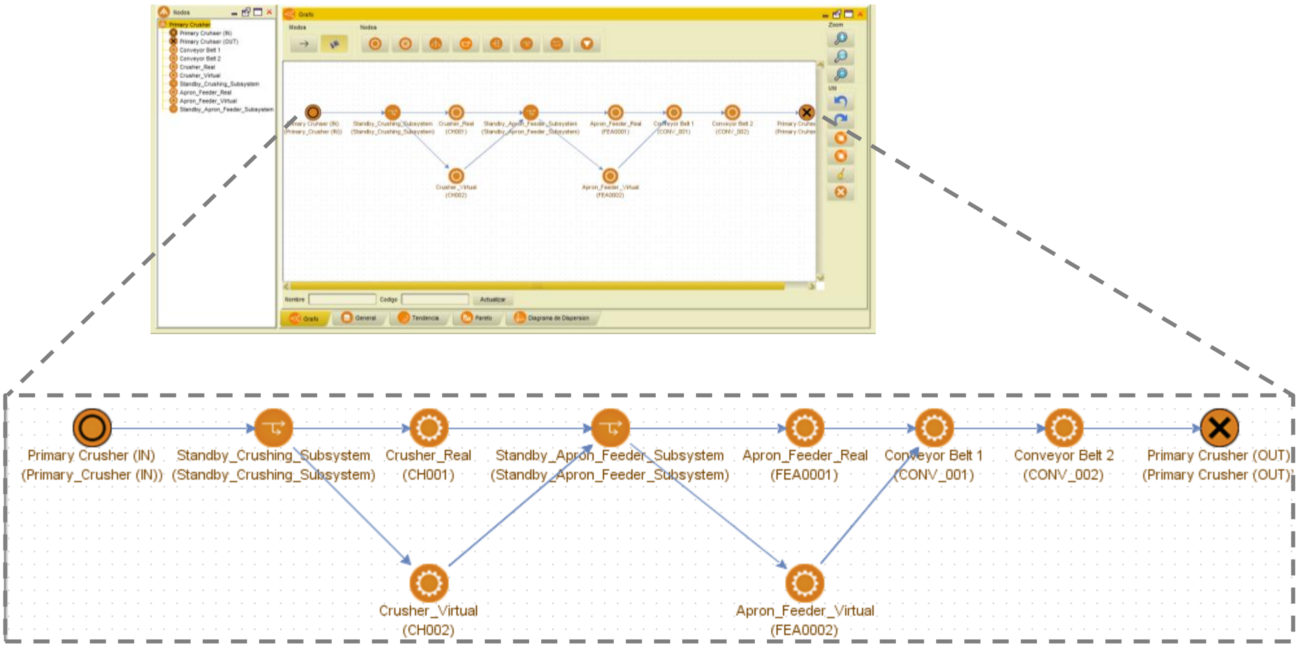


**Fig. 6 Graphical representation of modelling in RelPro environment – Resilience approximation scenario**

For both scenarios is required (inputs) the data about the characteristics of each piece of equipment considered in the simulation (See table 2). Furthermore, for "resilience approximation" it is assumed that the standby equipments (virtual machineries for modelling) come into operation immediately after the failure of the primary machinery (Crusher and Apron Feeder) and the repair actions are independent. This consideration is traditionally recognized as cold-standby [22].

As we know, the resiliencie time for primary machineries is between 30 and 40 minutes, so the parameters of life degradation and repair time will be modelled by Uniform Distribution..

### 4.2. Simulation Results

A total of 1000 replication were performed over a time horizon of 1 year (8760 hours) of operation. The main reason for selecting this simulation horizon, executed 1000 times, is to provide a representative sample to generate histograms readable and compelling indicators. In addition, some

pieces of equipments have small times to failure values (e.g. Belt Conveyors); so on the time horizon will become very significant. The results of the 1000 simulation are summarized in table 3 and table 4. The performance indicators to measure are: Mean % Availability, Mean % of Operation, MTTF, MTTR and the Mean of total production of the sys-tem.
The results for the immediate effect scenario are:

**Table 3. Summary of simulation results – Immediate effect scenario**

| Equipment | Indicator of Performance | | | | |
|---|---|---|---|---|---|
| | Mean % Availability | Mean % Oper. Time | Mean Production (MM Tons) | MTTF | MTTR |
| CRUSHING SYSTEM | 81,25% | 81,25% | 21,355 | 8,24 | 1,90 |
| CH_001 | 96,10% | 81,25% | 21,355 | 90,41 | 4,11 |
| FEED_001 | 95,72% | 81,25% | 21,355 | 75,06 | 3,93 |
| CONV_001 | 93,75% | 81,25% | 21,355 | 16,10 | 1,23 |
| CONV_002 | 94,18% | 81,25% | 21,355 | 18,56 | 1,32 |

According to the results and in relative terms, CONV_001 and CONV_002 will be the critical equipment in terms of availability (93,75% and 94,18%). The expected mean production of the system is 21,355 Million of Tons, equivalent to 7.118,17 hours of operation. As the model simulation does not include planned stoppages (maintenance or operational stoppages), the % mean availability of the crushing system is equal to the % mean operational (81,25%).
Another important result, from the systemic point of view, is the frequency of failure which is each 8,24 hours of functioning, and the mean time to repair is around 1,9 hours. These last indicators are the main reason of the low % mean operational time, mainly represented by the high frequency of failure of the system. As the logical configuration is in series, any change state (planned or not planned) of any equipment will impact over the change state of the overall system.
So, to improve the reliability of the overall process (decrease the frequency of system failure) will be necessary to improve the reliability of conveyors CONV_001 and CONV_002, this means increasing the mean times to failure, 16,10 and 18,56 respectively.
A direct analysis of maintainability indicators suggest that we should not be concern about it, however, if the direct cause of the reliability results of single equipments is the low quality of maintenance execution (e.g. poor technical skills of maintenance personnel, spare parts in poor condition, lack of work procedures, environmental conditions, and other.), efforts should be focused to correct deviations in reliability and maintainability.
Next will be presented the histogram of Production (Tons). The histograms for availability and % of Operational time can be obtained directly from the Software RelPro.

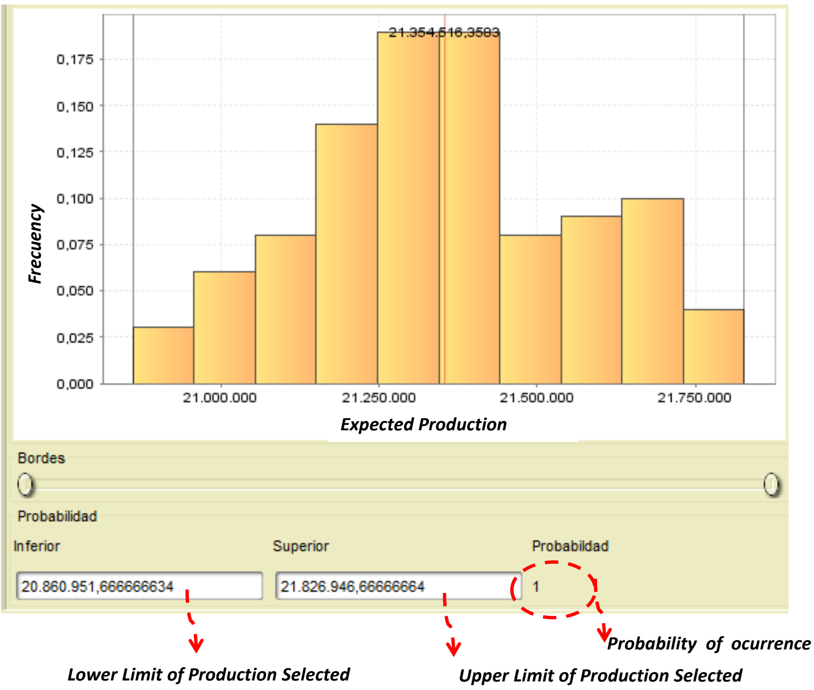


**Fig. 7 KPI´s Histograms for Immediate effect scenario**

**Table 4. Summary of simulation results – Resilience approximation scenario**

| Equipment | Indicator of Performance | | | | |
|---|---|---|---|---|---|
| | Mean % Availability | Mean % Oper. Time | Mean Production (MM Tons) | MTTF | MTTR |
| CRUSHING SYSTEM | 82,53% | 82,53% | 21,689 | 8,42 | 1,78 |
| STANDBY PRIMARY CRUSHER SUBSYSTEM | 96,89% | 82,53% | 21,689 | 93,44 | 3,53 |
| CH_001 | 96,29% | 82,53% | 21,568 | 92,85 | 4,12 |
| CH_002 | 14,56% | 82,53% | 0,012 | 0,59 | 4,11 |
| STANBY APRON FEEDER SUBSYSTEM | 96,43% | 82,53% | 21,689 | 76,63 | 3,29 |
| FEED_001 | 95,79% | 82,53% | 21,547 | 76,04 | 3,88 |
| FEED_002 | 15,19% | 82,53% | 0,142 | 0,59 | 3,91 |
| CONV_001 | 93,76% | 82,53% | 21,689 | 16,36 | 1,23 |
| CONV_002 | 94,25% | 82,53% | 21,689 | 18,87 | 1,30 |

Again, conveyors are the critical equipment in terms of availability. The primary crusher and Apron feeder subsystems have increased their availability thanks to the virtual equipments configured into the RelPro environment. The mean production is 21,689 Million of Tons, equivalent to 7.229,66 hours of operation. Similarity to the previous scenario simulated, the model simulation does not include planned stoppages (maintenance or operational stoppages), so the % mean availability of the crushing system is equal to the % mean operational time (82,53%). The latter is a key indicator to compare the results between simulation models. The results of frequency of failure (8,42 hours of functioning) and mean time to repair (1,78 hours) also have improved, supporting the increased production (+ 0.3 million of tones) and availability (+1,3%) results.

Next will be presented the histogram of Production (Tons). The histograms for availability and % of Operational time can be obtained directly from the RelPro environment.

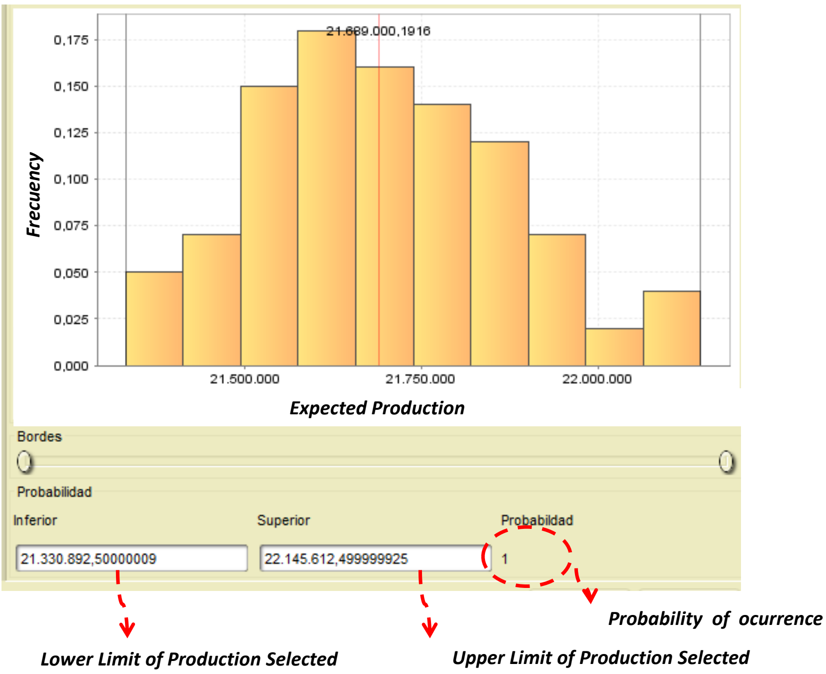


**Fig. 8 KPI´s Histograms for Resilience approximation scenario**

The variability in the production level shown in Fig. 7 and 8 is due to the stochastic characteristic of the behaviour of the equipments in the system. Also, the convergence and concentration of area around the aver-age of the production histogram supports the good results obtained with 1000 simulations.
As a special case, the % mean availability for virtual equipment (CH_002 and FEED_002) is calculated considering that the time horizon for the calculation is only during the primary equipment repair, so this percentage represent the mean % of time where the virtual equipment support to the primary equipment, and its equivalent to 14,5% and 15, 19% respectively.

Comparing the results of the simulated scenarios, it can be concluded:

- ✓ The considered resilience contributes significantly to the outcome of the business, validated by the increased availability, operation time and the expected production.
- ✓ The Standby approximation modeled in RelPro meets the objectives pursued by analysts.
- ✓ For both, the main problem is the reliability of the selected critical equipment, this because of the high frequency of failure. So, next research must be focused to identify the primary causes of high frequencies trough, e.g. root cause analysis [24].
- ✓ Maintainability is controlled and requires no further attention since the focus of improvement is the reliability.

## 5. CONCLUSION

Performance analysis must be an integral part of mine engineering assessment and operational management, controlling operating plants or evaluating new designs project. Simulation is powerful tool to estimate performance (design stage), even more when characteristics of reliability, maintainability, productivity and functional dependencies features are integrated to the model. The main result of this paper is a new modelling approach to simulate a production plant, developing a case study of a real mining process (primary crushing process), including a specific scenario with a restriction formally known as resilience. It was implemented via the simulation program RelPro.
The numerical results clarify the effect of the resilience in the performance results (1,3% increase in availability and production) and allows preliminarily identify critical equipment or possible

bottlenecks, in terms of reliability and maintainability. The detail of results are clearly specified and explained in last section.
As a summary, the result of the modelling allows:

- ✓ Project the performance of each piece of equipment, subsystems, and overall crushing systems.
- ✓ It is possible to identify the equipment (s) with the worst performance – Potential bottlenecks.
- ✓ Identify responsibilities in the outcome of system performance, acknowledging directly the effect of reliability and maintainability.
- ✓ With the histograms of the simulation will possible to make a decision with a level of risk (probability), e.g. Fig. 7 and 8 shows the histogram of production and the respective probability.
- ✓ Compare the result for both scenarios, calculating the expected effect of the operational restriction (resilience). Furthermore, for future research, the time of resilience may be sensitized and evaluated if necessary.

Future possibilities to analyze with RelPro:

- ✓ Histograms for each selected indicator of performance.
- ✓ Add new indicator, such as: number of failure events, preventive events and operational detention events; total time of corrective maintenance/preventive maintenance/operational detentions; budget for maintenance, and others.
- ✓ Basic cause of the Operational stoppages, it refers to intrinsic detention of the equipment (e.g. misalignment of the conveyor belts) or Operational stoppages propagated from other piece of equipment in the system (e.g. if the belt conveyor 1 fail the rest of the system will stop obligatory. So, this event will be recorded as a detention propagated in the rest of equipments of the system).
- ✓ The modelling method may be adopted in order to analyze more complex systems or process.

Future possibilities to sensitize and analyze with RelPro:

- ✓ Probabilistic parameters of life and repair (genetic).
- ✓ Preventive frequencies at equipment level.
- ✓ Design of the process, involving redundancies, priorities, load sharing and overload capacity. Furthermore, recirculation characteristics.
- ✓ Time of resilience (increase or decrease) and evaluate the impact evolution.

Finally, the authors encourage the use of this model to evaluate the expected performance as early as at the design stage, ensuring highly efficient investments and positive impacts on future productivity.

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