Application of GenRel for Maintainability Analysis of Underground Mining Equipment: Based on Case Studies of Two Hoist Systems

By

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Abstract

With the increasing costs of extracting ores, mines are becoming more mechanized and automated. Mechanization and automation can make considerable contributions to mine productivity, but equipment failures and maintenance have an impact on the profit. Implementing maintenance at suitable time intervals can save money and improve the reliability and maintainability of mining equipment. This thesis focuses on maintainability prediction of mining machinery. For this purpose, a software tool, GenRel, was developed at the Laurentian University Mining Automation Laboratory (LUMAL). GenRel is based on the application of genetic algorithms (GAs) to simulate the failure/repair occurrences during the operational life of equipment. In GenRel it is assumed that failures of mining equipment caused by an array of factors follow the biological evolution theory. GenRel then simulates the failure occurrences during a time period of interest using genetic algorithms (GAs) coupled with a number of statistical techniques. This thesis will show the applicability and limitation of GenRel through case studies, especially in using discrete probability distribution function.

One of the objectives of this thesis is to improve GenRel. A discrete probability distribution function named Poisson is added in the pool of available probabilities functions. After improving and enhancing GenRel, the author carries out two groups of case studies. The objectives of the case studies include an assessment of the applicability of GenRel using real-life data and an investigation of the relationship between data size and prediction results. Discrete and continuous distribution functions will be applied on the same input data. The data used in case studies is compiled from failure records of two hoist systems at different

mine sites from the Sudbury area in Ontario, Canada.

The first group of case studies involves maintainability analysis and predictions for a 3-month operating period and a six-month operating period of a hoist system. The second group of case studies investigates the applicability of GenRel as a maintainability analysis tool using historical failure/repair data from another mine hoist system in three different time periods, three months, six months and one year. Both groups apply two different distribution probability functions (discrete and continuous) to investigate the best fit of the applied data sets, and then make a comparative analysis. In each case study, a statistical test is carried out to examine the similarity between the predicted data set with the real-life data set in the same time period. In all case studies, no significant impact of the data size on the applicability of GenRel was observed. In continuous distribution fitting, GenRel demonstrated its capability of predicting future data with data size ranging from 166 to 762. In discrete probability fitting, the case studies indicated to a degree the applicability of GenRel for the hoist systems at Mine A and Mine B.

In the discussion and conclusion sections, the author discloses the findings from the case studies and suggests future research direction.

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Chapter 1 Introduction

1.1 Background

As mining equipment becomes more complex and sophisticated, its cost is rising sharply (e.g cost of materials and precision machined parts). Any minor failure which can cause equipment shut down will affect a mine's operating efficiency. To meet production targets, mining companies are increasingly demanding higher equipment reliability. Reliability is a performance indicator of overall equipment condition and is defined as the probability that a piece of equipment will perform its function satisfactorily for the desired period of time when used according to specified conditions. In the industrial sector reliability is frequently expressed in terms of Mean Time Between Failures (MTBF) (Dhillon, 2008).

There are many reasons for improving mining equipment reliability. Some of these are as follows:

- To maximize profit
- To reduce the cost of poor reliability
- To reduce unplanned maintenance costs and frequency
- To provide more accurate short-term forecasts for equipment operating hours
- To overcome challenges imposed by global competition
- To take advantage of lessons learned from other industrial sectors such as aerospace, defense, and nuclear power generation (Dhillon, 2008).

1.2 Reliability

1.2.1 Definition

According to an International Electrotechnical Commission (IEC) document published in 1974 (Dhillon, 2008), Reliability is defined as the capability of a product, system or service to perform its expected job under the specified conditions of use over an intend period of time.

The reliability function is defined by

$$R(t) = 1 - F(t) = 1 - \int_0^t f(x)dx$$

where

$F(t)$ is the cumulative failure distribution function.

$f(x)$ is the density failure distribution function.

$R(t)$ is the reliability function or simply reliability at time t.

1.2.2 Related measurements

Mean Time Between Failure (MTBF) is the mean of the failure distribution of a machine or component. For a constant failure rate, it is expressed as the total operating time divided by the total number of failures (Dhillon, 2008).

Mean Time Between Failure= $MTBF = \dfrac{TH - TDT - TSH}{NF}$

where

TH is the total hours

TDT is the total downtime hours

TSH is the standby hours

NF is the number of failures

For discrete distribution

$$MTBF = \sum t * p(t)$$

For continuous distribution

$$MTBF = \int t * f(t) dt$$

where

$p(t)$ is the discrete probability

$f(t)$ is the probability density function

1.2.3 Improving reliability

Basic steps for improving reliability include:

- Step 1: Measure the number of times and the reasons equipment is stopped.
- Step 2: Use suitable statistics methods to analysis the data collected in step 1, identify main reason of high frequency stoppages.
- Step 3: Analyze these high frequency stoppages.

1.2.4 General factors affecting equipment maintenance characteristics in mining operations (surface or underground)

Geology: Variability in digging conditions can lead to the need for shovels or trucks to stop, even momentarily. Similarly, ore grade that is different from what is expected also can cause the need for an interruption to production.

Accident Damage: A production issue, which causes an interruption to the production process if the equipment must be taken out of service for inspection or repairs.

Equipment Failure: Clearly a maintenance issue, which causes an interruption to the production process.

Routine Maintenance: Routine servicing, component replacements and overhauls cause interruptions while the equipment is taken out of service.

Weather: Rain or fog can interrupt the production process(surface mining). Cold weather can severely affect equipment working performance.

Downstream Processes: In a direct tipping situation, if the downstream process stops, this can cause an interruption to the mining operation. If during this stoppage, ore is tipped onto a stockpile, a further interruption is experienced when the downstream operation starts up again.

Shift Changes and Crib Breaks: Every shift change and crib break causes an interruption to the steady-state nature of the operation.

Spillage and Housekeeping: The need to stop to clean up spillage in the vicinity of the shovel, or in the dump area, also causes an interruption of the process.

Minor Production Stoppages: "Comfort stops," mirror adjustments and other minor stoppages interrupt the production process.

The Blast: Always for equipment near the blast in development. There is a need to stop the equipment during a blast.

Ineffective Blasting: If the blast is ineffective, this can lead to problems with diggability in certain areas. This also causes equipment not to operate reliably.

Refueling and Lubrication: Stopping equipment to refuel and to lubricate also interrupts the production process (Dunn,1997).

1.3 Maintainability

1.3.1 Definition

Maintainability is defined as a characteristic of design and installation expressed as a probability that an item will be retained in or restored to specified conditions within a given period of time, when maintenance action is performed in accordance with prescribed procedures and resources (Calabro, 1962).

A system with better maintainability would inherently provide the benefit of lower maintenance costs, less time to recover with lower breakdown frequency (design for simplicity), less complexity of maintenance tasks and relatively reduced man-hours (AMCP706-134, 1972).

For density function, the maintainability function is defined

$$M(T) = \int_0^T f_r(t)dt$$

For cumulative function, the maintainability function is defined

$$M(T) = F_r(t \leq T)$$

where

$M(T)$	is the maintainability function,
T and t	are time,
$f_r(t)$	is the repair time probability density function,
$F_r(t)$	is the repair time cumulative distribution function

1.3.2 Related measurements

Mean Time to Repair (MTTR)

The mean time required to repair a component, expressed as the total repair time divided by the total number of repairs, as shown in equation (Vayenas et al., 1997; Peng, 2011).

$$MTTR = \frac{RT}{NR}$$

Where,

RT is the total repair time,

NR is the number of repairs.

For discrete distribution

$$MTTR = \sum t * p(t)$$

For continuous distribution

$$MTTR = \int t * f(t) dt$$

Where,

$p(t)$ is discrete the probability

$f(t)$ is the probability density function

1.3.3 Factors affecting maintainability

There are several factors which affect maintainability and they may be grouped under the two major headings of design and installation.

Typical of those which are related to design are reliability, complexity, interchangeability, replace-ability, compatibility, visibility and configuration. The installation factors generally relate to the human being who is charged with maintaining the equipment. Other factors include the environment, equipment overhaul or modification, and available test and calibration techniques (Calabro, 1962).

1.4 Genetic Algorithms (GAs)

A Genetic Algorithm (GA) imitates a biological evolution process and is often used to seek optimal solution to a practical problem, expressed by the best fitted individual string of values (representing parameters of the practical problem). GAs encode the decision variables (or input parameters) of the underlying problem into strings. Each string, called individual, is a candidate solution. A fitness function to differentiate good candidate solutions from bad candidate solutions is used. A fitness function could be a mathematical expression, or a complex computer simulation, or in terms of subjective human evaluation and guide the evolution of solutions to the problem. The following is the procedure of Genetic Algorithms (Ahn, 2006):

- Initialization

Generate initial data list A from random numbers

- Fitness evaluation

Find suitable fitness function for this data list

- Selection

Select a set of promising candidates B from the data list

- Crossover

Apply crossover to the candidate set B, and get an offspring set C

- Mutation

Some mutations happen in the offspring set C, then obtain the new offspring set C'

- Replacement

Use the new offspring set C' to replace initial data list A

- <u>Termination</u>

If the termination criteria are not met, go to "Fitness evaluation". In this thesis, termination criteria are the convergence limit and the maximum number of iterations.

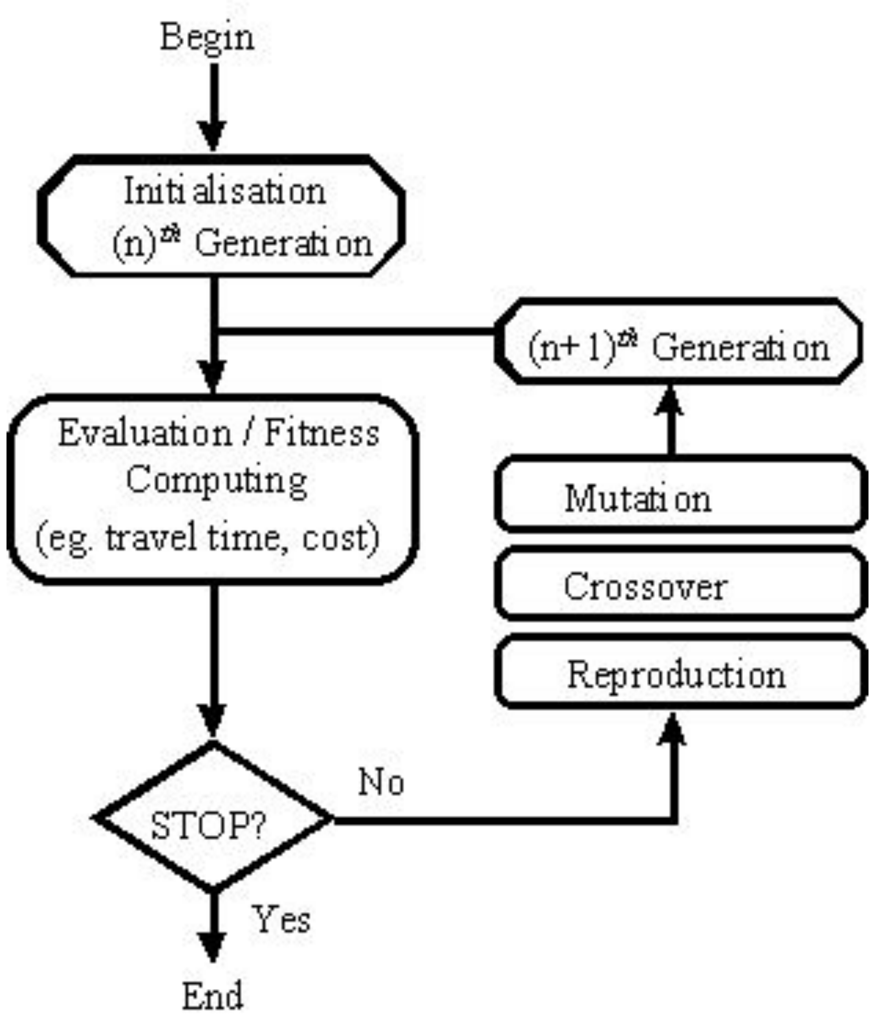

Figure 1.1 The flow chart of genetic algorithm

In a typical genetic algorithm, variables of interest are coded. Afterwards, the processes of mate selection, crossover, and mutation are repeated until the fitness function yields desired values (Goldberg, 1989). Figure 1.1 is the flow chart of genetic algorithm. The user can define the maximum number of iterations, the convergence limit, and the probability of mutation.

Research on GAs has a wide spectra of applications from computer science (Michalewicz, 1990; Srivastava and Kim, 2009) to engineering (Gen and Cheng, 1997; Goldberg, 1989; Shi et al., 2005) and, more recently, to fields such as molecular biology, immunology(McCall, 2005), economics(Aytug et al., 2003; Dawid and Kopel, 1998; Proudlove et al., 1998). In the mining engineering field GAs have been used, for examples, for ore grade estimation (Clement and Vayenas, 1994), ore grade optimization (Ataei and Osanloo, 2003), optimization of open-pit development system (Nie et al., 2007), coal mine production scheduling (Pendharkar and Rodger, 2000), and open pit truck dispatch (He et al., 2010).

Reliability and maintainability models with or without co-variates are based on the use of rigorous and complicated statistical techniques which include, for instance, theoretical probability distribution fitting, trend and serial correlation tests, and require assumptions of homogeneous or nonhomogeneous Poisson process or assumptions of proportionality of the hazard rate. The assumptions and statistical constraints of probabilistic reliability and maintainability models limit the ability of these models to accurately represent and fit all real life mining conditions (Vayenas and Nuziale, 2001).

GAs offer several key advantages over conventional mathematical models including: simplicity of randomized searches while retaining important historical information with the population, computational simplicity, GAs search from a population of solutions, not just from a single solution, and they can handle any kind of objective function linear or nonlinear constraints defined in discrete, continuous or mixed search spaces (Goldberg, 1989; Haupt and Haupt, 2004; Peng, 2011).

1.5 Thesis objectives and methodology

Each piece of mining equipment is comprised of electrical, hydraulic, instrumentation and mechanical parts. All these parts have their own characteristics. These characteristics affect reliability and maintainability of mining equipment, and they can be considered to be the genes of equipment. The genetic algorithm (GA) is an optimization and search technique based on the principles of genetics and natural selection (Haupt and Haupt, 2004). GenRel is a computerized model developed in MS-Excel using Visual Basic for Applications (VBA) for reliability and maintainability assessment of mobile mining equipment based on Genetic Algorithms (GAs). In an earlier version of GenRel, two continuous probability distribution functions, the Exponential and the Lognormal distribution functions were included in the function pool for distribution fitting purpose (Vayenas and Yuriy, 2007). Later, Wu (2009) added three more continuous distribution functions, the Weibull, Beta, and Normal distribution functions to the function pool with an improved algorithm logic in his thesis work. In the latest development, a discrete probability distribution, the Binomial distribution had also been added into GenRel (Peng, 2011).

There are two types of input, continuous and discrete. The Binomial distribution function is the only distribution function that can fit discrete data in GenRel. GenRel has a limited applicability for discrete distribution fitting of input data. The primary objective of this thesis is to add another discrete distribution function, the Poisson distribution function to GenRel. The Poisson function enhances GenRel in terms of applicability, particularly in cases of discrete data sets. Even though the Exponential probability distribution, the Lognormal probability distribution, the Weibull probability distribution, the Beta probability distribution and the Normal probability distribution can fit most data sets according to past research experience, a number of data sets cannot be fitted to any of the above five probability distribution functions. Driven by this fact, discrete probability distributions are introduced to fit input data.

The most common discrete probability distributions are the Binomial probability distribution and the Poisson probability distribution. The Binomial probability distribution has been added into GenRel by Peng, 2011. In this research, the primary objective is the addition of the Poisson probability distribution to further extend the applicability of GenRel. The second objective of this thesis is to examine the applicability of the latest version of GenRel to maintainability analysis of mine hoist systems using real-life data from mine sites. Data was collected from two underground mines, named for simplicity as Mine A and Mine B, in the Sudbury mining region in Ontario, Canada.

This is the first time that GenRel is applied in maintainability analysis of mine hoist systems. Previous applications of GenRel emphasized mainly reliability studies (see Peng, 2011). It is also the first time that a discrete distribution function fitting is applied for the input data in order to carry out the maintainability analysis.

Overall, this research attempts to determine the applicability and limitations of GenRel based on hoist data. Furthermore, this research attempts to assess whether the applied GAs based methodology can supplement existing probability reliability/maintainability methods based on GAs.

The methodology applied to this research work includes the following:

- Time To Repair (TTR) data from a hoist system was collected from a typical underground mine in Sudbury.
- Application of continuous and discrete distribution fitting functions on input data respectively, and finding the best fit.
- GenRel is then used to predict future TTR data (continuous or discrete). When GenRel is applied to the prediction of future data, criteria for convergence are considered, like maximum number of iterations and the numerical difference among the probability parameters of the generated output data in comparison with the probability parameters of the input data.
- Finally, comparison of the prediction in continuous and discrete distribution fitness to find a suitable distribution function for input data

1.6 Thesis organization

In Chapter one a general introduction is given. Chapter two offers an introduction to GenRel together with a new probability distribution and its inverse transform statistical technique. Chapter three presents an introduction of the case studies. Chapters four and five present three groups of case studies on maintainability prediction of a mine hoist system at Mine A, and another group of case studies of a mine hoist system at Mine B. Chapter six presents the discussion, possible reasons for GenRel's non-applicability, and suggestion for future research.

Chapter 2 Background and Improvements of GenRel

2.1 Introduction to GenRel

GenRel is a computer model developed in MS-Excel using Visual Basic for reliability and maintainability assessment of mining equipment based on Genetic Algorithms (GAs).

In a typical genetic algorithm, variables of interest are coded. Afterwards, the processes of mate selection, crossover, and mutation are repeated until the fitness function yields desired values (Goldberg, 1989). The application of GAs to GenRel is illustrated in Figure 2.1. The user can define the maximum number of iterations, the convergence limit, and the probability of mutation in the input interface, see Figure 2.2.

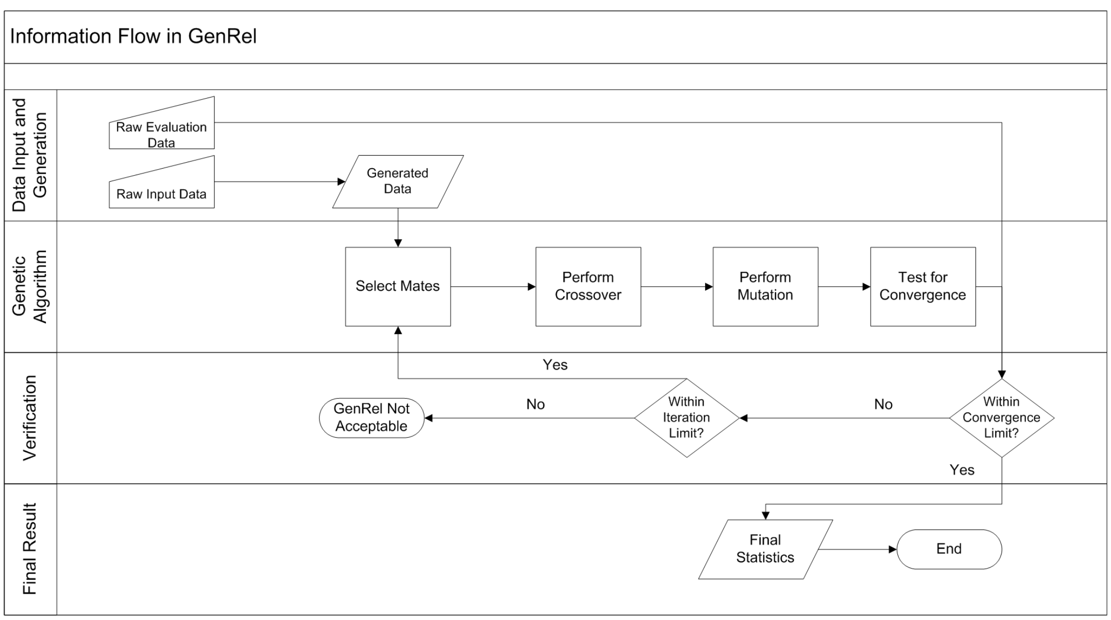

Figure 2.1 Information flow in GenRel

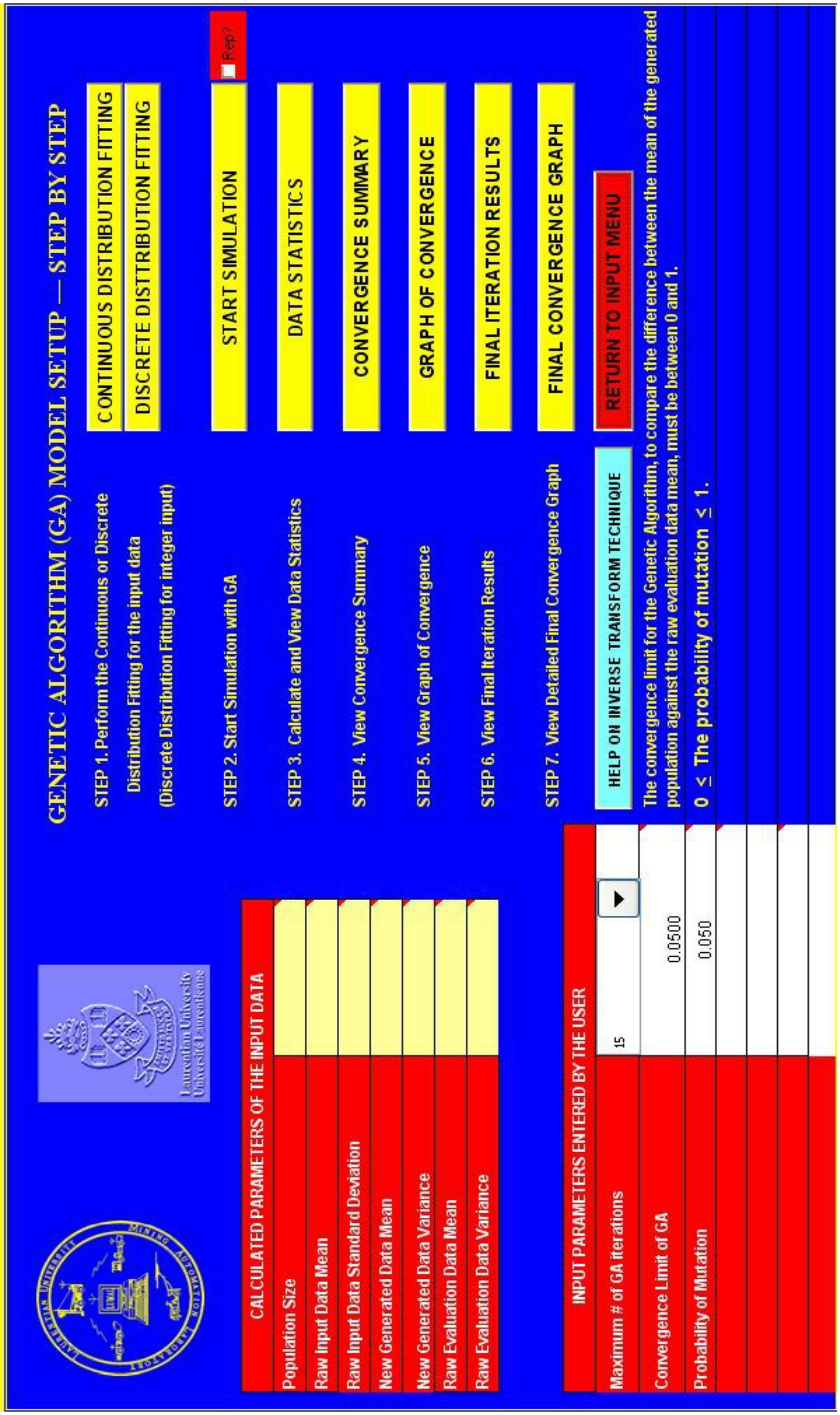

Figure 2.2 Input interface of GenRel

The raw data used in GenRel is derived from historical records in terms of Time Between Failures (TBF) in the case of reliability predictions and in terms of Time To Repair (TTR) in the case of maintainability studies. In GenRel, the distribution fitting process selects the best fitted probability distribution function $F(x)$ for the raw data. For example, take the exponential distribution (Kanji, 2006),

$$F(x) = 1 - \exp(-\frac{x-\gamma}{\beta}),\ (x \geq \gamma)$$

Where, x is a TBF value, β is the mean and γ is the location parameter.

The Raw Input Data set is used to generate new data sets, while the Raw Evaluation Data is used in the evaluation process of the generated data set. Suppose

$$\tilde{F}(x) = 1 - \exp(-\frac{x-\tilde{\gamma}_0}{\tilde{\beta}_0}),\ (x \geq \gamma_0)\ ,$$

and

$$F(x) = 1 - \exp(-\frac{x-\gamma_0}{\beta_0}),\ (x \geq \gamma_0)$$

where $\tilde{\beta}_0$ and β_0 are means, γ_0 and $\tilde{\gamma}_0$ are the location parameters, $F(x)$ and $\tilde{F}(x)$ are the best fitted probability distribution functions for the Raw Evaluation Data set and for the Raw Input Data set, respectively (Vayenas, Peng and Farah, 2011). In order to generate new data from the Raw Input Data, we use the Inverse Transform Technique (ITT) by transforming the Exponential distribution function into the inverse format and by generating a uniformly distributed random variable $R \sim U(0,1)$ for a general discussion about the ITT see (Law and Kelton, 2000). Then, six sets of generated data can be yielded by $x = -\tilde{\beta}_0 \ln(1-R) + \tilde{\gamma}_0$. Through experiments, it was found that six sets of new data are considered adequate for the prediction process within GenRel.

The generated data is then used for mate selection and crossover in which a random number determines the positions and total number of crossovers, yielding offspring data. Afterwards, mutation is performed at a specified rate defined by the user as mutation probability. Six sets of new offspring data follow the respective best fitted Exponential probability distribution functions, denoted by parameter pairs $(\beta_i, \gamma_i), (i = 1, 2, 3...6)$, where β_i and γ_i represent mean and location of the respective probability distribution functions. A fitness function

$$f = \frac{|\beta_i - \beta_0| + |\gamma_i - \gamma_0|}{|\beta_0| + |\gamma_0|}, (i = 1, 2, 3...6),$$

is designed to measure the fitness of each individual offspring data set, for detailed discussion of this procedure, see (Wu, 2009). The overall structure of this iterative procedure is shown in figure 2.1.

If the smallest value of the six fitness function values is not greater than the user-defined convergence limit, then the iterative process is terminated and GenRel is considered applicable for prediction of future failure data; otherwise another iteration will be implemented as long as the pre-set maximum number of iterations is not exceeded and the smallest fitness function value is within a user defined convergence limit. The convergence limit is the upper limit of deviation between the probability distribution functions of the generated data sets and the probability distribution function of the Raw Evaluation Data set.

2.1.1 Main steps in the application of GenRel:

Overall, after the above described algorithmic process is successful, GenRel can be applied to predict future failure data. Otherwise, GenRel is considered unacceptable for prediction in regards to the raw input data.

In summary, the three key steps in the application of GenRel are :

Step 1 Data Preparation: An adequate size of historical input data must be gathered (e.g. six months of failure data per piece of equipment). The data set must be divided chronologically into a set of Raw Input Data and into a set of Raw Evaluation Data. Failure data may include Time Between Failures (TBF) or Time To Repair (TTR) and type of failure per piece of mining equipment.

Step 2 Verification: The above two sets of data are used to verify whether GenRel can be used as a predictor of the reliability or maintainability of the mining equipment under study. If the verification process is successful, then the hypothesis that GenRel can be applied to predict future equipment failures based on these input data sets is acceptable. After the verification process is successfully completed, the Raw Input Data set and the Raw Evaluation Data set are merged to a single Raw Input data set.

Step 3 Prediction: In this step, GenRel is used to predict future failure data. The Raw Input Data in this step is generated in Step 2, and Raw Evaluation data in this step is the historical data of time period for prediction. After a distribution function is acquired to fit the Raw Input Data set, the inverse transform technique is used to generate random numbers as offspring data sets (Law and Kelton, 2000). These offspring data sets start the iteration of cross-over and mutation with a probability of mutation entered as an input by the end user of GenRel. When the model is applied for prediction of future failure data, criteria for convergence are considered such as the maximum number of iterations and the numerical difference of the probability parameters of the generated data in comparison with the probability parameters of the input data. The algorithm is terminated when either maximum number of iterations or a convergence limit pre-set by the end user is reached. If these criteria are not met, it is then considered that the model cannot be used with sufficient statistical confidence and thus, other maintainability methods for failure prediction should be examined (Peng, 2011).

For more details of the algorithmic procedure applied in GenRel, see (Vayenas and Wu, 2009). In general, the procedures in GenRel's logic are as follows:

2.2 Procedures in GenRel's logic

There are four main procedures in GenRel:

- Data preparation

Input data of GenRel can be either Time Between Failures (TBF) (for reliability assessment) or Time To Repair (TTR) data (for maintainability predictions), field data from mine sites must be applied as TBF/TTR data. For discrete distribution fitting, the requirement of input data is integer. TBF/TTR data need to transform to integer to meet the statistical fitting requirements

- Trend test and serial correlation test

Prior to statistical analysis and probability distribution fitting, the data should be tested for trends and serial correlations. The purpose of these test is to verify the assumption that the data is Independent and Identical Distribution (IID) (Vayenas et al., 1997). Trend test presents a linear relation between cumulative TTR and cumulative TTR numbers. Serial correlation test presents a scattered pattern between the ith TTR and (i-1)th TTR. If data is IID, then it can statistically be represented/ fitted by theoretical probability distribution.

- <u>Validation of convergence</u>

If there is a specific probability distribution fitting that can fit the Raw Input Data, then we can use the inverse transform technique to generate new data sets. In this thesis, six data sets will be generated, and used for prediction.

Convergence criteria includes the convergence limit, the probability of mutation, and the maximum number of iterations. If the smallest fitness function value falls within the convergence limit, then the validation of convergence is considered successful. Otherwise, we run the crossover and mutation process, iterating the initially generated data sets, achieving an acceptable value and not exceeding the maximum number of iteration.

- <u>Prediction</u>

Through the above procedures, GenRel can be applied to predict future failure data. Six data sets will go through selection, cross-over, and mutation until the smallest fitness function values fall within the convergence limit and if not, until a maximum number of iterations has been reached.

2.3 Improvement of GenRel

When GenRel was developed at first, two probability distribution models were included, the Exponential probability distribution and the Lognormal probability distribution (Vayenas and Yuriy, 2007). Later in the work of Wu (2009), more probability distribution models were added to expand the pool of probability fitting functions. These probability distribution functions included the Weibull probability distribution, the Beta probability distribution and the Normal probability distribution.

Table 2.1 shows the applicable probability distribution functions in GenRel's probability distribution pool.

Probability distribution	Continuous	Discrete
Exponential	Yes	No
Lognormal	Yes	No
Weibull	Yes	No
Beta	Yes	No
Normal	Yes	No
Binomial	No	Yes
Poisson	No	Yes

Table 2.1 Applicable probability distribution functions in GenRel's probability distribution pool

Even though the Exponential probability distribution, the Lognormal probability distribution, the Weibull probability distribution and the Binomial probability distribution can fit most data sets according to past research experience, a small number of data sets cannot be fitted to any of the above three probability distribution functions. Since the discrete probability distribution pool include only one probability distribution, namely the Binomial probability distribution, then GenRel had a limited applicability for discrete distribution fitting of discrete input data sets. Thus, the Poisson probability distribution function is added to the fitting pool in GenRel.

The Poisson cumulative function is

$$F(x,\lambda)=\sum_{k=0}^{x}\frac{e^{-\lambda}\lambda^{k}}{k!} \qquad \text{(Eq. 2.1)}$$

The Poisson density function is

$$P(X=k)=\frac{e^{-\lambda}\lambda^{k}}{k!} \qquad \text{(Eq.2.2)}$$

Where,

The random variable X denotes the number of successes in the whole interval.

λ is the mean number of successes in the interval

k is an discrete integer not less than one (Palisade, 2005)

2.3.1 Applicability of the Inverse Transform Technique for the Poisson distribution

In the Poisson distribution function, a problem arises when data is collected according to a Poisson process whose underlying intensity is indirectly related by a linear operator k (See Eq. 2.2) to the intensity (the object that we wish to estimate) of another Poisson process. This kind of indirect problem is referred to as a Poisson inverse problem(Antoniadis and Bigot, 2006). There is no analytical solution (mathematical formula) for the Poisson inverse transform (Matlab, 2014). Thus, a computerized procedure is suggested as shown in Figure 2.3 with the following steps:

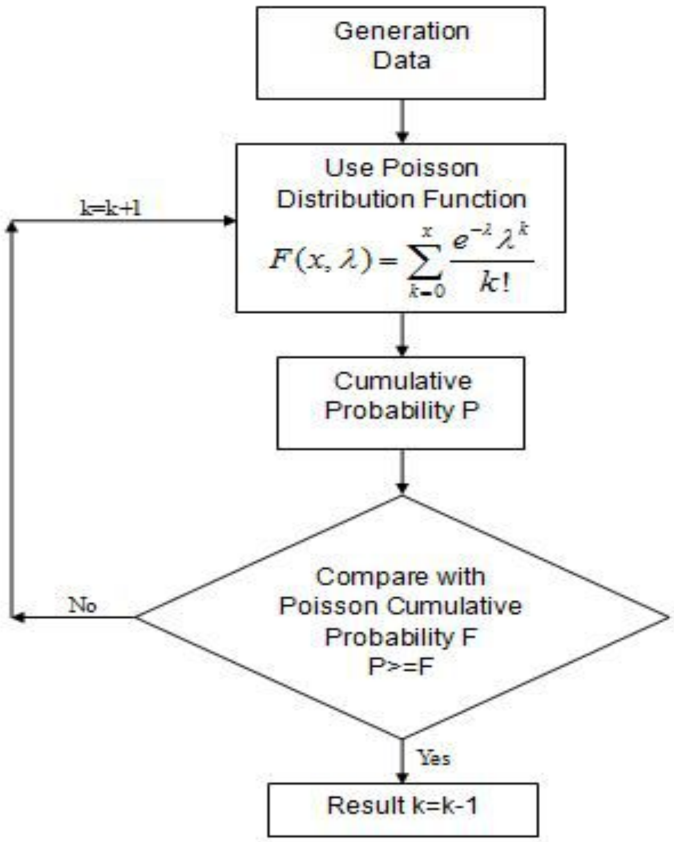

Figure 2.3 Flowchart of the applicable Poisson inverse transform technique

Where,

λ is the mean number of successes in the interval

k is an discrete integer not less than one (Palisade Corporation, 2002)

Cumulative Probability P is the Poisson cumulative probability value at x=k

Cumulative Probability F is the Poisson cumulative probability value which is generated by Raw Input data

Steps for the Poisson inverse transform technique

- input data follows the Poisson distribution
- Poisson distribution function for best fit
- Use the Poisson cumulative distribution function and perform iterations to find the point k

- For these points k whose cumulative probability function value is higher than the cumulative probability function value of the new generation data, then use k-1. The code is attached in Appendix A.

2.4 Introduction of underground hoist systems

Increases in depth of underground mines, requirements of increased productivity, expectations of reduction in energy consumption, together with better safety requirements provoke challenges to mine extraction systems. In deep underground mines, hoist systems play a more and more important role to turn mineral resources into profits.

Figure 2.4 (ABB, 2014) shows a typical underground mine hoist system. A hoist in an underground mine site is used to move the ore and waste rock, and also move personnel, equipment and other materials. As early as the 16th century, a hoist system was used to raise and lower conveyances within a mine shaft. Human, animal and water power were used to power the mine hoists. In today's mines, mine hoist systems are almost all driven by electric motors, using either direct current drives with solid-state converters (thyristors) or alternating current drives controlled by variable frequency (de la Vergne, 2003). Usually hoist systems can be classified into three categories, drum hoist, friction hoist (also known as Koepe hoist), and Blair multi-rope hoist (de la Vergne, 2003). A skip hoist system usually includes mechanical equipment, shaft equipment, power system, digital control and monitoring system.

The data used in the case studies is derived from computerized failure records of two hoist systems at different mine sites (called Mine A and Mine B for simplicity) from the Sudbury area in Ontario, Canada. The data was provided “as is”from the mine sites.

In Mine A, the capacity of the skip is 14.2 tons with production rate of 19 skips/hour. In Mine B, the capacity of the skip is 18 tons, with a production rate of 25 skips/hour.

A skip hoist system usually consists of the following subsystems:

1. Mechanical system;

- Prime mover (electric motor)
- Structural
- Skip
- Hoist ropes
- Drive Train components connected to the prime mover (including transmission, clutch and braking assembly)

2. Hydraulic system;

The hydraulic system is the power transmission system of the Hoist System which uses fluid mechanics to transit force from the prime mover of the machine to the dynamic components.

3. Electrical system;

A typical electrical system includes batteries, starter, hoist motor controls, wiring, and the automation components, also included are the digital control and monitoring system.

Figure 2.1 Mine hoist system (ABB, 2014)

Chapter 3 Introduction to the Case Studies

Currently, there are seven probability distribution functions in GenRel's fitting pool. The Exponential, Lognormal, Weibull, Beta and Normal are continuous distribution functions; Binomial and Poisson distributions are applicable for discrete data sets. The following case studies are used to analyze the maintainability of hoist systems in Mine A and in Mine B in the Sudbury mining region. Each case study in Mine A deals with input data for a period of three months and six months. Case studies in Mine B deals with input data for a period of three months, six months and of one year. Data was collected from Jan 1st, 2006 to Dec 31st, 2008. Since data sets from Jan 1st, 2006 to Dec 31st, 2008 have already been used to analyze reliability of hoist systems (see Peng, 2011), using data from the same time period we can demonstrate the feasibility of the latest version of GenRel in the case of maintainability studies. Figure 3.1 and 3.2 depict the case studies for Mine A and Mine B. Case studies in three months, six months and one year will show the applicability of GenRel for short term, medium-term and long term time periods.

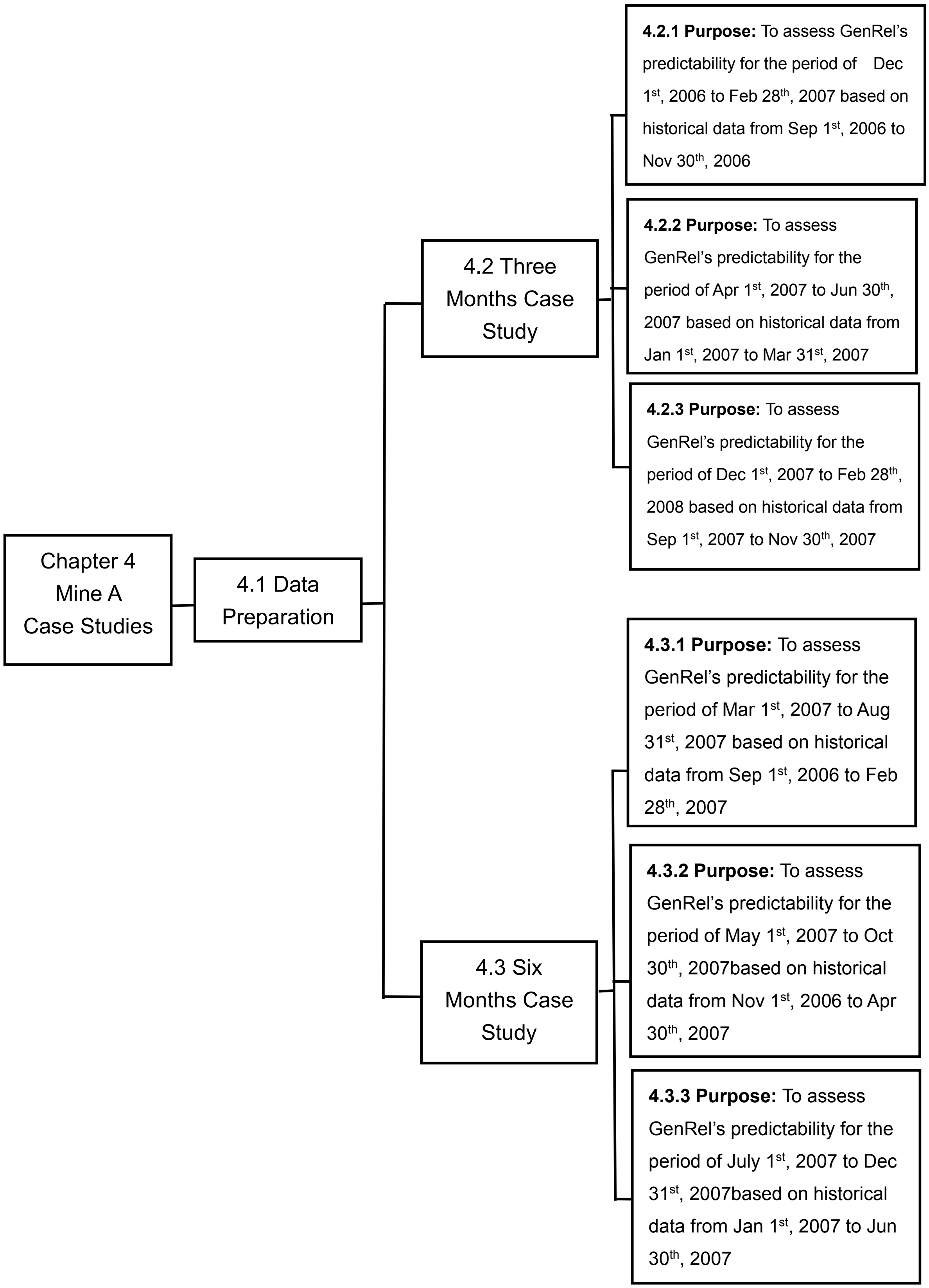

Figure 3.1 Case Studies flowchart of Mine A

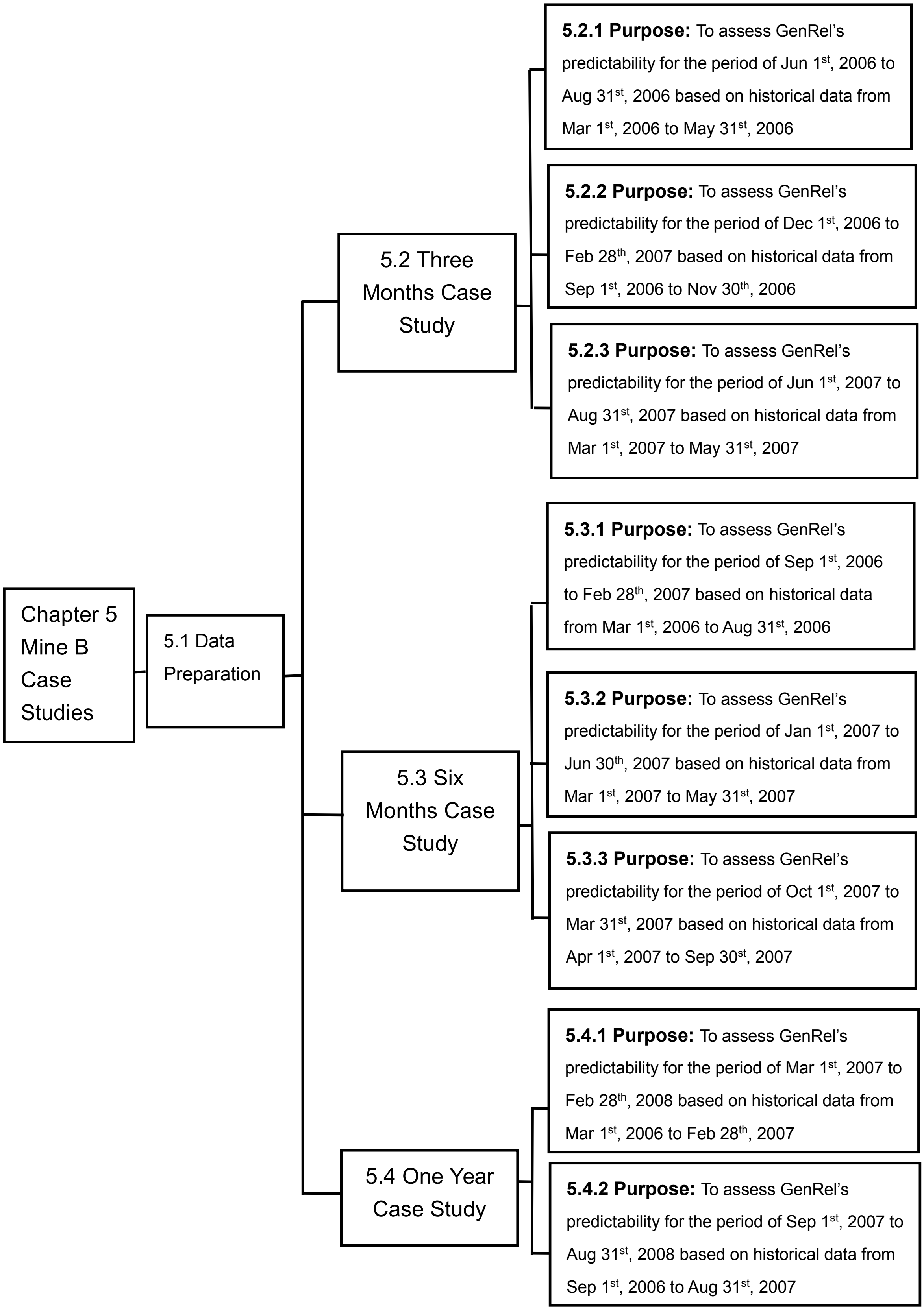

Figure 3.2 Case Studies flowchart of Mine B

Steps followed in the case studies:

- Data preparation

To fit the data into the maintenance analysis, the original data is processed in the form of Time To Repair (TTR). Field data was collected in the form of delays/repair. Original data format was collected as shown below:

9 Thu NOV - 2006		7 AM	8 AM	9 AM	10 AM	11 AM	12 PM	1 PM	2 PM	3 PM	4 PM	5 PM	6 PM	ORE	ROCK	Legend
CCNM SKIP HOIST	Sch	mp	ore	ore	ore	ore	ore	ore	ore	ore	ore	ore	ore	5396	0	Scheduled
	15	mp	MM	MM	MM	ore	ore	ore	ore	ore	ore	DM	DM	5059	0	Assumed
	30	mp	MM	MM	MM	ore	ore	ore	ore	ore	NX	DM	DM			
22-SKHST -HOIST	45	mp	MM	MM	ore	ore	ore	ore	ore	ore	ore	DM	ore	5540	0	Actual
24 HR Check	60	mp	MM	MM	ore	ore	ore	ore	ore	ore	ore	RF	ore			
REQUIRED	Fcst													0	0	Forecast

MP is planned maintenance, MM is mechanical down, ore means hoist ore, sch is schedule and fcst is forecast

Original data was provided from the mine's computerized system, "as is".

To convert the original data into TTR data to run GenRel, assumptions have been made as follows regarding the interpretation and manipulation of the collected data.

- The operating hours of the skip hoist includes the hours of hoisting rock and the hours of hoisting ore. In each day, the summation of the machine delay hours and the machine working hours equals to 24 hours.
- In the original data sheet, if any data cell is blank, we assume it is unaccounted delay time and fill that data cell with delay code "NX".
- The delay types of skip hoist are divided into types of machine stand-by and types of machine failure. Machine stand-bys represent the delays of the skip hoist which are due to failures of other associated equipment factors. Machine failures represent the delays of the skip hoist which are due to the machine failures.

- Data entries are recorded with a time unit of 0.25 hour, as per the mine’s computerized data collection system.

- Data composition

An overview of the Failure data composition (see 4.2.2.1) of input data will show in this step. It be can intuitive understand the main reason for delay.

- Trend test and serial correlation test

Prior to statistical analysis and probability distribution fitting, the data should be tested for trends and serial correlations (Vayenas et al., 1997). The purpose of these tests is to verify the assumption that the data is Independent and Identical Distribution (IID). This step is critical for the probabilistic modeling approach (Peng, 2011). If the data presents a trend or serial correlation, then the data is considered not independent and not identically distributed (Law and Kelton, 2000). In this case, nonstationary reliability models are more appropriate than models based on probability distribution fitting to analyze the data (Peng, 2011).

- Distribution fitting

If a specific probability distribution function can best fit the input data then the inverse transform technique (see Law and Kelton, 2000) of this specific probability distribution function must be applied to generate new sets of data. In our study, six sets of generated data having the same size as the input data set are considered sufficient to simulate the biological process for the prediction of future failures.

- Prediction

After the successful completion of the above steps, GenRel then can be applied to predict future failures. Six data sets are considered sufficient. For these purpose, these six data sets perform selection, cross-over, and mutation until the applied fitness value falls within the user-defined convergence limit or the total iterations reach the user-defined maximum number of iterations.

Chapter 4 Case Studies: Hoist System at Mine A

In those case studies, the main steps in the application of GenRel are applied, as described in Section 2.1.1.

4.1 Data pre-processing for the case study at Mine A

Data was collected from a mine site, called Mine A for simplification. (See Table 4.1)

<table>
<tr><td colspan="11">Mine A Hoist System</td></tr>
<tr><td>Thu</td><td>Nov-09</td><td>2006</td><td></td><td>7 AM</td><td>8 AM</td><td>9 AM</td><td>10 AM</td><td>ORE</td><td>ROCK</td><td>Legend</td></tr>
<tr><td colspan="3" rowspan="3">Mine A SKIP HOIST</td><td>Sch</td><td>MP</td><td>ore</td><td>ore</td><td>ore</td><td>5396</td><td>0</td><td>Scheduled</td></tr>
<tr><td>15</td><td>MP</td><td>MM</td><td>MM</td><td>MM</td><td rowspan="2">5059</td><td rowspan="2">0</td><td rowspan="2">Assumed</td></tr>
<tr><td>30</td><td>MP</td><td>MM</td><td>MM</td><td>MM</td></tr>
<tr><td colspan="3"></td><td>45</td><td>MP</td><td>MM</td><td>MM</td><td>ore</td><td rowspan="2">5540</td><td rowspan="2">0</td><td rowspan="2">Actual</td></tr>
<tr><td colspan="2">24 HR Check</td><td>OK</td><td>60</td><td>MP</td><td>MM</td><td>MM</td><td>ore</td></tr>
<tr><td colspan="3">REQUIRED</td><td>Fcst</td><td></td><td></td><td></td><td></td><td>0</td><td>0</td><td>Forecast</td></tr>
</table>

*Here MP is planned maintenance, MM is mechanical down, ore means hoist ore, sch is schedule and fcst is forecast.

Table 4.1: A sample of original data record of a mine hoist system

Table 4.1 is the basic information of this hoist system. There are four periods in one hour, 15 minutes each. Middle part is the operation status of the hoist system in different periods, Right part is the basic statistics of ore and waste.

The delay types of skip hoist are divided into types of machine stand-by and types of machine failure. Machine stand-bys represent the delays of the skip hoist which are due to failures of other equipment and environmental factors. Machine failures represent the delays of the skip hoist which are due to the machine failures. In the following case studies, machine failures will be used to generate input data, since these failures are representative of mechanical characteristics. All case studies' input data is based on machine failures (no system delays).Table 4.2 explains the codes for delays/failure types (Vayenas et.al., 2010).

Code	Explanation	Stand By or Failure
AV	Available	Stand By
DB	Blasting Delay	Stand By
DD	Destination. Full	Stand By
DE	Other Equipment	Stand By
DM	Source Empty	Stand By
DP	Utilities Down	Stand By
DY	High Fines	Stand By
DZ	High Water	Stand By
ME	Electrical Down	Failure
MH	Hydraulic Down	Failure
MI	Instrument Down	Failure
MM	Mechanical Down	Failure
MO	Maintenance Out Of Plan	Failure
MP	Planned Maintenance	Failure
NT	Travel Time	Stand By
NX	Not Reported	Stand By
OI	Operator Planned Inspection	Failure
OP	Operator Repairs	Failure
RF	Pre-operation	Stand By
Notice: Failures include scheduled maintenance and unscheduled downtime.		

Table 4.2 Delay code explanation

Then, original data was processed as shown in Table 4.3

Data	Type of Delay	Delay Time (hours)
9/5/2006	MP	1
9/5/2006	OI	8
9/5/2006	ME	3
9/5/2006	NT	1
9/5/2006	ME	10.5
9/6/2006	MP	1
9/6/2006	OI	8

Table 4.3 An example of data processing

The final data table is shown in Table 4.4. Our case studies in GenRel is for maintainability analysis and thus TTR data will be used for input. In the following case studies, continuous and discrete distribution fitting will be tested based on the input data. The following section of this chapter presents a series of case studies of failure data in different time periods of a hoist system in the Sudbury mining area, Ontario, Canada.

Type of Failures	Time To Repair (TTR) (hours)
MP	1
OI	8
ME	14.5
MP	1
OI	8

Table 4.4 An example of TTR data as it can be entered in GenRel after processing the original field data from the mine site.

4.2 Three month case study in Mine A

4.2.1 Prediction of TTR data for a Three Months Period

Three case studies of maintainability are examined for a time period of three months. These case studies include:

1. Prediction of TTR data for the period from December 1st, 2006 to

February 28^{th}, 2007 based on historical data from September 1^{st}, to November 30^{th}, 2006

2. Prediction of TTR data for the period from April 1^{st} to June 30^{th}, 2007 based on historical data from January 1^{st} to March 31^{st}, 2007

3. Prediction of TTR data for the period from December 1^{st}, 2007 to February 28^{th} 2008 based on historical data from September 1^{st} to November 30^{th}, 2007

4.2.2 Prediction of TTR data for the period from December 1^{st}, 2006 to February 28^{th}, 2007 based on historical data from September 1^{st} to November 30^{th}, 2006

As per section 2.1.1, the following steps are implemented:

4.2.2.1 Step-1: Data Preparation

4.2.2.1.1 Failure data composition

The following Table 4.5 displays failure data composition for the period from September 1^{st} to November 30^{th}, 2006.

Type of Failures	TTR (Hours)	TTR Frequency	Percent of TTR
MP	220	80	32.80%
MM	83.25	30	12.41%
ME	52.75	19	7.86%
OI	227	54	33.84%
MO	19.75	9	2.94%
OP	68	38	10.14%
Total	670.75	230	100.00%

Table 4.5 Failure data composition from September 1^{st} to November 30^{th}, 2006, Mine A

4.2.2.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before a GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be examined. Figure 4.1 shows the trend test of TTR data for the period from September 1st to November 30th 2006. Trend test presents a linear relation between cumulative TTR and cumulative TTR numbers. Figure 4.2 shows the serial correlation test graph. Serial correlation test presents a scattered pattern between the i th TTR and (i-1) th TTR. Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

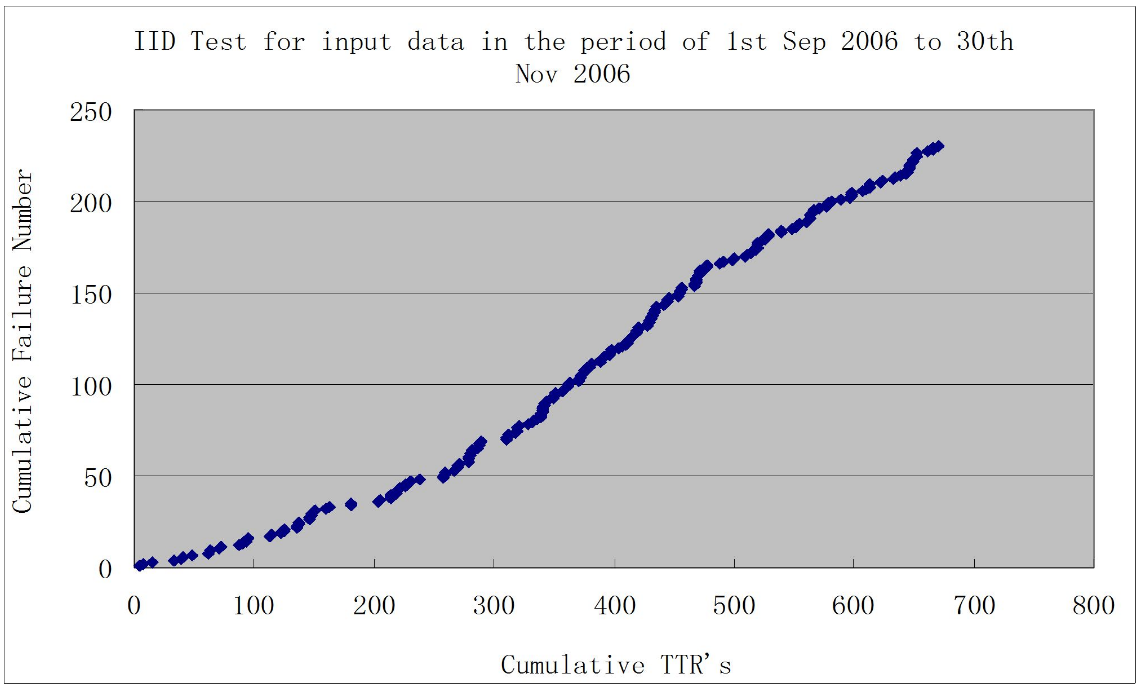

Figure 4.1 Trend test of TTR data for the period from September 1st to November 30th, 2006, Mine A

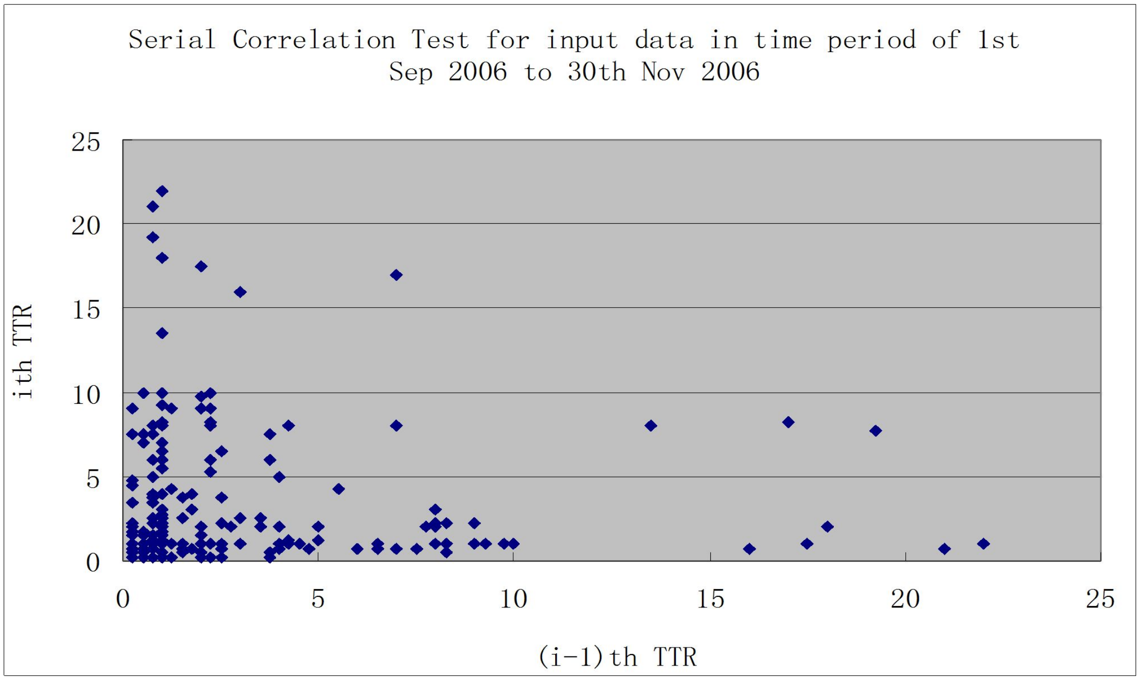

Figure 4.2 Serial correlation test of TTR data for the period from September 1st to November 30th, 2006, Mine A

4.2.2.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel in this case study

Under the verification process, if GenRel is to be found applicable, TTR data from the period of September 1st to November 30th 2006, can be used as the Raw Input Data set to predict repair data for the period of December 1st, 2006 to February 28th, 2007.

In the data input interface (see Figure 4.3), TTR data for the period of September 1st to November 30th, 2006 is divided chronologically into two parts (Raw Input Data set and Raw Evaluation Data set) with equal number of data entries, 190.

Since we can assume that the data can be either considered as discrete or continuous, using @Risk® we select to fit the data with a discrete distribution for the purpose of this case study.

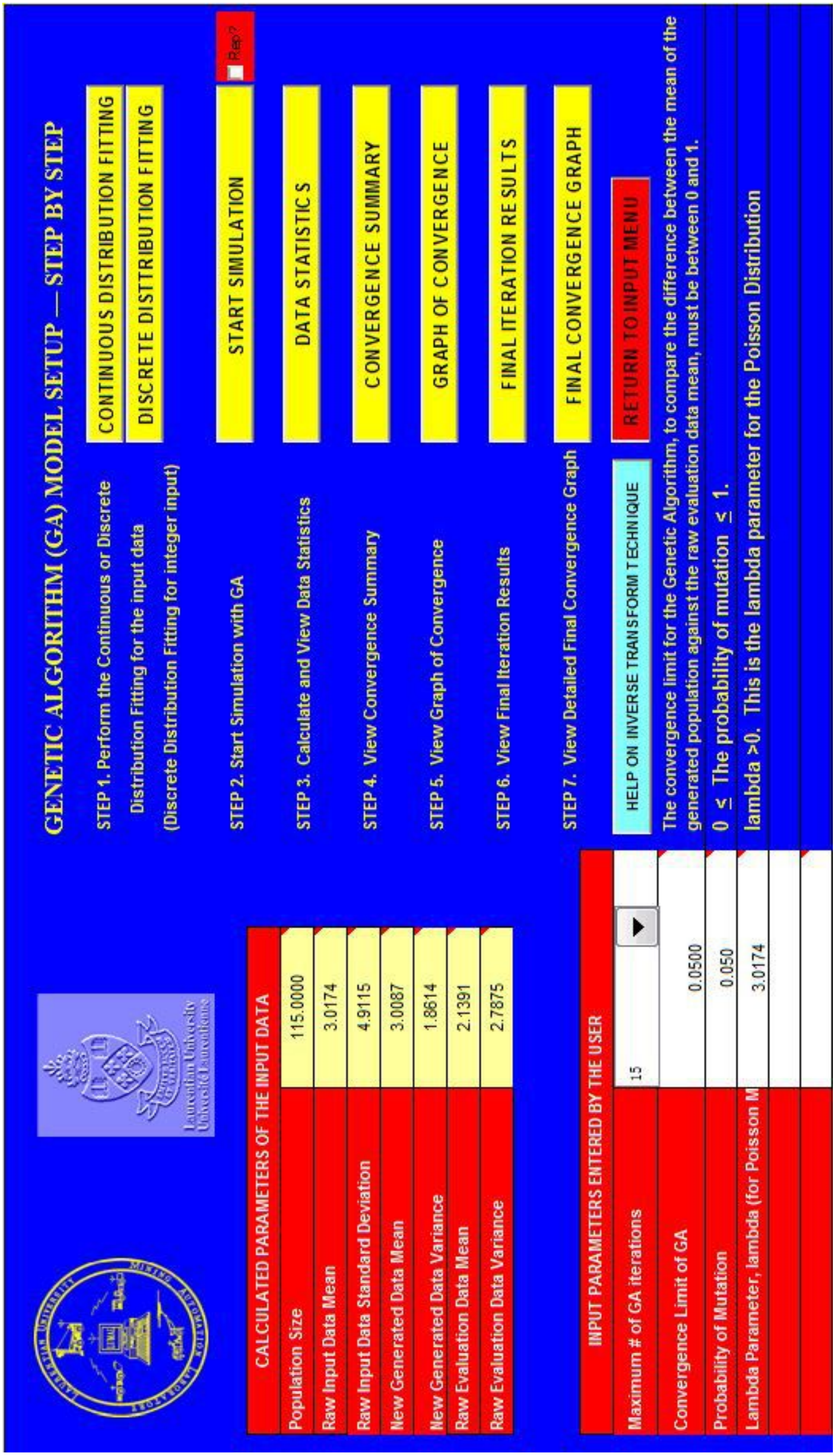

Figure 4.3 Input interface of GenRel for this case study

As per Step 3 in Section 2.1.1, an attempt is made to find the best fit discrete distribution function for the Raw Input Data set. The best fitting discrete distribution function, given by @Risk® (Palisade Corporation, 2005), is the Poisson distribution for the Raw Input Data, with lambda=3.0174. GenRel produces six sets of data which have the same size as the Raw Input Data set. These six sets of data generated through the inverse transform technique constitute the initial population for the following cross-over and mutation operations. Then, the six sets of generated data start to cross over and mutate. User can define the rate of mutation probability e.g 0.05. These genetic operations iterate until either the maximum number of iterations, which is set to 15, or the data reached the convergence limit, which is 0.05. The maximum number of iterations is set to 15, since through past experimentation it was found that it is an adequate number of runs to converge for the case studies discussed in this thesis. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 4.6.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	3.0174	0.15087	0	0.0087	yes

Table 4.6 Iteration results of TTR data from September 1st to November 30th, 2006, Mine A

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

4.2.2.3 Step 3 Prediction: Prediction of TTR data for the period from December 1st , 2006 to February 28th, 2007 based on data from September 1st to November 30th, 2006 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures for the hoist system at Mine A for the period from December 1st , 2006 to February 28th, 2007. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best, with the lambda value = 2.5783.

Figure 4.4 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from September 1st to November 30th, 2006. At a level of significance of 5%, t-test statistic is 1.76 with 458 degrees of freedom (Kanji, 2006) (Appendix D). Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5%. It is then considered that the model cannot be used with sufficient statistical confidence.

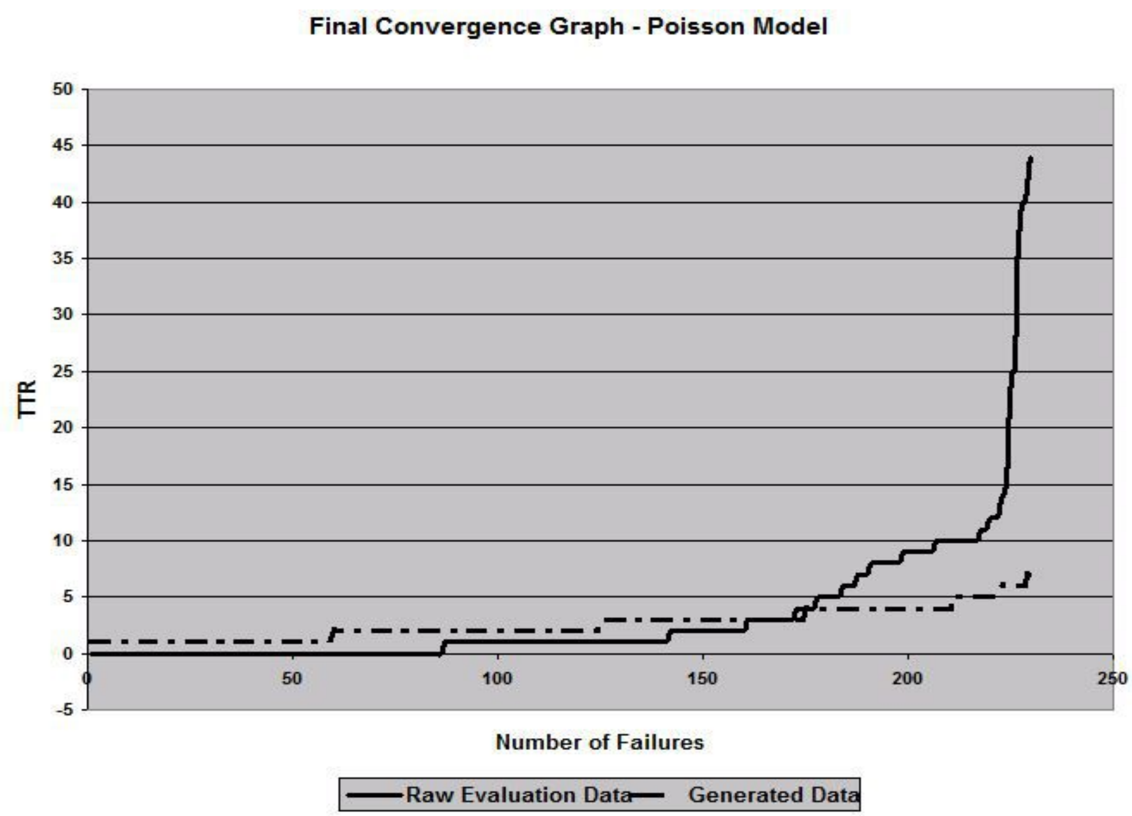

Figure 4.4 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from September 1st to November 30th, 2006, Mine A

4.2.2.4 Step-2 Verification: Continuous probability distribution fitting to verify the applicability of GenRel in this case study

When the input data is assumed to be continuous then the Lognormal probability distribution is the best fit for the Raw Input Data based on the derivation by @Risk®. Table 4.7 shows that after one iteration, GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from September 1st to November 30th, 2006.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	16.16416	0.808208	0	0.63162	yes

Table 4.7 Iteration results of TTR data from September 1st to November 30th, 2006, Mine A

4.2.2.5 Step-3 Prediction: Prediction of TTR data for the period from December 1st, 2006 to February 28th, 2007 based on data from September 1st to November 30th, 2006 based on continuous probability distribution function

After three iterations, GenRel returns a set of TTR data as the final prediction of failures for the hoist system at Mine A during the time period from December 1st, 2006 to February 28th, 2007. Results from @Risk® show the Lognormal probability distribution fits the predicted data set best. The parameters of Lognormal probability distribution are μ=3.1666, σ=8.5893 and shift=0.1974, see Figure 4.5.

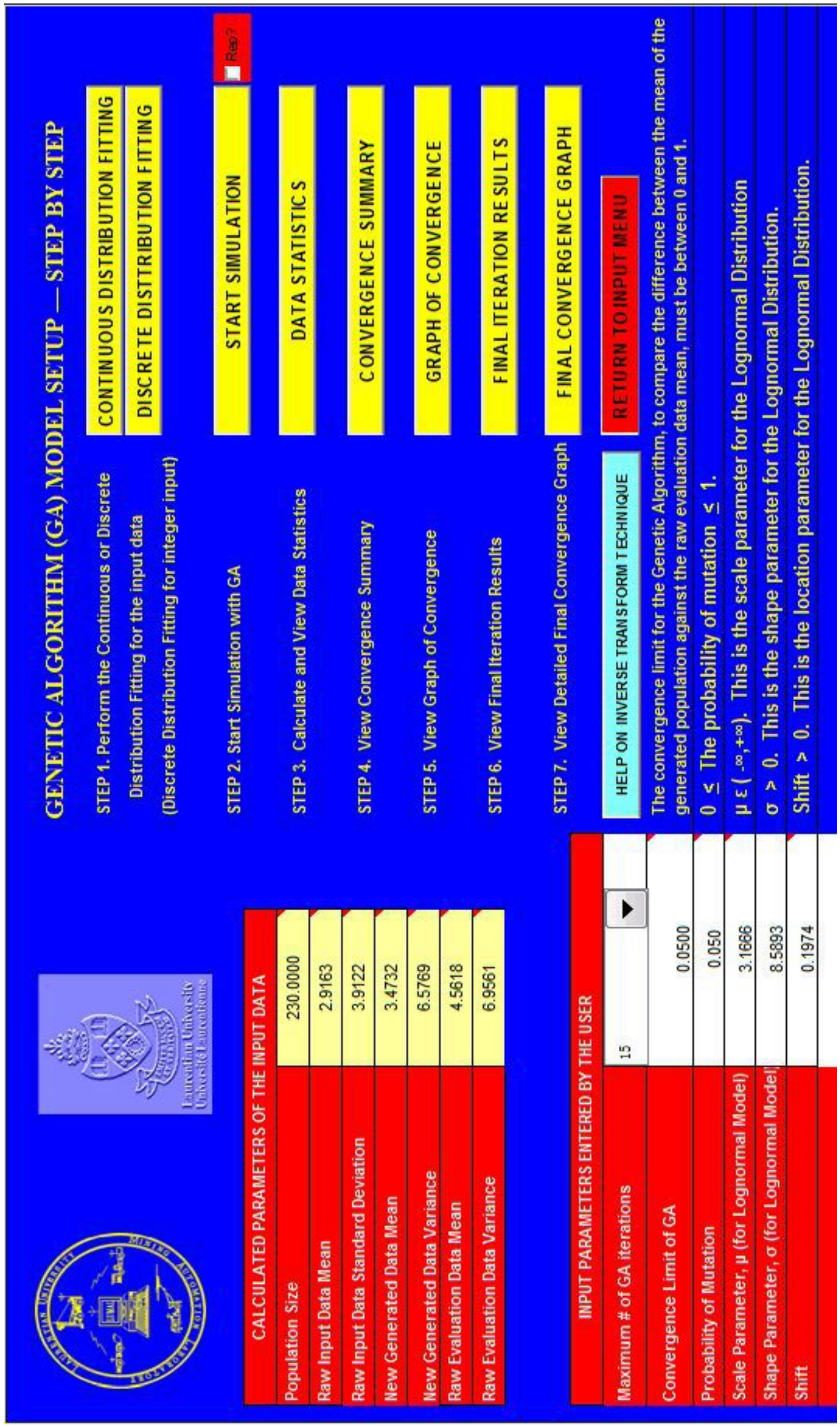

Figure 4.5 Results from the Lognormal probability distribution fit

Figure 4.6 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from December 1st, 2006 to February 28th, 2007. At a level of significance of 5%, t-test statistic is 1.62 (borderline) with 406 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D).

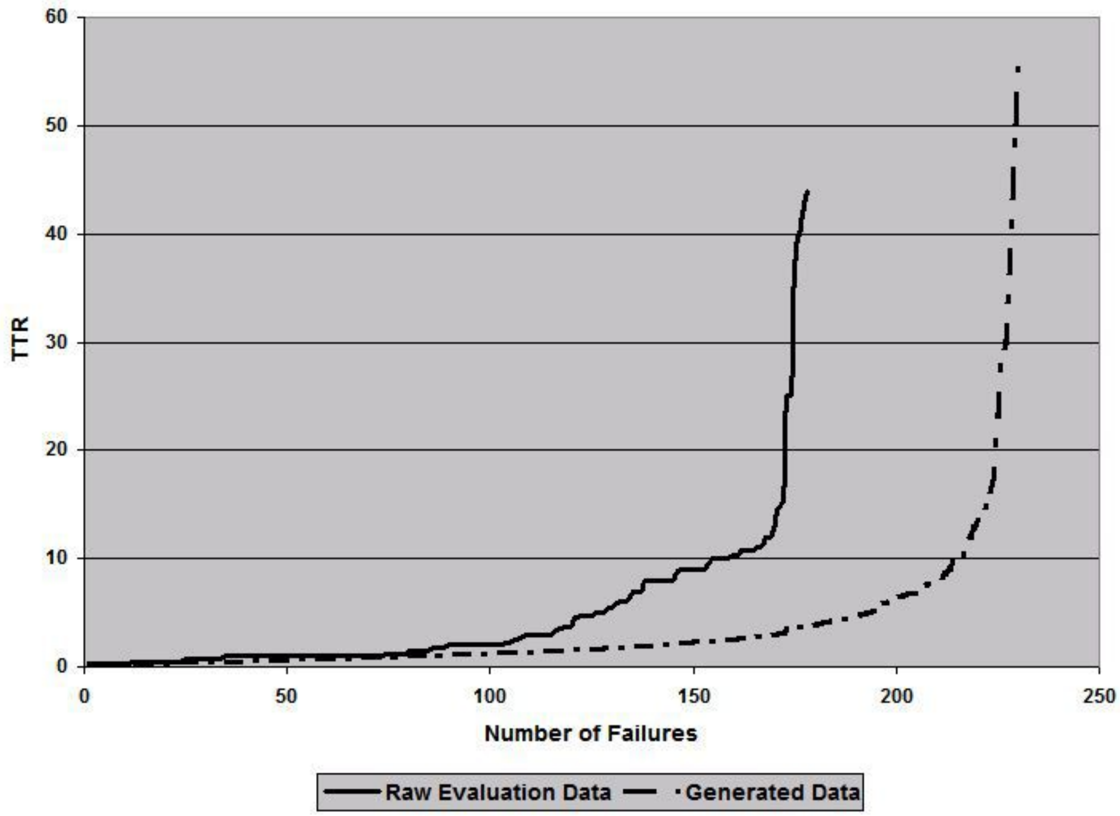

Figure 4.6 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from December 1st, 2006 to February 28th, 2007, Mine A

Combining the definition of maintainability (see 1.3.1) and applying the Lognormal cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.3):

$$M(T)=\int_{0}^{T}\frac{1}{\sigma'(x-\theta)\sqrt{2\pi}}e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2}dx$$

with

$$\sigma'\equiv\sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu'\equiv\ln\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

where

θ	is a shift,
σ	is the mean of associated Normal distribution,
μ	is the standard deviation of associated Normal distribution,

Following are some maintainability values based on TTR

TTR(Hours)	5	10	15	20	25	30	35	40
Maintainability M(T)	42.81%	45.99%	47.87%	49.21%	50.24%	51.09%	51.80%	52.42%
μ=3.1666, σ=8.5893 and θ =0.1974								

4.2.3 Prediction of TTR data for the period from April 1st to June 30th, 2007 based on historical data from January 1st to March 31st, 2007

4.2.3.1 Step-1: Data Preparation

4.2.3.1.1 Failure data composition

The Table 4.8 displays failure data composition for the period from January 1st to March 31st, 2007.

Type of TTR	TTR (Hours)	TTR Frequency	Percent of Total TTR
MP	320.25	65	45.57%
OI	294.25	36	41.87%
MM	21.75	14	3.09%
MO	16.5	7	2.35%
ME	50	26	7.11%
Total	702.75	148	100.00%

Table 4.8 Failure data composition from January 1st to March 31st, 2007, Mine A

4.2.3.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

4.2.3.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

Since we can assume the data can be either considered as discrete or continuous, using @Risk® we select to fit the data with a discrete distribution for the purpose of this case study.

In the verification process, the best fitting discrete probability distribution function is the Poisson distribution for the Raw Input Data, with lambda=5.0135. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 4.9.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	5.0135	0.250675	0	0.027	yes

Table 4.9 iteration results of TTR data from January 1st to March 31st, 2007, Mine A

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

4.2.3.3 Step 3-Prediction: Prediction of TTR data for the period from April 1st to June 30th, 2007 based on data from January 1st to March 31st, 2007 based on a discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures for the hoist system at Mine A during the time period from April 1st to June 30th, 2007. Results from @Risk® show that the Poisson probability distribution best fits the predicted data set. The parameter of the Poisson probability distribution is Lambda=4.5203.

Figure 4.7 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from April 1st to June 30th, 2007. At a level of significance of 5%, t-test statistic is 2.02 with 404 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

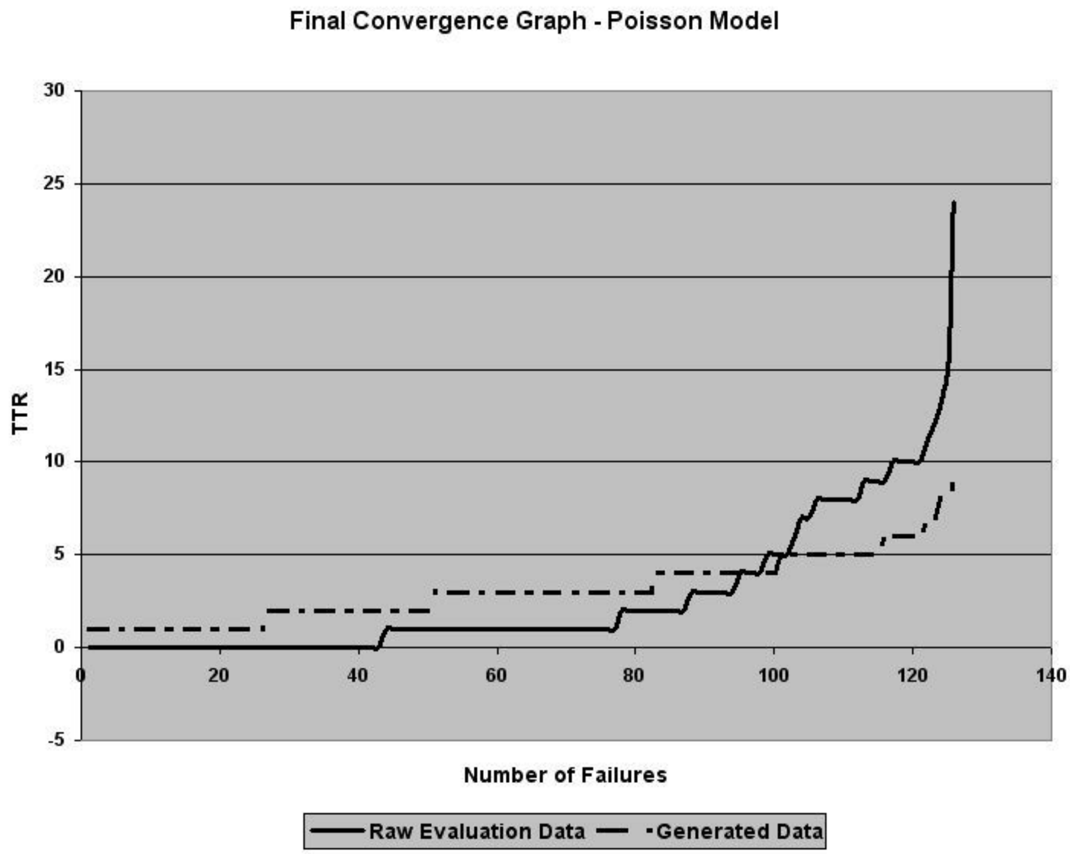

Figure 4.7 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from January 1st to March 31st, 2007, Mine A

4.2.3.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

In this case, the input data is assumed to be continuous, the Beta probability distribution is the best fit for the Raw Input Data based on derivation by @Risk.

In the verification process, the best fit continuous distribution function is the Beta distribution for the Raw Input Data. Table 4.10 shows that after 15 iterations GenRel still cannot generate an offspring data which is within the convergence limit. So GenRel is not a good prediction tool for future failure data in this case study of historical data from January 1st to March 31st, 2007.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	908.09027	45.4045135	0	332.4346	no
2	908.09027	45.4045135	0	332.4346	no
3	908.09027	45.4045135	0	332.4346	no
4	908.09027	45.4045135	0	332.4346	no
5	908.09027	45.4045135	0	332.4346	no
6	908.09027	45.4045135	0	332.4346	no
7	908.09027	45.4045135	0	332.4346	no
8	908.09027	45.4045135	0	169.1355	no
9	908.09027	45.4045135	0	169.1355	no
10	908.09027	45.4045135	0	169.1355	no
11	908.09027	45.4045135	0	169.1355	no
12	908.09027	45.4045135	0	169.1355	no
13	908.09027	45.4045135	0	169.1355	no
14	908.09027	45.4045135	0	169.1355	no
15	908.09027	45.4045135	0	169.1355	no

Table 4.10 iteration results of TTR data from January 1st to March 31st, 2007, Mine A

4.2.4 Prediction of TTR data for the period from December 1st, 2007 to February 28th, 2008 based on historical data from September 1st to November 30th, 2007

4.2.4.1 Step-1: Data Preparation

4.2.4.1.1 Failure data composition

Table 4.11 displays failure data composition for the period from September 1st to November 30th, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	516.25	39	67.24%
OI	239	33	31.13%
ME	2	4	0.26%
MO	9.5	2	1.24%
MM	1	1	0.13%
Total	767.75	79	100.00%

Table 4.11 Failure data composition from 1st September to 30th, November 2007, Mine A

4.2.4.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before a GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be examined (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

4.2.4.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fit of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=8.3333. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table

4.12.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	8.3333	0.416665	0	0.0512	yes

Table 4.12 iteration results of TTR data from September 1st to November 30th 2007, Mine A

Based on the above, it is suggested that GenRel is applicable to analyze the set of TTR data under this study.

4.2.4.3 Step 3-Prediction: Prediction of TTR data for the period from December 1st, 2007 to February 28th, 2008 based on data from September 1st to November 30th, 2007 based on discrete distribution function

With one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from December 1st, 2007 to February 28th, 2008. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. The parameter of the Poisson probability distribution Lambda=9.5256.

Figure 4.8 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from December 1st, 2007 to February 28th, 2008. At a level of significance of 5%, t-test statistic is 2.41 with 194 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

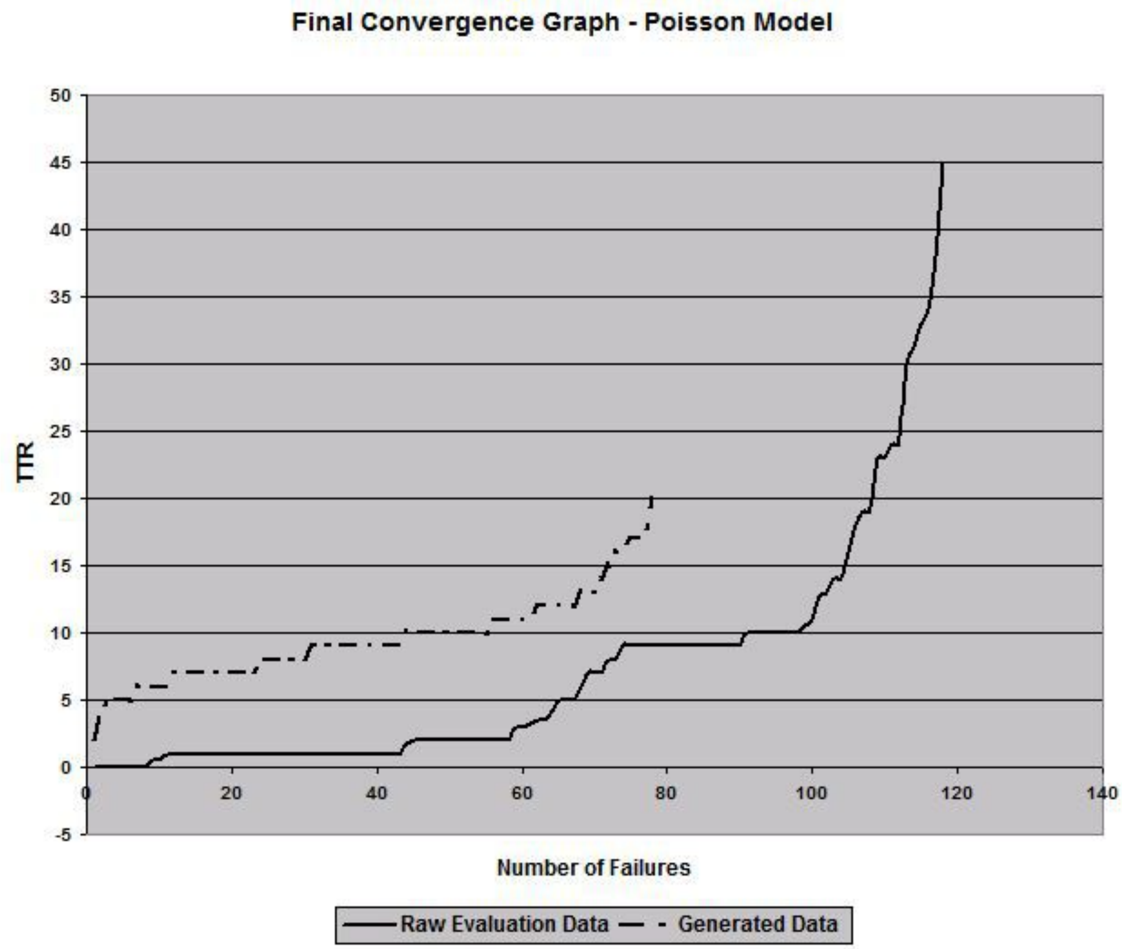

Figure 4.8 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from December 1st, 2007 to February 28th, 2008, Mine A

4.2.4.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

The best fitting of continuous distribution function is the Beta distribution for the Raw Input Data. Table 4.13 shows that after thirteen iterations GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from September 1st to November 30th, 2007.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	307.15601	15.3578005	0	246.2848	no
2	307.15601	15.3578005	0	229.13427	no
3	307.15601	15.3578005	0	227.2494	no
4	307.15601	15.3578005	0	37.46848	no
5	307.15601	15.3578005	0	37.46848	no
6	307.15601	15.3578005	0	37.46848	no
7	307.15601	15.3578005	0	37.46848	no
8	307.15601	15.3578005	0	37.46848	no
9	307.15601	15.3578005	0	37.46848	no
10	307.15601	15.3578005	0	37.46848	no
11	307.15601	15.3578005	0	25.9547	no
12	307.15601	15.3578005	0	25.9547	no
13	307.15601	15.3578005	0	6.49216	yes

Table 4.13 Iteration results of TTR data from September 1st to November 30th, 2007, Mine A

4.2.4.5 Step 3-Prediction: Prediction of TTR data for the period from December 1st, 2007 to February 28th, 2008 based on data from September 1st to November 30th, 2007 based on continuous distribution function

With one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from December 1st, 2007 to February 28th, 2008. Results from @Risk® show that the Lognormal probability distribution fits the predicted data set best. The parameters of Lognormal probability distribution are μ=11.725, σ=34.194 and shift=0.16827

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Figure 4.9 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from December 1st, 2007 to February 28th, 2008. At a level of significance of 5%, t-test statistic is 1.71 with 194 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

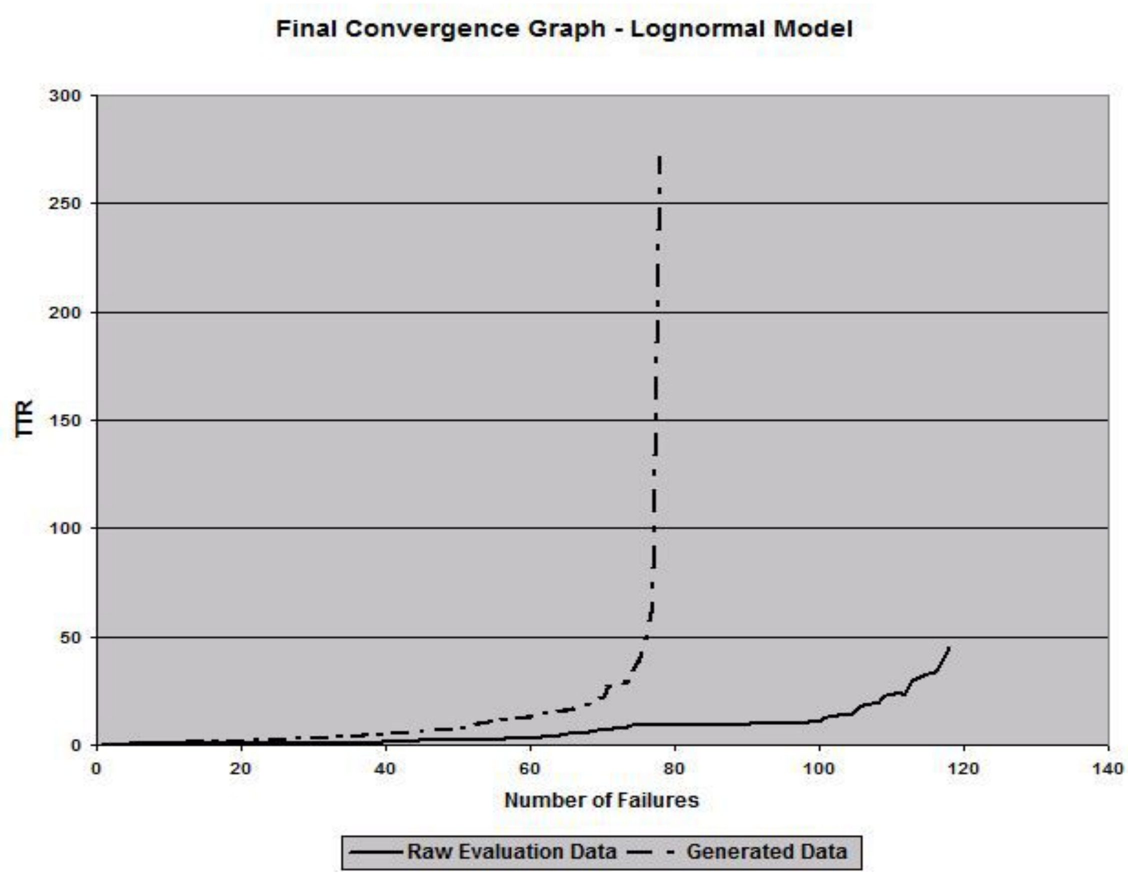

Figure 4.9 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from December 1st, 2007 to February 28th, 2008, Mine A

4.3 Six months in Case study in Mine A

4.3.1 Prediction of TTR data for six Months Period

1. Prediction of TTR data for the period from March 1st to August 31st, 2007 based on historical data from September 1st, 2006 to February 28th, 2007

2. Prediction of TTR data for the period from May 1st to October 31st, 2007 based on historical data from November 1st, 2006 to April 30th, 2007

3. Prediction of TTR data for the period from July 1st to December 31st, 2007 based on historical data from January 1st to June 30th, 2007

4.3.2 Prediction of TTR data for the period from March 1st to August 31st, 2007 based on historical data from September 1st, 2006 to February 28th, 2007

4.3.2.1 Step-1: Data Preparation

4.3.2.1.1 Failure data composition

Table 4.14 displays failure data composition for the period from September 1st, 2006 to February 28th, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	585	150	38.83%
MM	108.25	46	7.18%
ME	69.5	30	4.61%
OI	533.5	91	35.41%
MO	41	21	2.72%
OP	169.5	71	11.25%
Total	1506.75	409	100.00%

Table 4.14 Failure data composition from September 1st, 2006 to February 28th, 2007, Mine A

4.3.2.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before a GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be examined (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

4.3.2.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel in this case study

The best fitting of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=2.5735. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 4.15.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	2.5735	0.128675	0	0.103	yes

Table 4.15 iteration results of TTR data from September 1st to November 30th, 2007, Mine A

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data in this case study.

4.3.2.3 Step 3-Prediction: Prediction of TTR data for the period from March 1st to August 31st, 2007 base on data from September 1st, 2006 to February 28th, 2007 based on discrete distribution function

With one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from March 1st to August 31st, 2007. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. Parameter of the Poisson probability distribution Lambda=3.3888.

Figure 4.10 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from March 1st to August 31st, 2007. At a level of significance of 5%, t-test statistic is 1.96 with 816 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

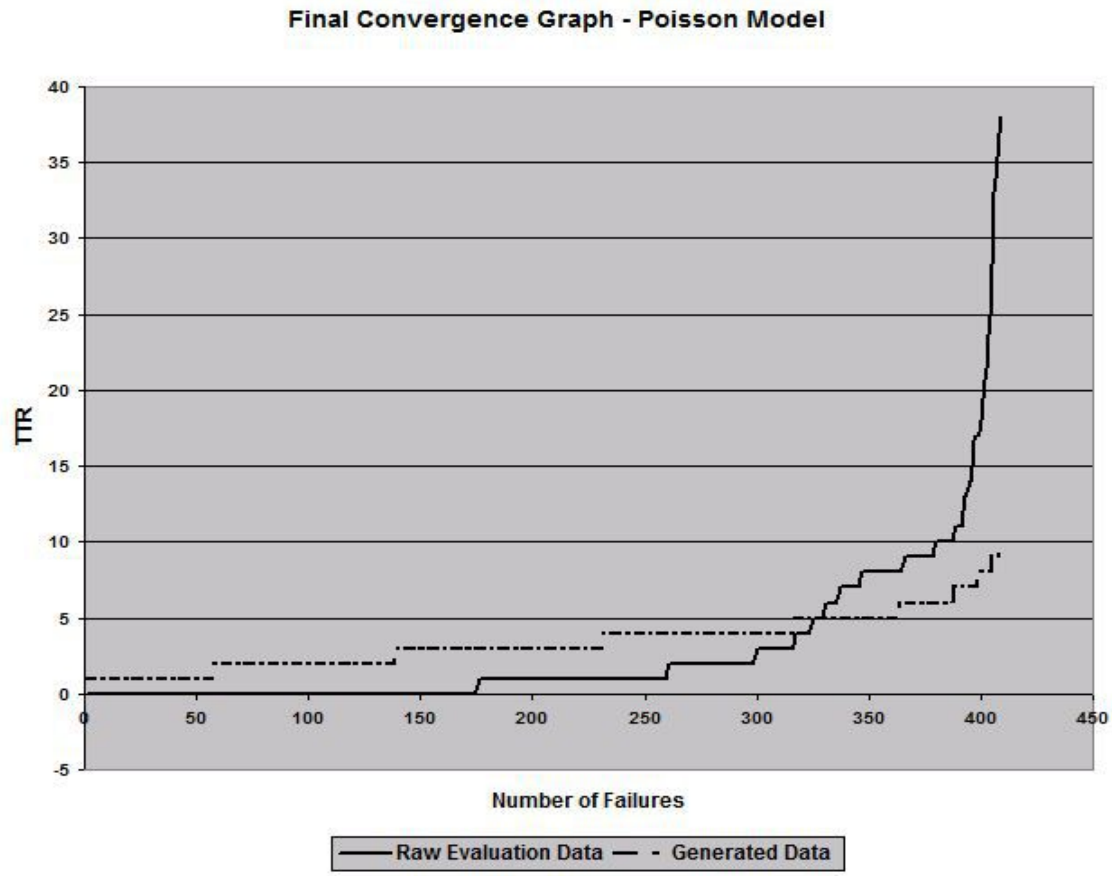

Figure 4.10 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from March 1st to August 31st, 2007, Mine A

4.3.2.4 Step 2-Verification: Continuous distribution fitting to verify the applicability of GenRel under this case study

The best fitting of continuous distribution function is the Lognormal distribution for the Raw Input Data. Table 4.16 shows after one iteration GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from September 1st, 2006 to February 28th, 2007.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	11.66964	0.583482	0	0.42314	Yes

Table 4.16 iteration results of TTR data from September 1^{st}, 2006 to February 28^{th}, 2007, Mine A

4.3.2.5 Step 3-Prediction: Prediction of TTR data for the period from March 1^{st} to August 31^{st}, 2007 based on data from September 1^{st}, 2006 to February 28^{th}, 2007 based on continuous probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from March 1^{st} to August 31^{st}, 2007. Results from @Risk® show that the Lognormal probability distribution fits the predicted data set best. Parameters of Lognormal probability distribution are μ=4.0305, σ=11.328 and shift=0.19331.

Figure 4.11 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from March 1^{st} to August 31^{st}, 2007. At a level of significance of 5%, t-test statistic is 0.32 with 738 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D).

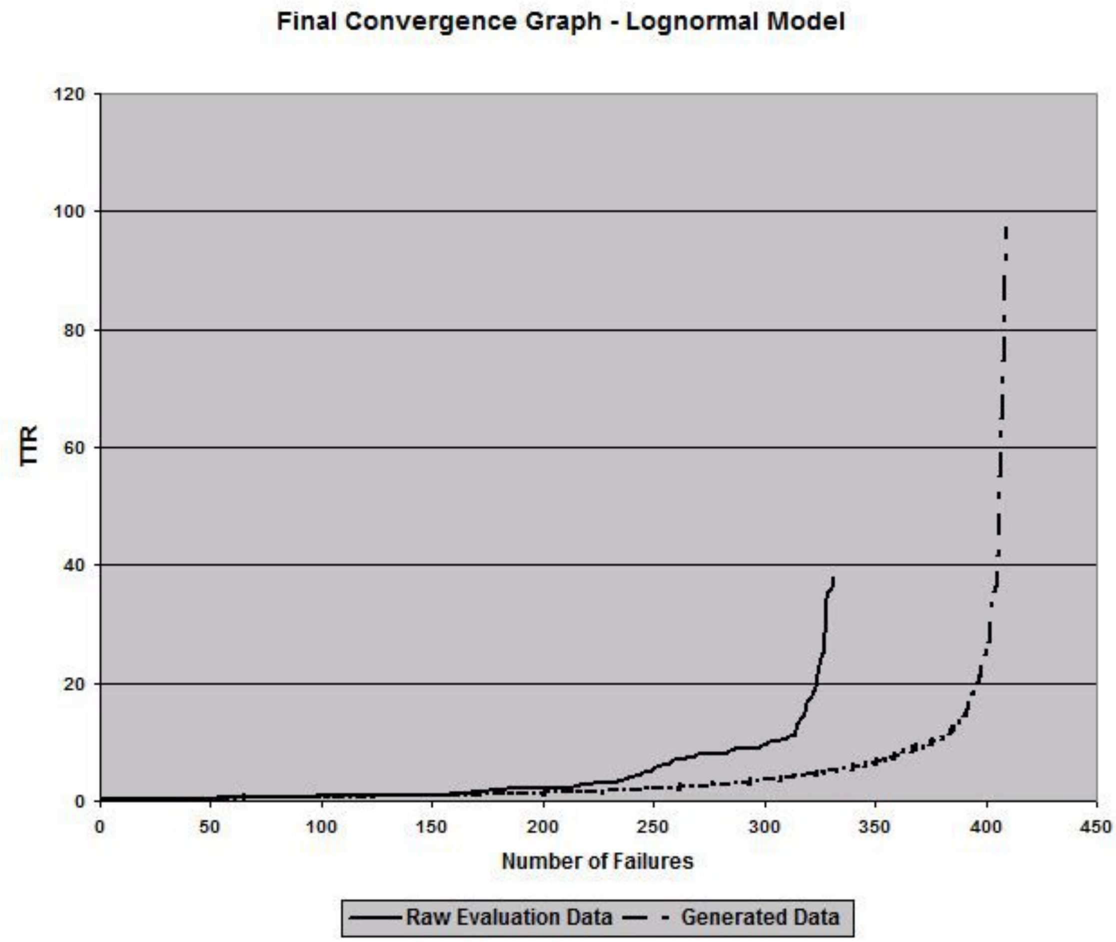

Figure 4.11 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from March 1st to August 31st, 2007, Mine A

Combining the definition of maintainability (see 1.3.1) and applying the Lognormal cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.3):

$$M(T) = \int_0^T \frac{1}{\sigma'(x-\theta)\sqrt{2\pi}} e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2} dx$$

with

$$\sigma' \equiv \sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu' \equiv \ln\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

where

θ is a shift,

σ is the mean of associated Normal distribution,

μ is the standard deviation of associated Normal distribution,

Following are some maintainability values based on TTR

TTR(Hours)	5	10	15	20	25	30	35	40
Maintainability M(T)	41.54%	43.94%	45.35%	46.36%	47.14%	47.78%	48.33%	48.80%
μ=4.0305, σ=11.328 and θ=0.19331								

4.3.3 Prediction of TTR data for the period from May 1st to October 31st, 2007 based on historical data from November 1st, 2006 to April 30th, 2007

4.3.3.1 Step-1: Data Preparation

4.3.3.1.1 Failure data composition

Table 4.17 displays failure data composition for the period from November 1st, 2006 to April 30th, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	679	151	43.37%
OI	551.25	72	35.21%
OP	159.25	78	10.17%
MM	58.25	31	3.72%
ME	63.5	39	4.06%
MO	54.5	25	3.48%
Total	1565.75	396	100.00%

Table 4.17 Failure data composition from November 1st, 2006 to April 30th, 2007, Mine A

4.3.3.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before a GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be examined (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

4.3.3.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fitting of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=3.5. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 4.18.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	3.5	0.175	0	0.0606	yes

Table 4.18 iteration results of TTR data from November 1st, 2006 to April 30th, 2007, Mine A

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

4.3.3.3 Step 3-Prediction: Prediction of TTR data for the period from May 1st to October 31st, 2007 based on data from November 1st, 2006 to April 30th, 2007 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from May 1st to

October 31st, 2007. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. Parameters of the Poisson probability distribution Lambda=3.7348.

Figure 4.12 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from May 1st to October 31st, 2007. At a level of significance of 5%, t-test statistic is 0.21 with 790 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

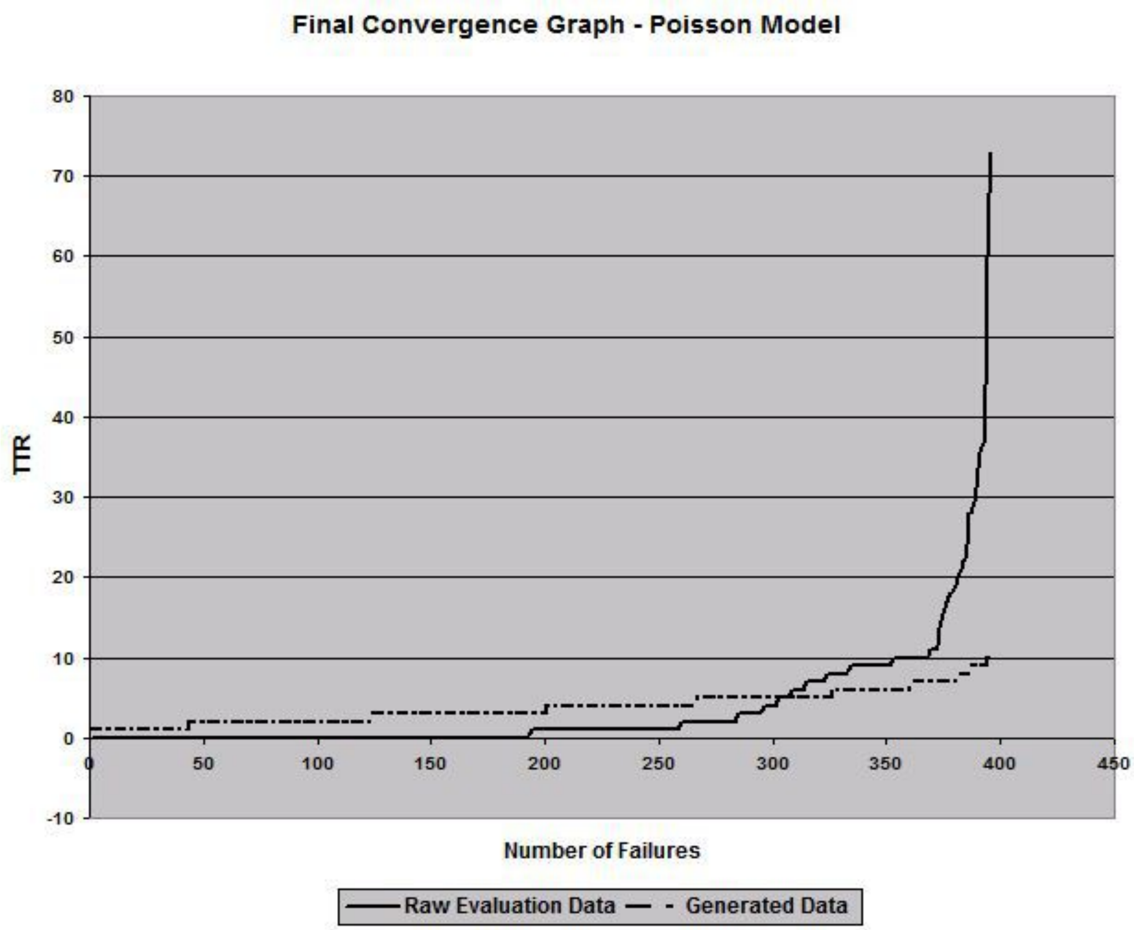

Figure 4.12 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from May 1st to October 31st, 2007, Mine A

Combining the definition of maintainability (see 1.3.1) and applying the Poisson cumulative distribution function, the maintainability equation can be expressed(Appendix B):

$$M(T) = e^{-3.7348} \sum_{n=0}^{T} \frac{3.7348^n}{n!}$$

Following are some maintainability function value at some representative TTR

TTR(Hours)	1	2	3	4	5	6	7	8
Maintainability M(T)	11.31%	27.96%	48.69%	68.05%	82.51%	91.51%	96.31%	98.55%
λ=3.7348								

4.3.3.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

The best fitting of continuous distribution function is the Exponential distribution for the Raw Input Data. Table 4.19 shows that after one iteration, GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from November 1st, 2006 to April 30th, 2007.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	3.71471	0.1857355	0	0.0501	yes

Table 4.19 iteration results of TTR data from November 1st, 2006 to April 30th, 2007, Mine A

4.3.3.5 Step 3-Prediction: Prediction of TTR data for the period from May 1st to October 31st, 2007 based on data from November 1st, 2006 to April 30th, 2007 based on continuous probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from May 1st to

October 31st, 2007. Results from @Risk® show that the Lognormal probability distribution fits the predicted data set best. Parameters of Lognormal probability distribution are μ=4.6514, σ=14.048 and shift=0.18658.

Figure 4.13 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from May 1st to October 31st, 2007. At a level of significance of 5%, t-test statistic is 0.7 with a degree of freedom of 664. Based on the result of the t-test, it is concluded that there is no significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D).

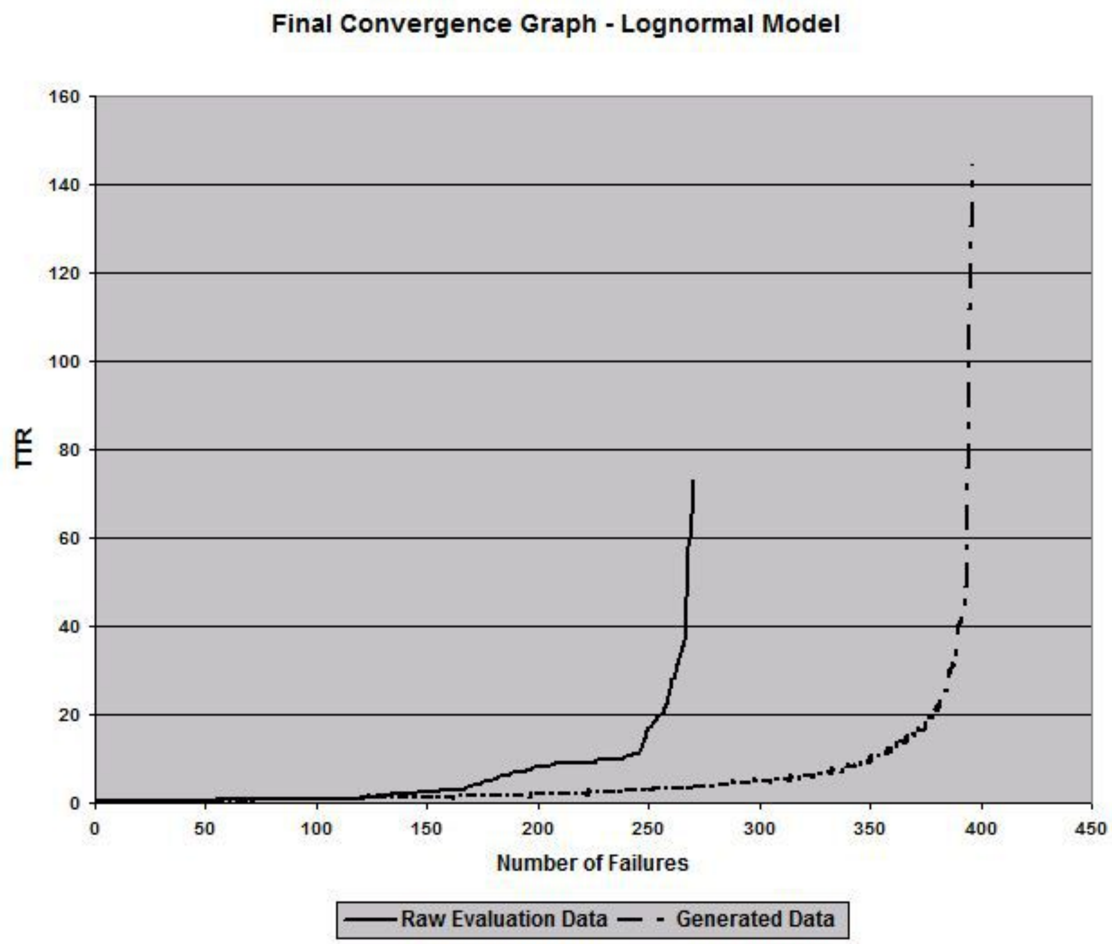

Figure 4.13 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from May 1st to October 31st, 2007, Mine A

Combining the definition of maintainability (see 1.3.1) and applying the Lognormal cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.3):

$$M(T)=\int_0^T \frac{1}{\sigma'(x-\theta)\sqrt{2\pi}} e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2} dx$$

with

$$\sigma' \equiv \sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu' \equiv \ln\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

where

θ is the shift,

σ is the mean of associated Normal distribution,

μ is the standard deviation of associated Normal distribution,

Following are some maintainability values based on the TTR data

TTR(Hours)	5	10	15	20	25	30	35	40
Maintainability M(T)	41.43%	43.36%	44.50%	45.31%	45.94%	46.45%	46.89%	47.27%
μ=4.6514, σ=14.048 and θ=0.18658								

4.3.4 Prediction of TTR data for the period from July 1st to December 31st, 2007 based on historical data from January 1st to June 30th, 2007

4.3.4.1 Step-1: Data Preparation

4.3.4.1.1 Failure data composition

Table 4.20 displays failure data composition for the period from January 1st to

June 30^{th}, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	815.25	148	47.41%
OI	523.75	69	30.46%
OP	231	122	13.43%
MM	29.25	21	1.70%
MO	40.25	21	2.34%
ME	80	55	4.65%
Total	1719.5	436	100.00%

Table 4.20 Failure data composition from January 1^{st} to June 30^{th}, 2007, Mine A

4.3.4.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

4.3.4.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fitting of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=4.0321. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 4.21.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.0321	0.201605	0	0.0046	yes

Table 4.21 iteration results of TTR data from January 1^{st} to June 30^{th}, 2007, Mine A

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

4.3.4.3 Step 3-Prediction: Prediction of TTR data for the period from July 1st to December 31st, 2007 based on data from January 1st to June 30th, 2007 based on discrete distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from July 1st to December 31st, 2007. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. The parameter of the Poisson probability distribution is Lambda=4.4926.

Figure 4.14 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from July 1st to December 31st, 2007. At a level of significance of 5%, t-test statistic is 3.54 with 270 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

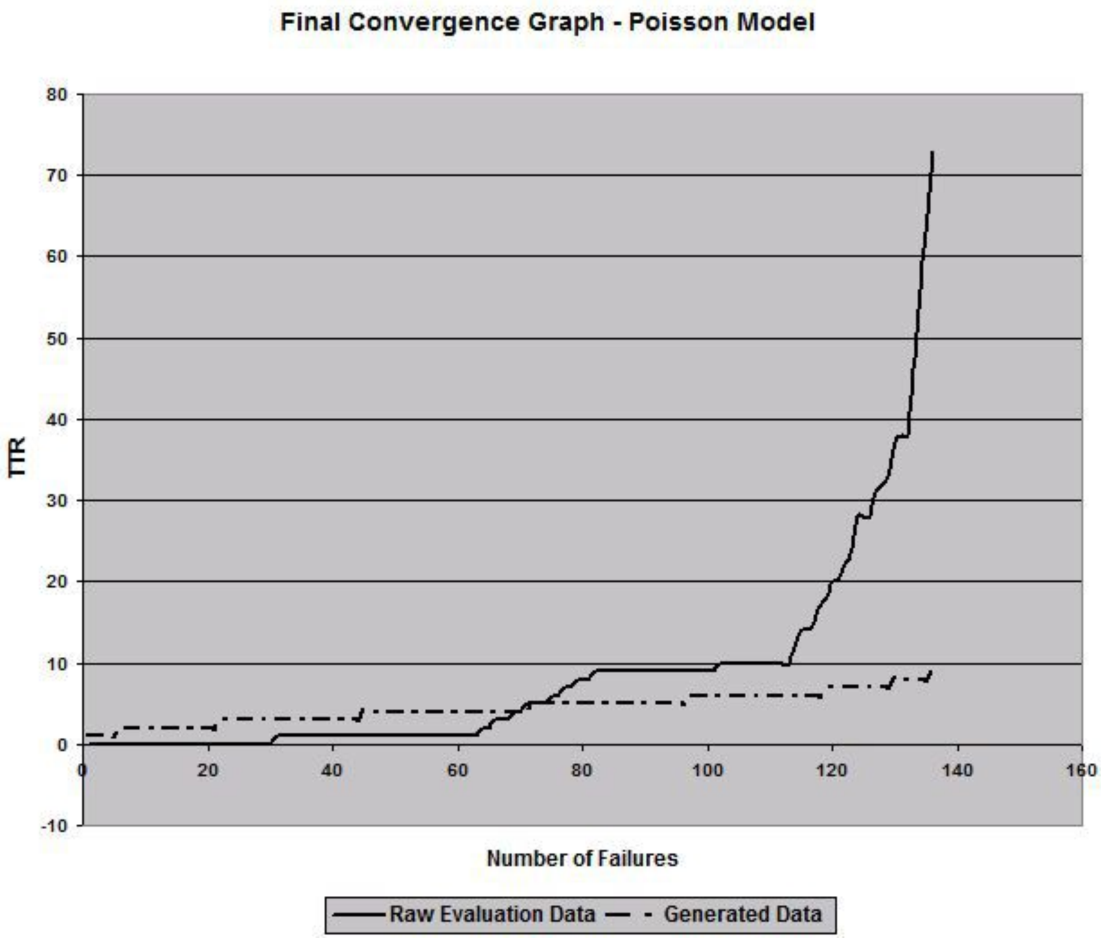

Figure 4.14 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from July 1st to December 31st, 2007, Mine A

4.3.4.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

The best fit of continuous distribution function is the Lognormal distribution for the Raw Input Data. Table 4.22 shows that after one iteration, GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from from January 1st to June 30th, 2007.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	18.93346	0.946673	0	0.46615	yes

Table 4.22 iteration results of TTR data from January 1st to June 30th, 2007, Mine A

4.3.4.5 Step 3-Prediction: Prediction of TTR data for the period from July 1st to December 31st, 2007 based on data from January 1st 2007 to June 30th, 2007 based on continuous probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine A during the time period from July 1st to December 31st, 2007. Results from @Risk® show that the Lognormal probability distribution fits the predicted data set best. The parameters of Lognormal probability distribution are μ=5.1352, σ=10795 and shift=0.15093.

Figure 4.15 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from July 1st to December 31st, 2007. At a level of significance of 5%, t-test statistic is 3.45 with 244 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

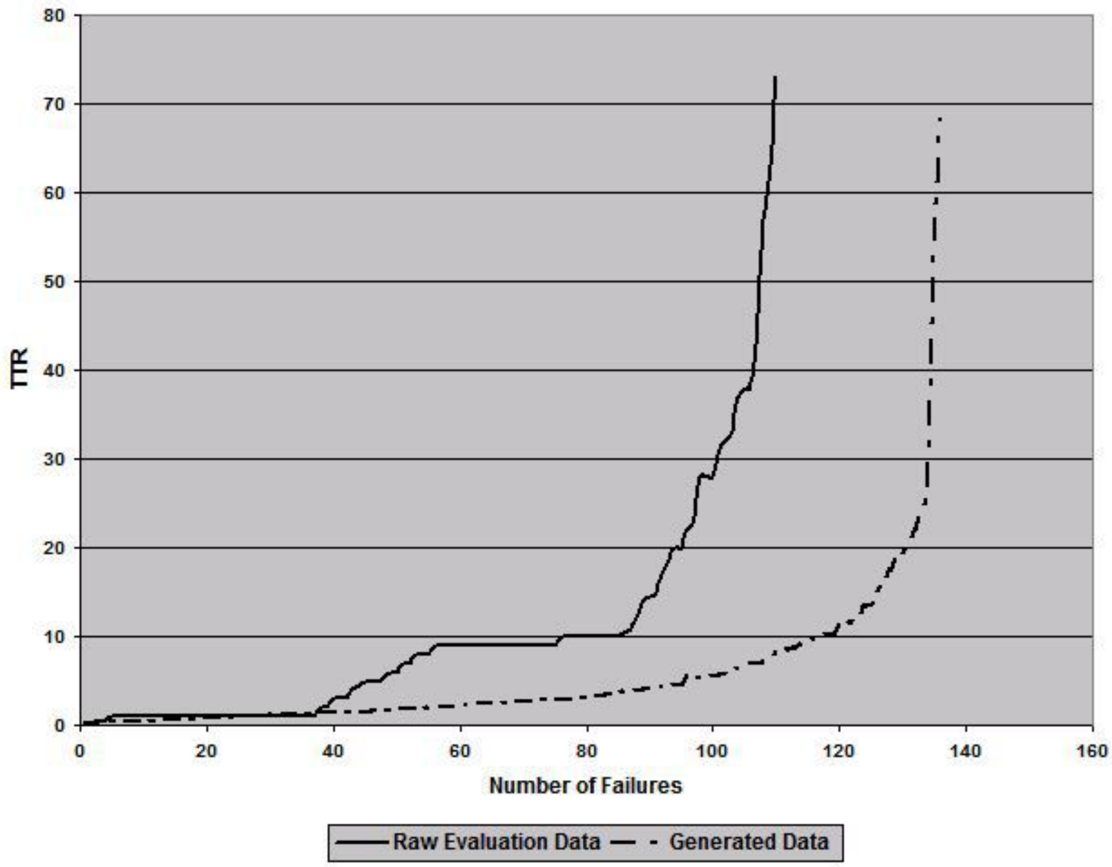

Figure 4.15 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from July 1st to December 31st, 2007, Mine A

4.4 Remarks

There are two groups of case studies discussed in this chapter, with each group having three sub-case studies. For all case studies, the Poisson distribution function was determined to be the best fit for Raw Input Data in discrete probability distribution fitting. In the study of the three month period and the six month period, the size of the Raw Input Data ranged from 78 to 409 and the fitness function value fell within the user-defined convergence limit after one iteration run in GenRel. In these case studies, only the one six month case study (with input data from November 1st, 2006 to April 30th, 2007) succeeded in making a prediction. The t-statistic test of other case studies showed a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5%. In those case studies, GenRel showed limited applicability for prediction of future failure data.

In the case studies with continuous probability distribution fitting, the Lognormal probability distribution has been found to be the best fit in most cases. A three month (with input data from January 1st to March 31st, 2007) case study failed in the verification step. A case study of six month period (with input data from January 1st to June 30th, 2007) failed in the prediction step due to a significance difference between generated data set and the Raw Evaluation Data set. For the other case studies, it was found no significant difference between the generated data set and the Raw Evaluation Data set in terms of mean values at a given level of significance of 5% using the t-statistic test. The Raw Input Data size in these successful case studies is from 78 to 409. GenRel demonstrated its applicability in these case studies, which may lead to the suggestion that the data size has no significant impact on the applicability of GenRel.

Chapter 5 Case Studies: Hoist System at Mine B

In those case studies, the main steps in the application of GenRel are applied, as described in Section 2.1.1.

5.1 Data pre-processing for the entire case study

Table 5.1 displays the failure code for hoist system at mine B.

Code	Explanation	Stand By or Failure
AV	Available	Stand By
CRUSH	Crusher Problems	Stand By
DB	Blasting Delay	Stand By
DD	Can't Dump	Stand By
DE	Other Equipment	Stand By
DH	Material Hung Up	Stand By
DM	Source Empty	Stand By
DP	Mine Utilities BO	Stand By
DX	Change Hoist Horizon	Stand By
DZ	High Water	Stand By
ME	Electrical Problems	Failure
MH	Hydraulic Problems	Failure
MI	Instrumentation Problems	Failure
MM	Mechanical Problems	Failure
MO	Maintenance out Of Plan	Failure
MP	Planned Maintenance	Failure
NL	Lunch/meeting	Stand By
NO	No Operator	Stand By
NT	Shift change	Stand By
NX	Not Reported	Stand By
OI	Operator Planned Inspection	Failure
OP	Operator RMPairs	Failure
SL	Bin Empty of Porkets	Stand By
RC	Routine Checks	Stand By

RW	Related Work	OPERATING
Notice : Failures include scheduled maintenance and unscheduled downtime.		

Table 5.1 Delay code explanation

Use the same method to convert original data to get input data, see table 5.2.

Type of Failures	Time To Repair (hours)
MP	13
OI	4
MP	2
MM	2
OI	1
MP	3

Table 5.2 An example of data processing

In the following case studies, machine failures will be used to generate input data, since these failures are representative of mechanical characteristics. All case studies' input data is based on machine failures (no system delays).

5.2 Three month case study at Mine B

5.2.1 Prediction of TTR data for a Three Months Period

1. Prediction of TTR data for the period from June 1st, 2006 to August 31st, 2006 based on historical data from March 1st, 2006 to May 31st, 2006
2. Prediction of TTR data for the period from December 1st, 2006 to February 28th, 2007 based on historical data from September 1st, 2006 to November 30th, 2006
3. Prediction of TTR data for the period from June 1st, 2007 to August 31st, 2007 based on historical data from March 1st, 2007 to May 31st, 2007

5.2.2 Prediction of TTR data for the period from June 1^{st} to August 31^{st}, 2006 based on historical data from March 1^{st} to May 31^{st}, 2006

5.2.2.1 Step-1: Data Preparation

5.2.2.1.1 Failure data composition

Table 5.3 displays failure data composition for the period from March 1^{st} to May 31^{st}, 2006.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	363.5	61	49.46%
OI	230	38	31.29%
MM	24.5	10	3.33%
ME	41.5	15	5.65%
OP	73.5	44	10.00%
MO	2	2	0.27%
Total	735	170	100.00%

Table 5.3 Failure data composition from March 1^{st} to May 31^{st}, 2006, Mine B

5.2.2.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before a GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be examined. Figure 5.1 shows the trend test of TTR data for the period from March 1^{st} 2006 to May 31^{st}, 2006. Figure 5.2 shows the serial correlation test graph. Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

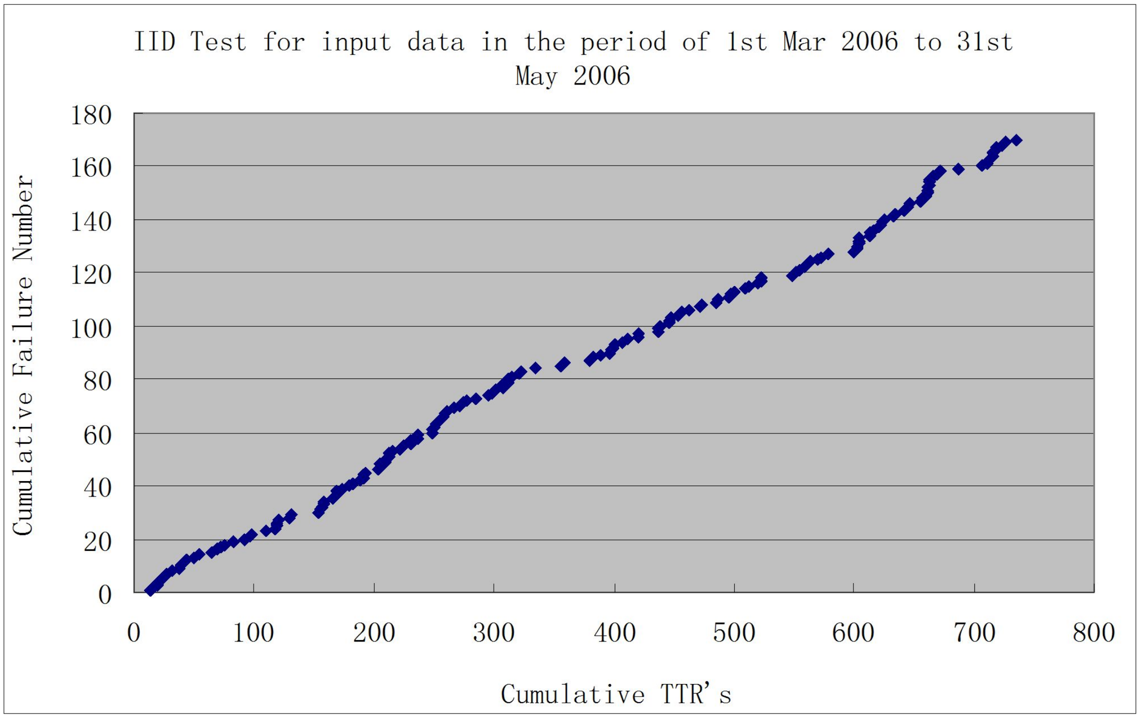

Figure 5.1 Trend test of TTR data for the period from March 1st 2006 to May 31st, 2006, Mine B

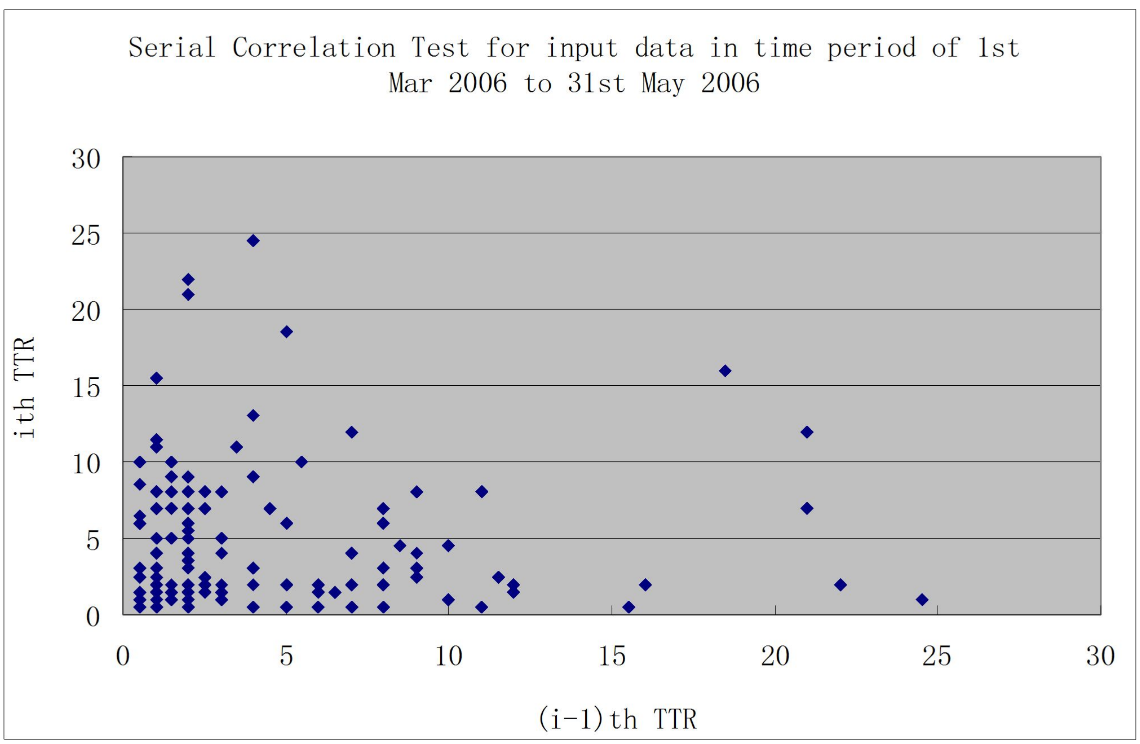

Figure 5.2 Serial correlation test of TTR data for the period from March 1st 2006 to May 31st, 2006, Mine B

5.2.2.2 Step 2-Verification: Discrete probability distribution fitting to Verify the applicability of GenRel under this case study

Since we can assume that the data can be either considered discrete or continuous, using @Risk® we select to fit the data with a discrete distribution for the purpose of this case study.

The best fit of discrete probability distribution function is Poisson distribution for the Raw Input Data, with lambda=4.0706. Table 5.4 shows after one iteration GenRel yields a set of data within the pre-defined convergence limit.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.0706	0.20353	0	0.0353	yes

Table 5.4 iteration results of TTR data from March 1st 2006 to May 31st, 2006, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data for this case study.

5.2.2.3 Step 3-Prediction: Prediction of TTR data for the period from June 1st to August 31st, 2006 based on data from March 1st to May 31st, 2006 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from June 1st to August 31st, 2006. Results from @Risk® show the Poisson probability distribution fits the predicted data set best. Parameters of the Poisson probability distribution Lambda=4.1824.

Figure 5.3 shows a convergence graph comparison between the Raw Evaluation

Data and the Generated Data for the time period from June 1st to August 31st, 2006. At a level of significance of 5%, t-test statistic is 7.61 with 338 degrees of freedom. Based on the result of the t-test, it is concluded there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

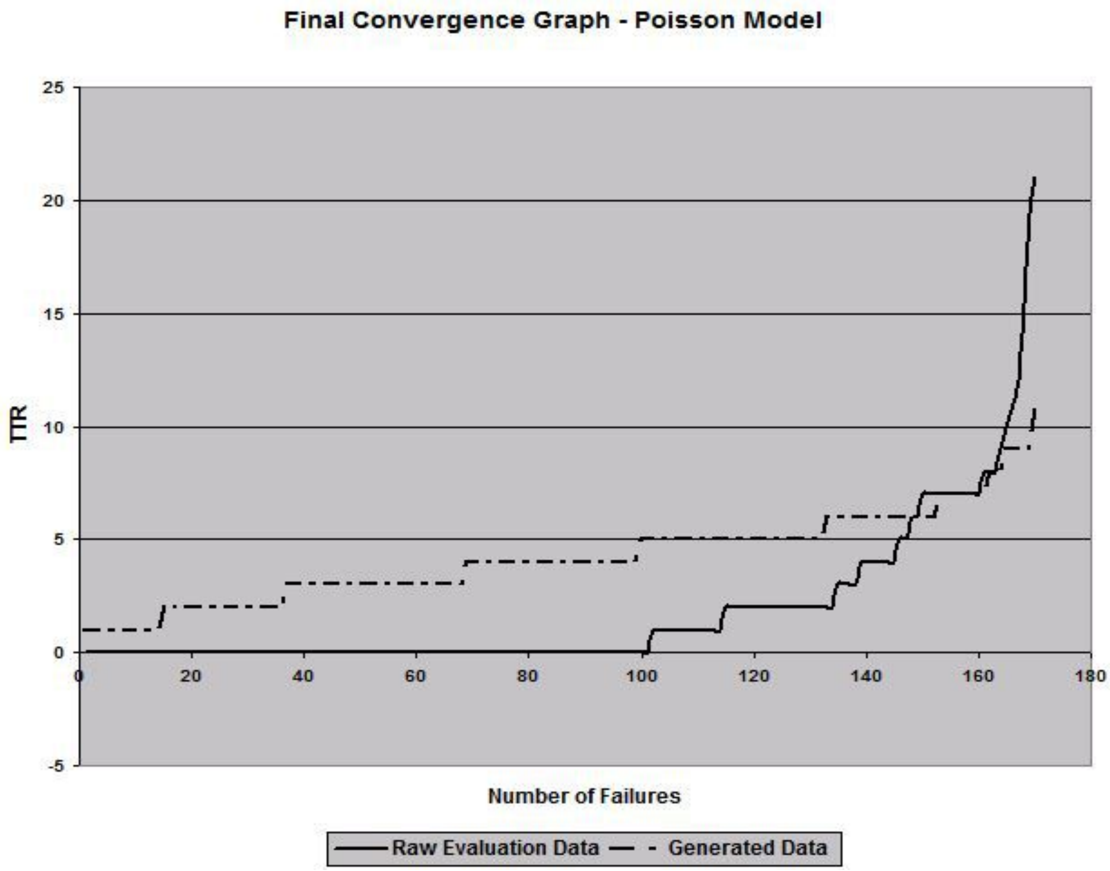

Figure 5.3 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from June 1st to August 31st, 2006, Mine B

5.2.2.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

When the input data is assumed to be continuous, the Lognormal probability distribution is the best fit for the Raw Input Data based on derivation by @Risk. Table 5.5 shows after one iteration GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from March 1st 2006 to May 31st, 2006.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	11.62182	0.581091	0	0.41841	yes

Table 5.5 iteration results of TTR data from March 1st 2006 to May 31st, 2006, Mine B

5.2.2.5 Step 3-Prediction: Prediction of TTR data for the period from June 1st to August 31st, 2006 based on data from March 1st to May 31st, 2006 based on continuous probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from June 1st to August 31st, 2006. Results from @Risk® show that the Lognormal probability distribution fits the predicted data set best. Parameters of the Lognormal probability distribution are μ =4.6941, σ =9.9615 and shift=0.33657.

Figure 5.5 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from June 1st to August 31st, 2006. At a level of significance of 5%, t-test statistic is 0.42 with 241 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

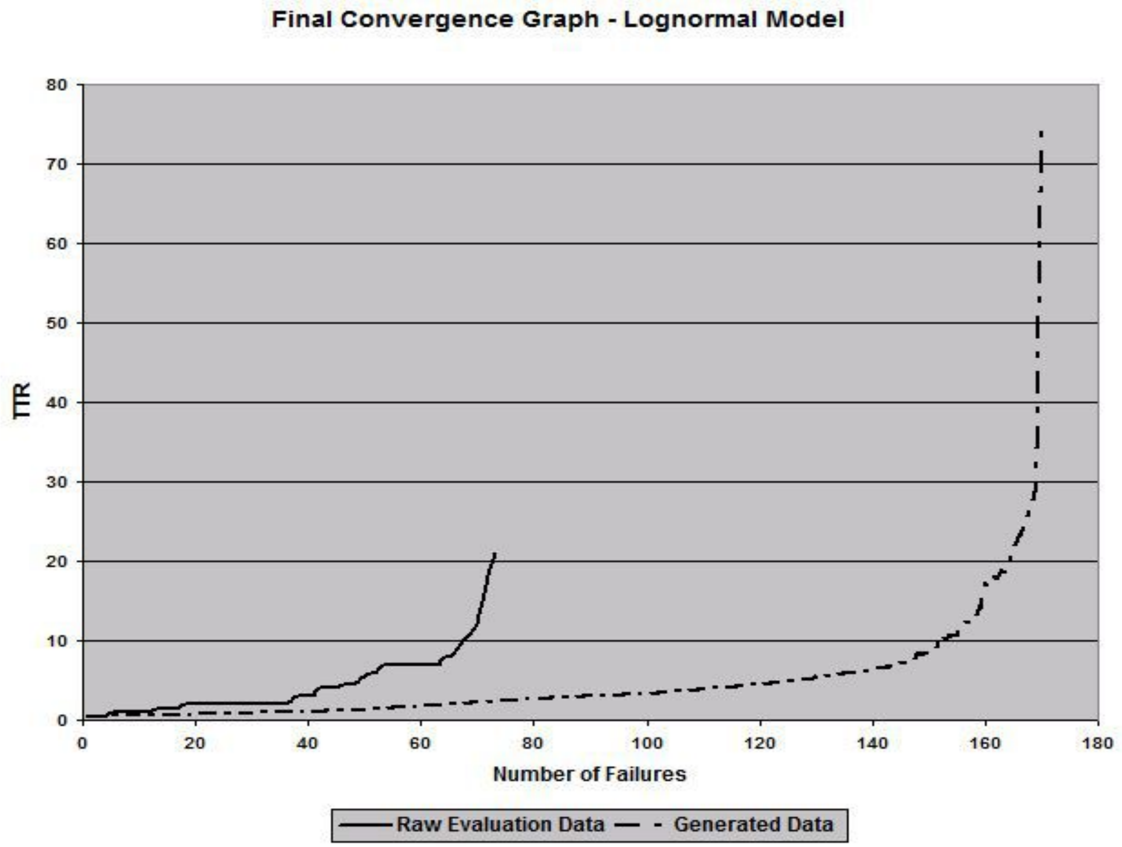

Figure 5.4 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from June 1st to August 31st, 2006, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the Lognormal cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.3):

$$M(t) = \int_0^t \frac{1}{\sigma'(x-\theta)\sqrt{2\pi}} e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2} dx$$

with

$$\sigma' \equiv \sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu' \equiv \ln \frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

Following are some maintainability values based on TTR data

TTR(Hours)	5	10	15	20	25	30	35	40
Maintainability M(T)	37.84%	40.51%	42.10%	43.23%	44.11%	44.84%	45.45%	45.98%
μ=4.6941, σ=9.9615 and θ=0.33657								

5.2.3 Prediction of TTR data for the period from December 1st, 2006 to February 28th, 2007 based on historical data from September 1st to November 30th, 2006

5.2.3.1 Step-1: Data Preparation

5.2.3.1.1 Failure data composition

Table 5.6 displays failure data composition for the period from September 1st to November 30th, 2006.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	370	58	55.22%
ME	59	29	8.81%
OI	175.5	42	26.19%
OP	26	14	3.88%
MM	22.5	15	3.36%
MO	15	7	2.24%
MH	2	1	0.30%
Total	670	166	100.00%

Table 5.6 Failure data composition from September 1st to November 30th, 2006, Mine B

5.2.3.1.2 Test the data for the assumption of the Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.2.3.2 Step 2-Verification: Discrete probability distribution fitting on verify the applicability of GenRel under this case study

The best fit of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=4.0723. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 5.7.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.0723	0.203615	0	0.0241	yes

Table 5.7 iteration results of TTR data from September 1st to November 30th, 2006, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.2.3.3 Step 3-Prediction: Prediction of TTR data for the period from December 1st, 2006 to February 28th, 2007 based on data from September 1st to November 30th, 2006 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at mine A during the time period from December 1st, 2006 to February 28th, 2007. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. The parameter of the Poisson probability distribution Lambda=3.8373.

Figure 5.5 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from December 1st, 2006 to

February 28th, 2007. At a level of significance of 5%, t-test statistic is 6.15 with 330 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

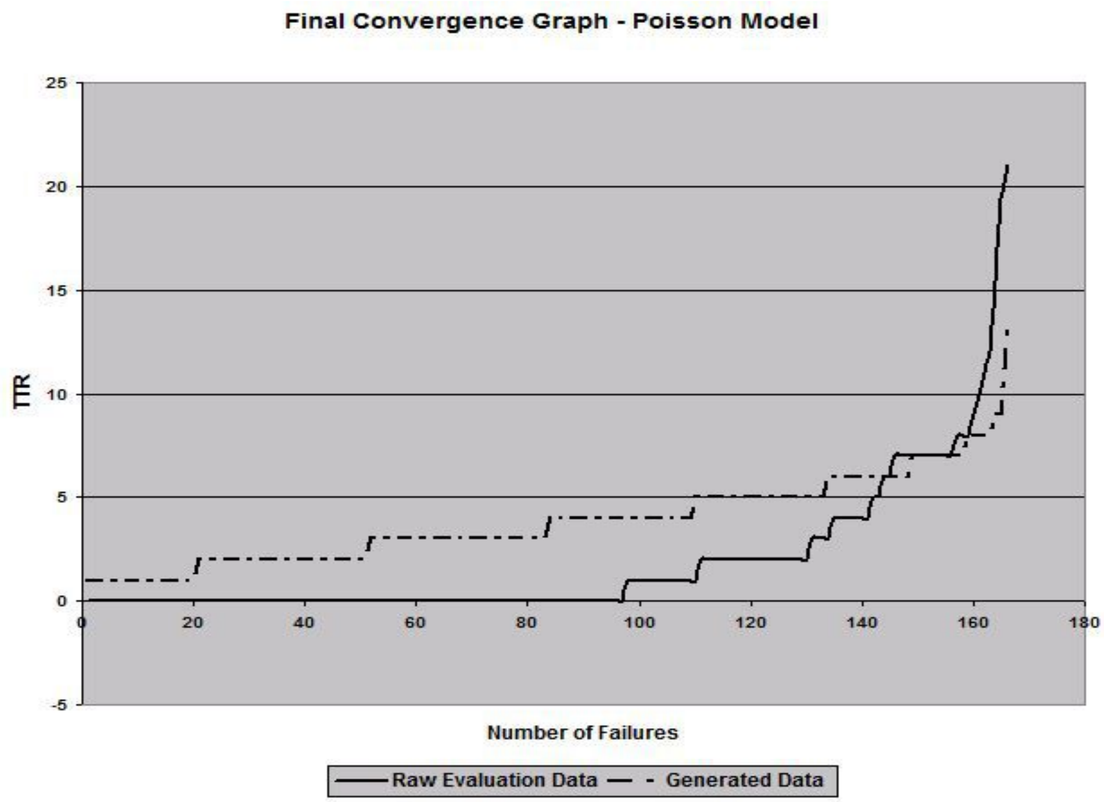

Figure 5.5 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from December 1st, 2006 to February 28th, 2007, Mine B

5.2.3.4 Step 2-Verification: Continuous probability distribution fitting on verify the applicability of GenRel under this case study

The best fit of continuous distribution function is Lognormal distribution for the Raw Input Data. Table 5.8 shows after three iteration GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from

September 1st, 2006 to November 30th, 2006.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	12.84297	0.6421485	0	1.53946	no
2	12.84297	0.6421485	0	1.53946	no
3	12.84297	0.6421485	0	0.60852	yes

Table 5.8 iteration results of TTR data from September 1st, 2006 to November 30th, 2006, Mine B

5.2.3.5 Step 3-Prediction: Prediction of TTR data for the period from December 1st, 2006 to February 28th, 2007 based on data from September 1st to November 30th, 2006 based on continuous probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at mine A during the time period from December 1st, 2006 to February 28th, 2007. Fitting result from @Risk® shows the Exponential probability distribution fits the predicted data set best. The parameters of Lognormal probability distribution are β =3.5361 and shift=0.4787.

Figure 5.6 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from December 1st, 2006 to February 28th, 2007. At a level of significance of 5%, t-test statistic is 0.84 with 237 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5%.

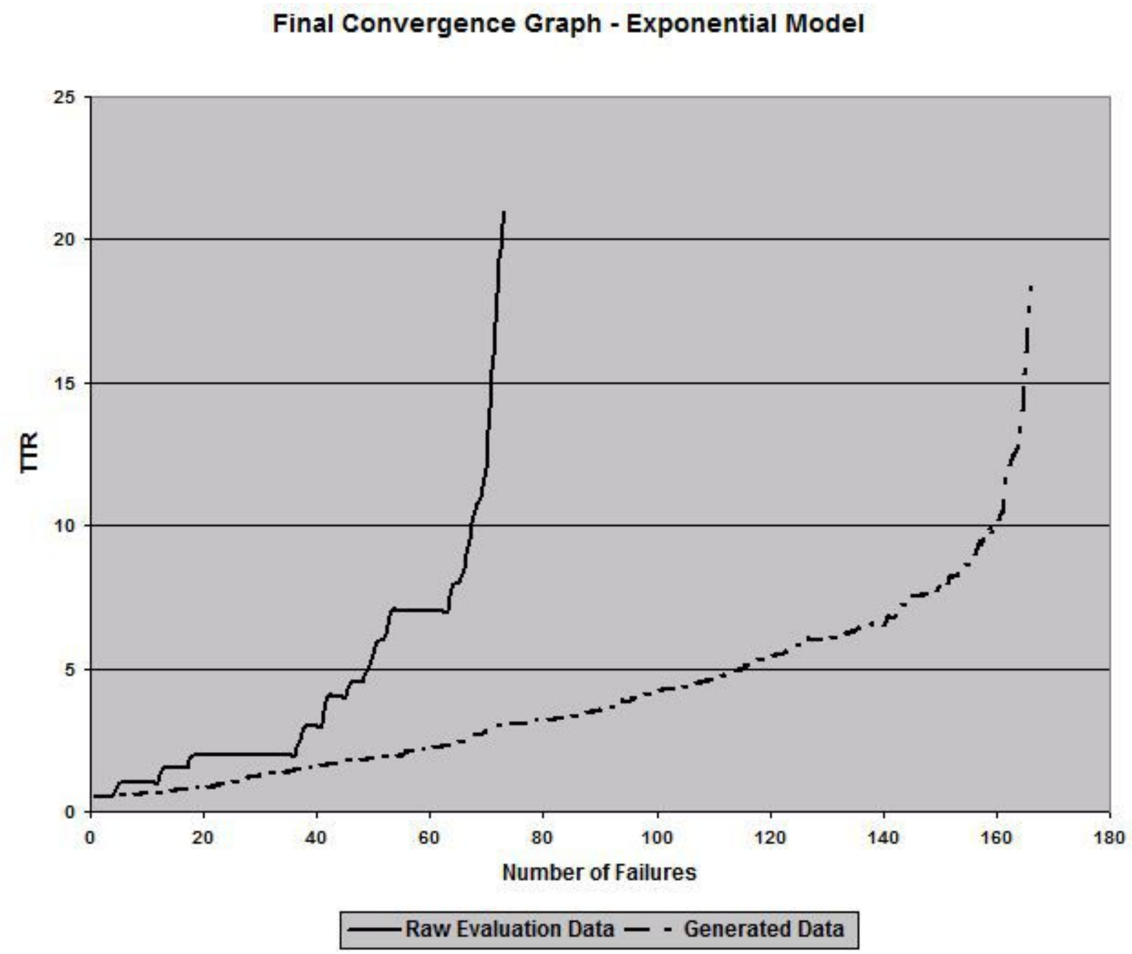

Figure 5.6 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from December 1st, 2006 to February 28th, 2007, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the Exponential cumulative distribution function, maintainability equation can be expressed (Appendix B.4):

$$M(T) = 1 - e^{-\frac{T - shift}{\beta}}$$

where

t is time

shift is the location parameter,

β is the scale parameter

Following are some maintainability values based on TTR

TTR(Hours)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Maintainability M(T)	29.79%	50.70%	65.38%	75.69%	82.93%	88.02%	91.59%	94.09%
β =3.5361 and shift=0.4787								

5.2.4 Prediction of TTR data for the period from June 1st, 2007 to August 31st, 2007 based on historical data from March 1st, 2007 to May 31st, 2007

5.2.4.1 Step-1: Data Preparation

5.2.4.1.1 Failure data composition

Table 5.9 displays failure data composition for the period from March 1st, 2007 to May 31st, 2007

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	394	72	49.16%
MM	69.5	44	8.67%
MO	22	4	2.74%
MH	8	6	1.00%
ME	88.5	43	11.04%
OI	132	32	16.47%
OP	87.5	36	10.92%
Total	801.5	237	100.00%

Table 5.9 Failure data composition from March 1st, 2007 to May 31st, 2007, Mine B

5.2.4.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.2.4.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fit of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=3.6356. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 5.10.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	3.6356	0.18178	0	0.0254	yes

Table 5.10 iteration results of TTR data from March 1st, 2007 to May 31st, 2007, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.2.4.3 Step 3-Prediction: Prediction of TTR data for the period from June 1st to August 31st, 2007 based on data from March 1st, 2007 to May 31st, 2007

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at mine B during the time period from June 1st to August 31st, 2007. Result from @Risk® show that the Poisson probability distribution fits the predicted data set best. Parameters of the Poisson probability distribution Lambda=3.1097.

Figure 5.7 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from June 1st to August 31st,

2007. At a level of significance of 5%, t-test statistic is 7.97 with 472 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5%. It is then considered that the model cannot be used with sufficient statistical confidence.

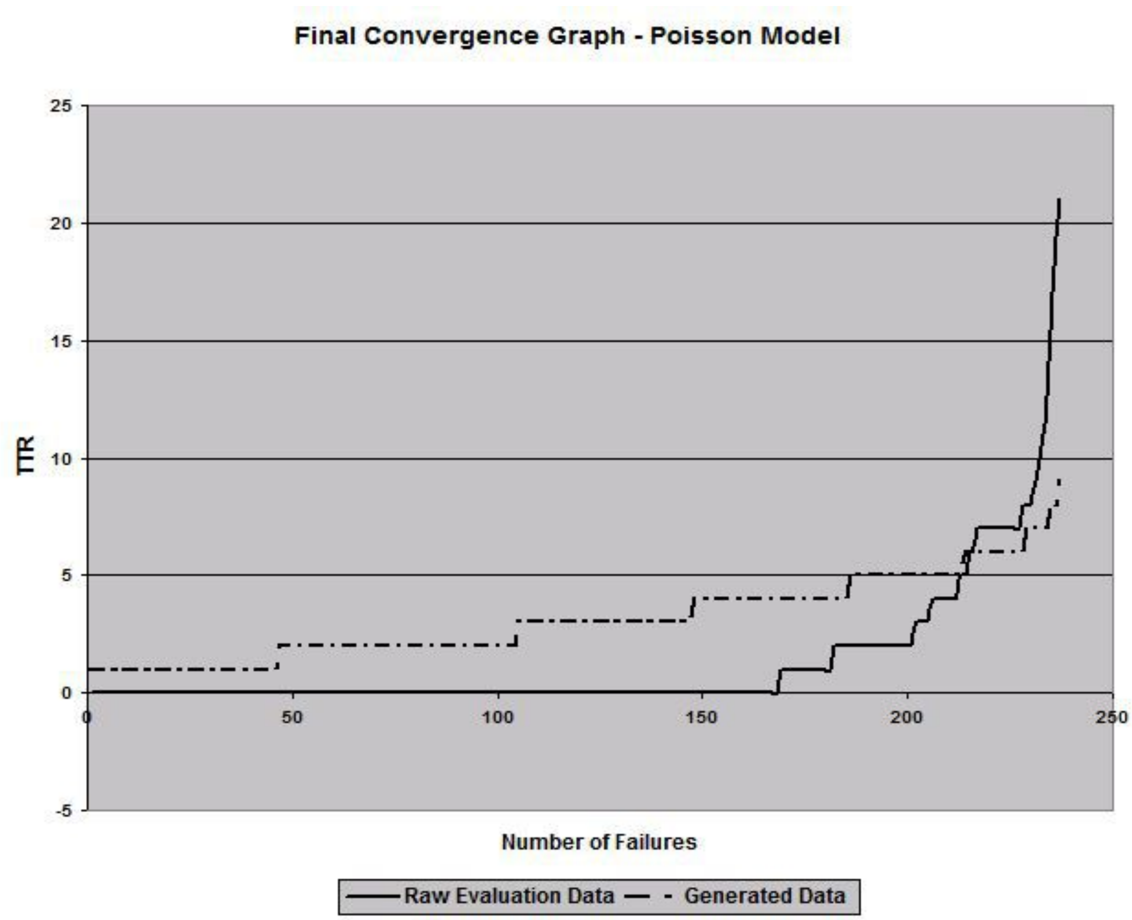

Figure 5.7 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from June 1st to August 31st, 2007, Mine B

5.2.4.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

After 15 iterations GenRel still cannot generate an offspring data which within the convergence limit. So GenRel is not applicable to predict future failure data in this case study.

5.3 Six month case study for Mine B

5.3.1 Prediction of TTR data for Six Months Period

1. Prediction of TTR data for the period from September 1st, 2006 to February 28th, 2007 based on historical data from March 1st, 2006 to August 31st, 2006
2. Prediction of TTR data for the period from January 1st, 2007 to June 30th, 2007 based on historical data from July 1st, 2006 to December 31st, 2006
3. Prediction of TTR data for the period from October 1st, 2007 to March 31st, 2008 based on historical data from April 1st, 2007 to September 30th, 2007

5.3.2 Prediction of TTR data for the period from September 1st, 2006 to February 28th, 2007 based on historical data from March 1st to August 31st, 2006

5.3.2.1 Step-1: Data Preparation

5.3.2.1.1 Failure data composition

Table 5.11 displays failure data composition for the period from March 1st, 2006 to August 31st, 2006.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	505	86	47.80%
OI	307.5	52	29.11%
MM	30	12	2.84%
ME	79	28	7.48%
OP	121.5	59	11.50%
MO	12.5	4	1.18%
MH	1	1	0.09%
Total	1056.5	242	100.00%

Table 5.11 Failure data composition from March 1st, 2006 to August 31st, 2006, Mine B

5.3.2.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.3.2.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel

The best fit of distribution function is the Poisson distribution for the Raw Input Data, with lambda=4.4545. In this case, after one iteration, the fitness function value fell within the user-defined convergence limit, as shown in Table 5.12.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.4545	0.222725	0	0.0083	yes

Table 5.12 iteration results of TTR data from March 1st, 2006 to August 31st, 2006, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.3.2.3 Step 3-Prediction: Prediction of TTR data for the period from September 1st, 2006 to February 28th, 2007 based on data from March 1st 2006 to August 31st, 2006 based on discrete distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from September 1st, 2006 to February 28th, 2007. Result from @Risk® show that the Poisson probability distribution fits the predicted data set best. The parameter of the Poisson probability distribution Lambda=4.2314.

Figure 5.8 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from September 1st, 2006 to February 28th, 2007. At a level of significance of 5%, t-test statistic is 0.71 with 582 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

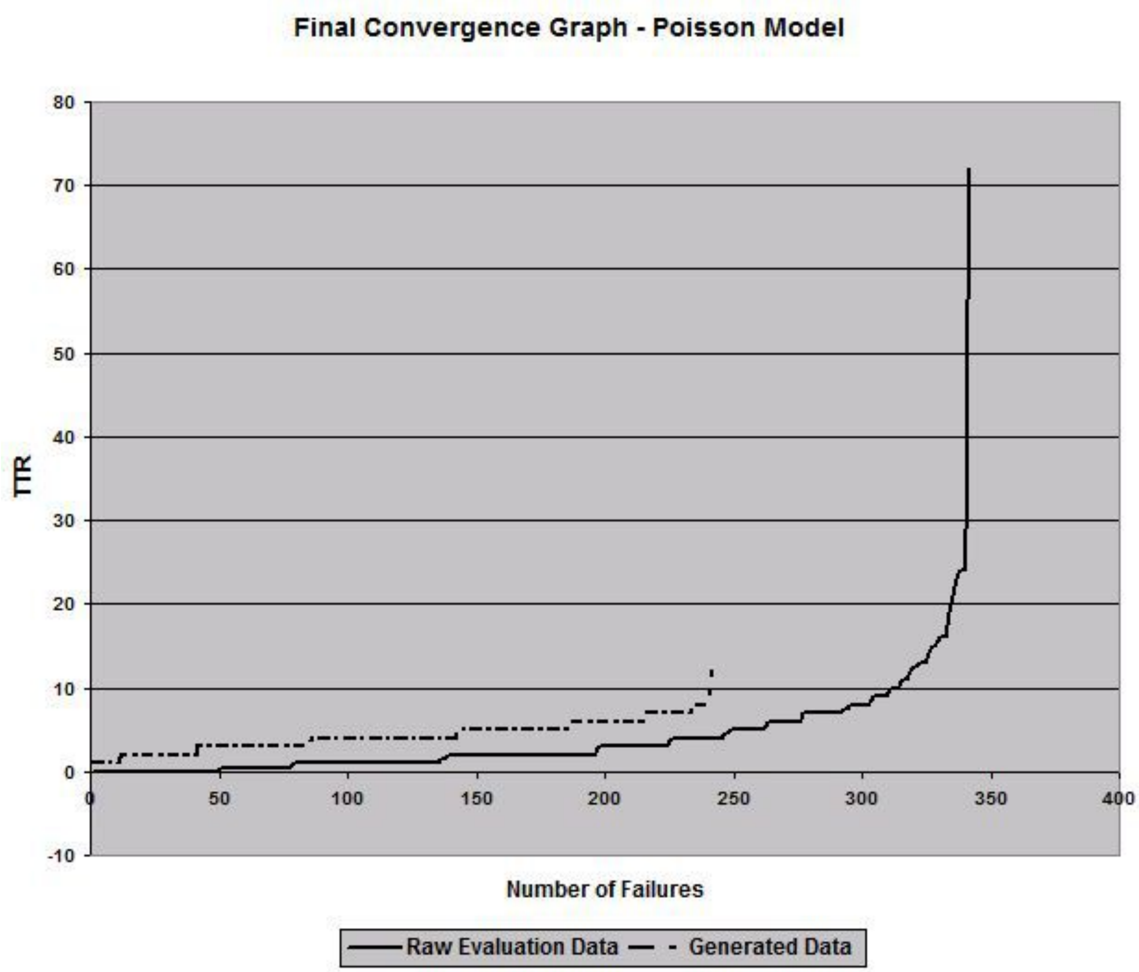

Figure 5.8 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from September 1st, 2006 to February 28th, 2007, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the Poisson cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.2):

$$M(T) = e^{-4.2314} \sum_{n=0}^{T} \frac{4.2314^n}{n!}$$

Following are some maintainability values based on TTR

TTR(Hours)	1	2	3	4	5	6	7	8
Maintainability M(T)	7.60%	20.61%	38.96%	58.37%	74.80%	86.39%	93.39%	97.09%
λ =4.2314								

5.3.2.4 Step 2-Verification: Continuous distribution fitting to verify the applicability of GenRel under this case study

The best fit of continuous distribution function is the Lognormal distribution for the Raw Input Data. Table 5.13 shows after seven iterations GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from March 1st, 2006 to August 31st, 2006.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	13.18383	0.6591915	0	0.76189	no
2	13.18383	0.6591915	0	0.76189	no
3	13.18383	0.6591915	0	0.76189	no
4	13.18383	0.6591915	0	0.76189	no
5	13.18383	0.6591915	0	0.76189	no
6	13.18383	0.6591915	0	0.76189	no
7	13.18383	0.6591915	0	0.28638	yes

Table 5.13 iteration results of TTR data from March 1st 2006 to August 31st, 2006, Mine B

5.3.2.5 Step 3-Prediction: Prediction of TTR data for the period from September 1st, 2006 to February 28th, 2007 based on data from March 1st, 2006 to August 31st, 2006 based on continuous distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from September 1st, 2006 to February 28th, 2007. Results from @Risk® show that the Lognormal probability distribution fits the predicted data set best. The parameters of Lognormal probability distribution are μ =4.5284, σ =7.7881 and shift=0.27088.

Figure 5.9 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from September 1st, 2006 to February 28th, 2007. At a level of significance of 5%, t-test statistic is 1.63 (borderline) with 582 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

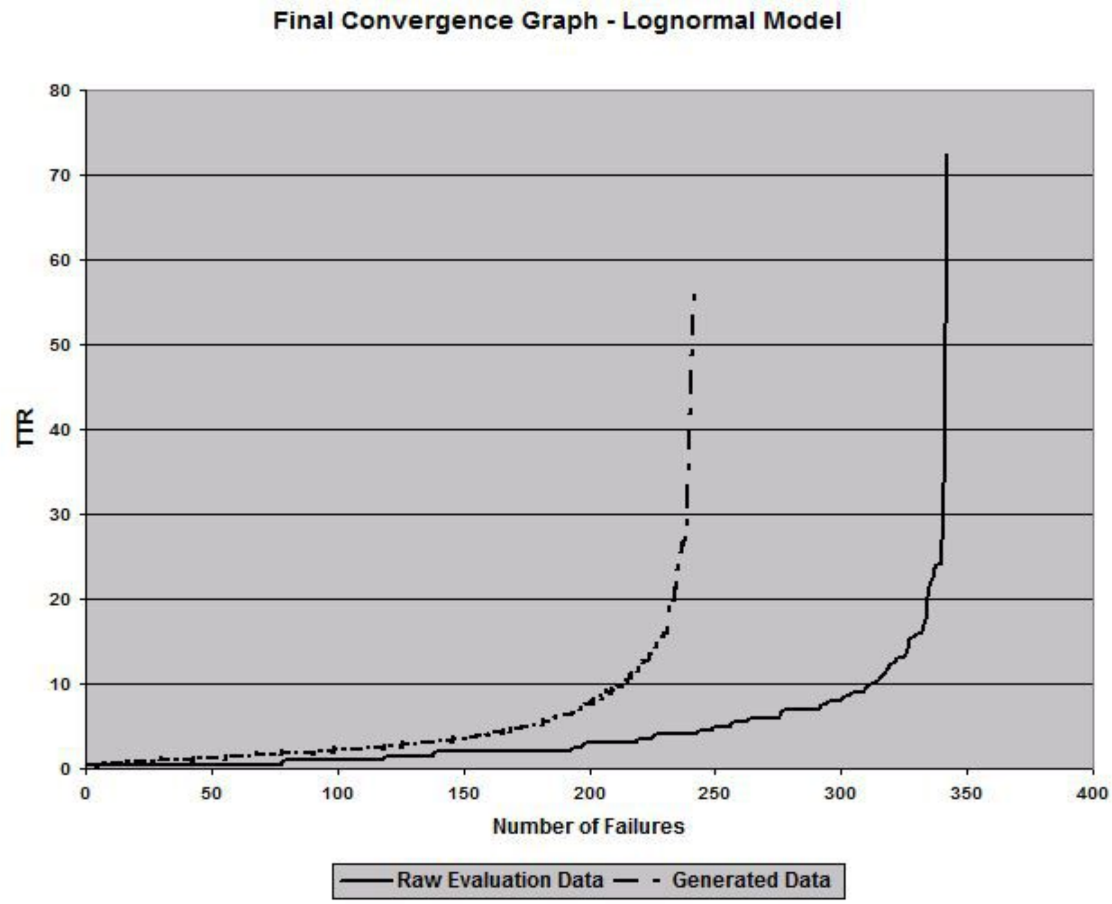

Figure 5.9 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from September 1st, 2006 to February 28th, 2007, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the Lognormal cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.3):

$$M(t) = \int_0^t \frac{1}{\sigma'(x-\theta)\sqrt{2\pi}} e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2} dx$$

with

$$\sigma' \equiv \sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu' \equiv \ln \frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

Following are some maintainability values based on TTR

TTR(Hours)	5	10	15	20	25	30	35	40
Maintainability M(T)	35.39%	38.75%	40.76%	42.20%	43.32%	44.25%	45.03%	45.71%
μ =4.5284, σ =7.7881 and θ =0.27088								

5.3.3 Prediction of TTR data for the period from January 1st, 2007 to June 30th, 2007 based on historical data from July 1st, 2006 to December 31st, 2006

5.3.3.1 Step-1: Data Preparation

5.3.3.1.1 Failure data composition

Table 5.14 displays failure data composition for the period from July 1st, 2006 to December 31st, 2006.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	635	91	56.54%
OI	250.5	58	22.31%
MM	28	17	2.49%
ME	102.5	46	9.13%
OP	53.5	27	4.76%
MH	7	5	0.62%
MO	30.5	12	2.72%
NX	16	2	1.42%
Total	1123	258	100.00%

Table 5.14 Failure data composition from July 1st, 2006 to December 31st, 2006, Mine B

5.3.3.1.2 Test the data for assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.3.3.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fitting of distribution function is the Poisson distribution for the Raw Input Data, with lambda=4.3125. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 5.15.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.3125	0.215625	0	0.0391	yes

Table 5.15 iteration results of TTR data from March 1st, 2006 to August 31st, 2006, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data for this case study.

5.3.3.3 Step 3-Prediction: Prediction of TTR data for the period from January 1st to June 30th, 2007 based on data from July 1st, 2006 to December 31st, 2006 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from January 1st to June 30th, 2007. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. Mean of the Poisson probability distribution Lambda=4.1406.

Figure 5.10 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from January 1st to June 30th,

2007. At a level of significance of 5%, t-test statistic is 2.97 with 713 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5%. It is then considered that the model cannot be used with sufficient statistical confidence.

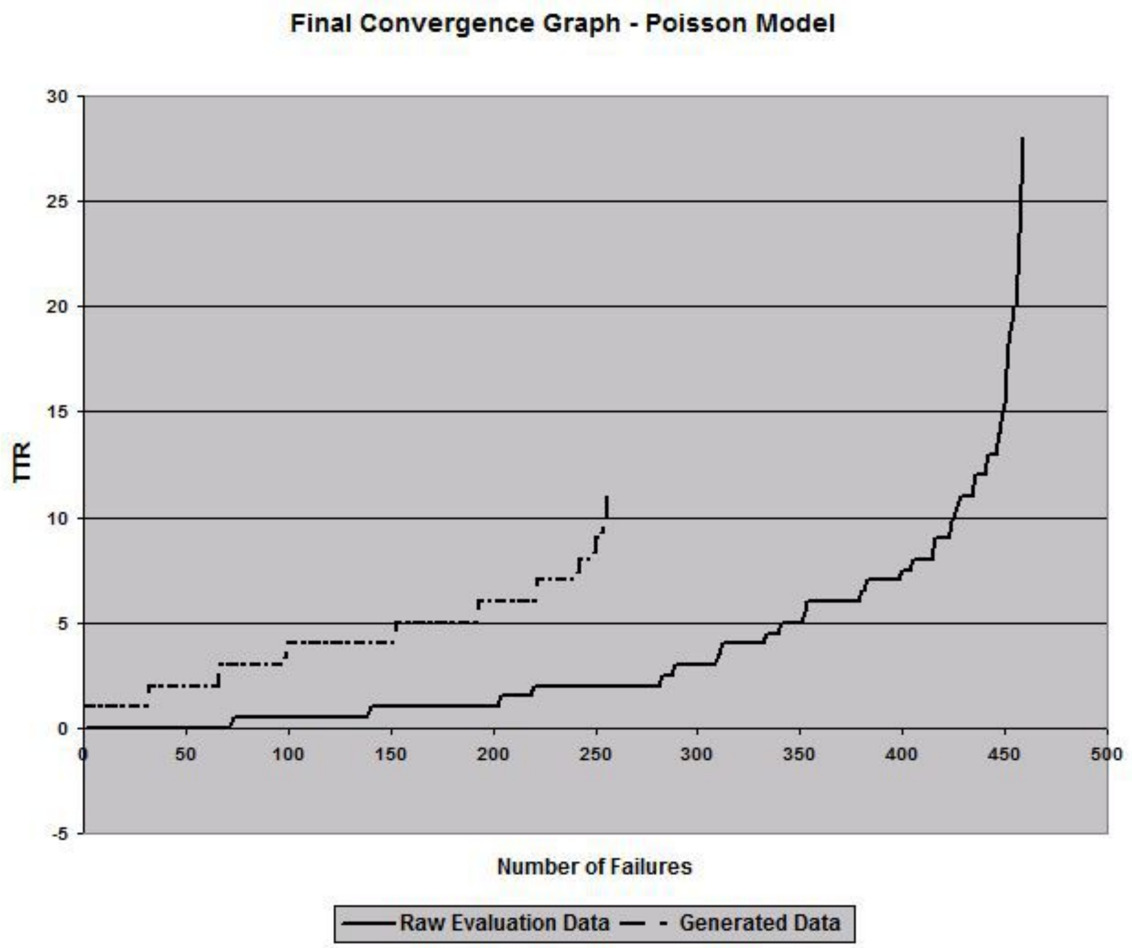

Figure 5.10 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from July 1st, 2006 to December 31st, 2006, Mine B

5.3.3.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

The best fit of continuous distribution function is the Lognormal distribution for the Raw Input Data. Table 5.16 shows after five iterations GenRel yields a set of data within the pre-defined convergence limit.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	12.34848	0.617424	0	0.72352	no
2	12.34848	0.617424	0	0.72352	no
3	12.34848	0.617424	0	0.72352	no
4	12.34848	0.617424	0	0.72352	no
5	12.34848	0.617424	0	0.49025	yes

Table 5.16 iteration results of TTR data from July 1st 2006 to December 31st, 2006, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data for this case study.

5.3.3.5 Step 3-Prediction: Prediction of TTR data for the period from January 1st to June 30th, 2007 based on data from July 1st, 2006 to December 31st, 2006 based on continuous probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from January 1st to June 30th, 2007. Result from @Risk® show that the Exponential probability distribution fits the predicted data set best. Parameters of Exponential probability distribution are β =3.8242 and shift=0.48506.

Figure 5.11 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from January 1st to June 30th, 2007. At a level of significance of 5%, t-test statistic is 2.84 with 713 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

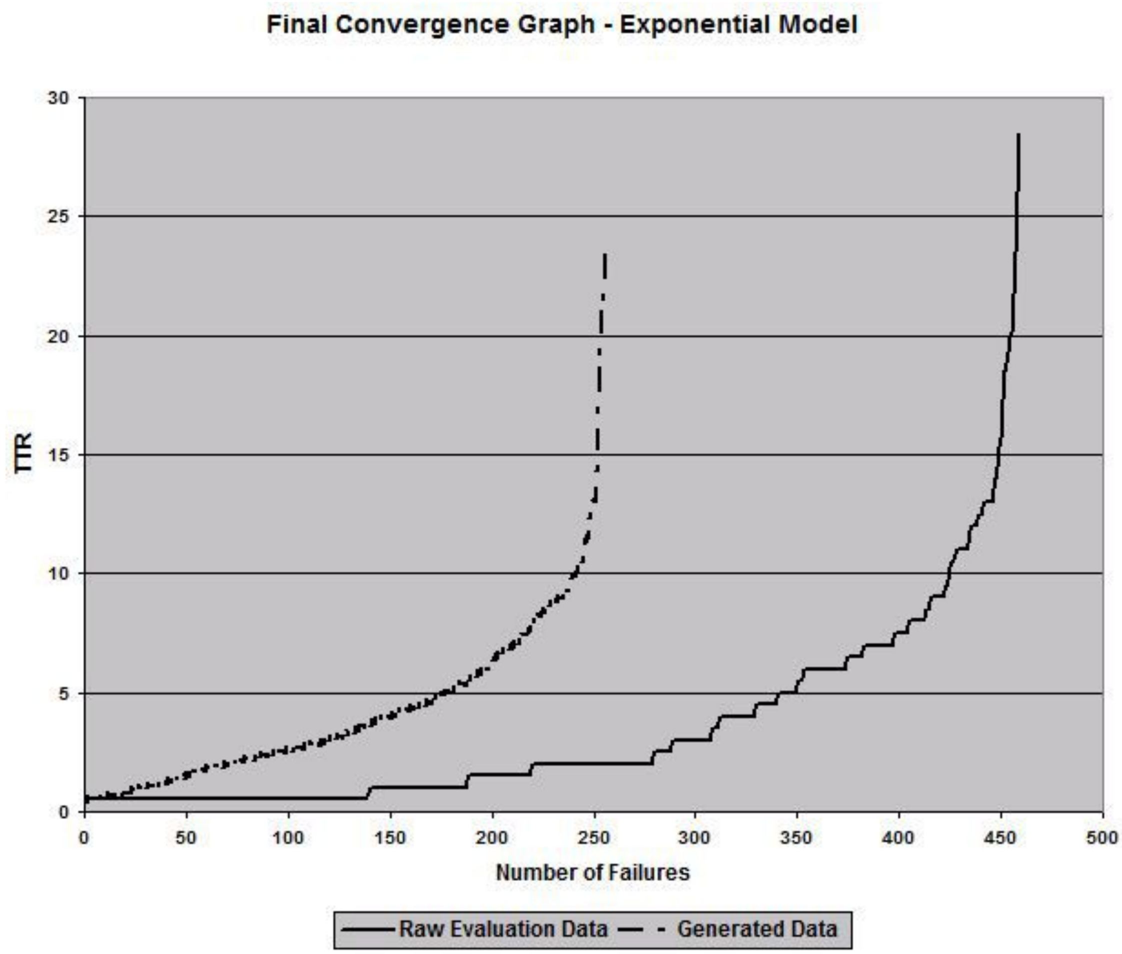

Figure 5.11 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from January 1st to June 30th, 2007, Mine B

5.3.4 Prediction of TTR data for the period from October 1st, 2007 to March 31st, 2008 based on historical data from April 1st to September 30th, 2007

5.3.4.1 Step-1: Data Preparation

5.3.4.1.1 Failure data composition

Table 5.17 displays failure data composition for the period from April 1st to September 30th, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	712.5	123	50.97%
MM	105	63	7.51%
OI	262.5	67	18.78%
OP	160.5	72	11.48%
ME	133.5	75	9.55%
MO	11	6	0.79%
MH	6	4	0.43%
MI	7	1	0.50%
Total	1398	411	100.00%

Table 5.17 Failure data composition from April 1st to September 30th, 2007, Mine B

5.3.4.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.3.4.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fit of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=2.9415. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 5.18.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	2.9415	0.147075	0	0.0097	yes

Table 5.18 iteration results of TTR data from April 1st 2007 to September 30th, 2007, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.3.4.3 Step 3-Prediction: Prediction of TTR data for the period from October 1st, 2007 to March 31st, 2008 based on data from April 1st, 2007 to September 30th, 2007 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from October 1st, 2007 to March 31st, 2008. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. The mean of the Poisson probability distribution Lambda=3.1606.

Figure 5.12 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from October 1st, 2007 to March

31st, 2008. At a level of significance of 5%, t-test statistic is 1.31 with 886 degrees of freedom. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

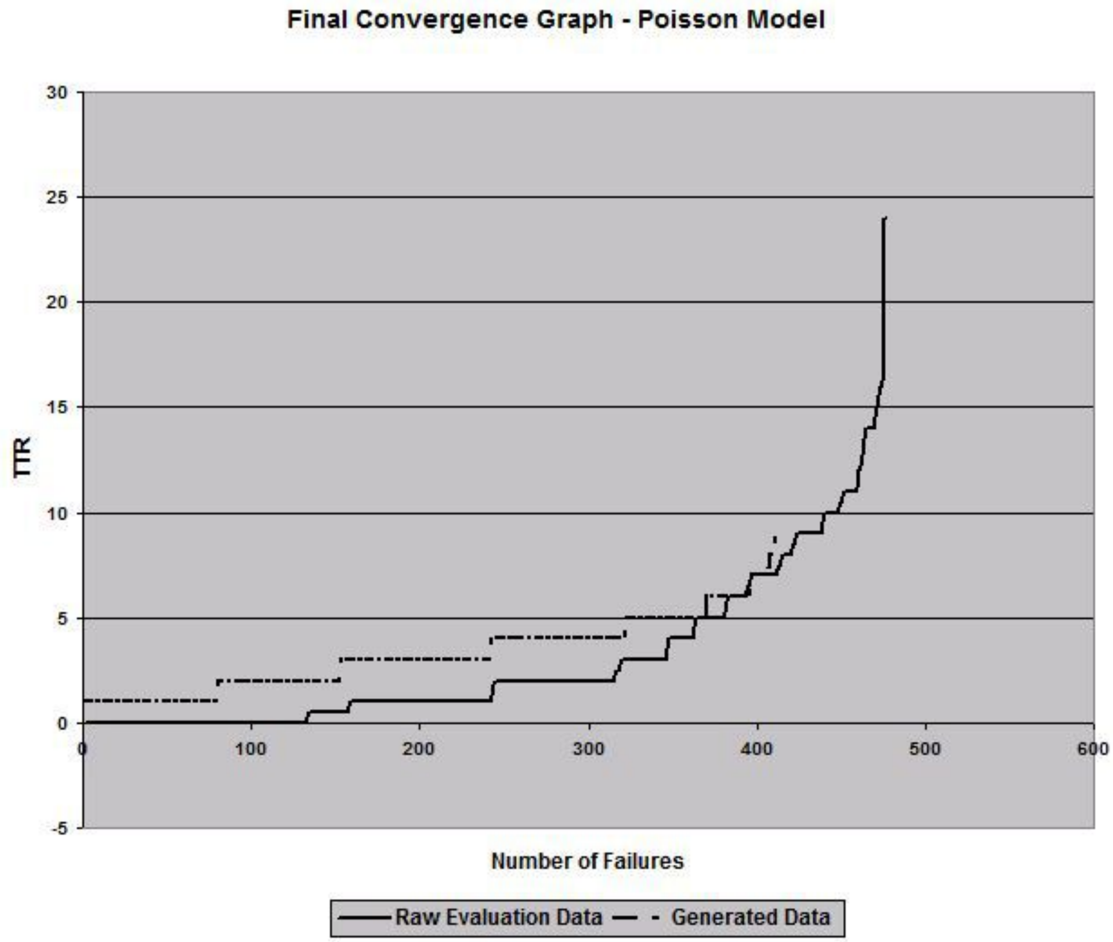

Figure 5.12 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from October 1st, 2007 to March 31st, 2008, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the Poisson cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B):

$$M(T) = e^{-3.1606} \sum_{n=0}^{T} \frac{3.1606^n}{n!}$$

Following are some maintainability values based on TTR

TTR(Hours)	1	2	3	4	5	6	7	8
Maintainability M(T)	17.64%	38.82%	61.13%	78.76%	89.90%	95.77%	98.42%	99.47%
λ=3.1606								

5.3.4.4 Step 2-Verification: Continuous probability distribution fitting to verify the applicability of GenRel under this case study

The best fitting of continuous distribution function is the Normal distribution for the Raw Input Data. Table 5.19 shows that after 15 iterations GenRel still cannot generate an offspring data which within the convergence limit. So GenRel is not applicable to predict future failure data in this case study.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	7.2969	0.364845	0	1.546	no
2	7.2969	0.364845	0	1.546	no
3	7.2969	0.364845	0	1.546	no
4	7.2969	0.364845	0	1.546	no
5	7.2969	0.364845	0	1.546	no
6	7.2969	0.364845	0	1.546	no
7	7.2969	0.364845	0	1.5001	no
8	7.2969	0.364845	0	1.3466	no
9	7.2969	0.364845	0	1.3466	no
10	7.2969	0.364845	0	1.3466	no
11	7.2969	0.364845	0	1.3466	no
12	7.2969	0.364845	0	1.3466	no
13	7.2969	0.364845	0	1.3466	no
14	7.2969	0.364845	0	1.2786	no
15	7.2969	0.364845	0	1.2786	no

Table 5.19 iteration results of TTR data from April 1st to September 30th, 2007, Mine B

5.4 One year case study at Mine B

5.4.1 Prediction of TTR data for One Year Period

1. Prediction of TTR data for the period from March 1st, 2007 to February 28th, 2008 based on historical data from March 1st, 2006 to February 28th, 2007
2. Prediction of TTR data for the period from September 1st, 2007 to August 31st, 2008 based on historical data from September 1st, 2006 to August 31st, 2007

5.4.2 Prediction of TTR data for the period from March 1st, 2007 to February 28th, 2008 based on historical data from March 1st, 2006 to February 28th, 2007

5.4.2.1 Step-1: Data Preparation

5.4.2.1.1 Failure data composition

Table 5.20 displays failure data composition for the period from March 1st, 2006 to February 28th, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	1443	229	53.36%
OI	682	135	25.22%
MM	72.5	41	2.68%
ME	230	98	8.50%
OP	196	114	7.25%
MO	65.5	21	2.42%
MH	15.5	11	0.57%
Total	2704.5	649	100.00%

Table 5.20 Failure data composition from March 1st, 2006 to February 28th, 2007, Mine B

5.4.2.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically

Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.4.2.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

Verification process is a very effective method which uses suitable data set to check GenRel's applicability in case study. In this case, If GenRel is to be found applicable through the verification process, TTR data from the period of March 1st, 2006 to February 28th, 2007, which is to be used as Raw Input Data set to predict repair data for the period of March 1st, 2007 to February 28th, 2008.

Since we can assume that the data can be either considered as discrete or continuous, using @Risk® we select to fit the data with a discrete distribution for the purpose of this case study.

The best fitting of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=4.1944. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 5.21.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.1944	0.20972	0	0.0061	yes

Table 5.21 Iteration results of TTR data from March 1st, 2006 to February 28th, 2007, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.4.2.3 Step 3-Prediction: Prediction of TTR data for the period from March 1st, 2007 to February 28th, 2008 based on data from March 1st, 2006 to February 28th, 2007 based on discrete probability distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at Mine B during the time period from March 1st, 2007 to February 28th, 2008. Results from @Risk® show that the Poisson probability distribution fits the predicted data set best. The mean of the Poisson probability distribution Lambda=3.9861.

Figure 5.13 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from March 1st, 2007 to February 28th, 2008. At a level of significance of 5%, t-test statistic is 4.85 with 1518 degrees of freedom. Based on the result of the t-test, it is concluded that there is a significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D). It is then considered that the model cannot be used with sufficient statistical confidence.

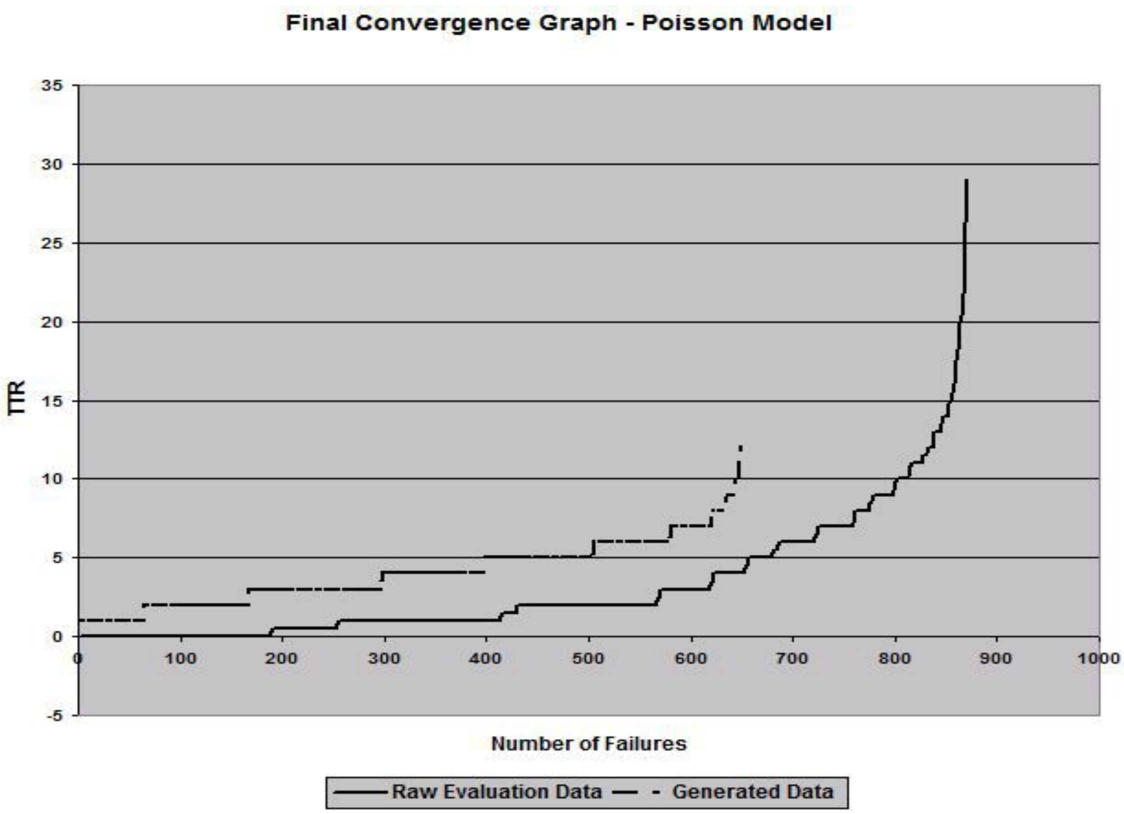

Figure 5.13 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from March 1st, 2007 to February 28th, 2008, Mine B

5.4.2.4 Step 2-Verification: Continuous Probability distribution fitting to verify the applicability of GenRel under this case study

In the input data is assumed to be continuous then the Lognormal probability distribution is the best fit for the Raw Input Data as based on calculation by @Risk. Table 5.22 shows after one iteration GenRel yields a set of data within the pre-defined convergence limit. Therefore, GenRel is considered applicable for the prediction of future failure data based on the historical data from March 1st, 2006 to February 28th, 2007.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	12.70941	0.6354705	0	0.31273	yes

Table 5.22 iteration results of TTR data from March 1st, 2006 to February 28th, 2007, Mine B

5.4.2.5 Step 3-Prediction: Prediction of TTR data for the period from March 1st, 2007 to February 28th, 2008 based on data from March 1st, 2006 to February 28th, 2007 based on continuous distribution function

After fifteen iterations, GenRel still cannot generate an offspring data within the convergence limit. GenRel failed to predict future failure data from March 1st, 2006 to February 28th, 2007 based on continuous distribution function.

5.4.3 Prediction TTR data for the period from September 1st, 2007 to August 31st, 2008 based on historical data from September 1st, 2006 to August 31st, 2007

5.4.3.1 Step-1: Data Preparation

5.4.3.1.1 Failure data composition

Table 5.23 diaplays failure data composition for the period from September 1st, 2006 to August 31st, 2007.

Type of Failure	TTR (Hours)	TTR Frequency	Percent of TTR
MP	1518	249	54.10%
ME	279.5	140	9.96%
OI	594	138	21.17%
OP	204	113	7.27%
MM	128	87	4.56%
MO	55	20	1.96%
MH	20.5	14	0.73%
MI	7	1	0.25%
Total	2806	762	100.00%

Table 5.23 Failure data composition from September 1st, 2006 to August 31st, 2007, Mine B

5.4.3.1.2 Test the data for the assumption of Independent and Identical Distribution (IID)

Before GenRel simulation is run, the validity of the Independent and Identically Distributed (IID) assumption should be checked (Appendix C). Combined trend test result and serial correlation test indicate that the data under study is independent and identically distributed. Therefore the condition of using GenRel is satisfied, data being independent and identically distributed.

5.4.3.2 Step 2-Verification: Discrete probability distribution fitting to verify the applicability of GenRel under this case study

The best fit of discrete distribution function is the Poisson distribution for the Raw Input Data, with lambda=3.8635. In this case, after one iteration, the fitness function value falls within the user-defined convergence limit, as shown in Table 5.24.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	3.8635	0.193175	0	0.0184	yes

Table 5.24 iteration results of TTR data from September 1st 2006 to August 31st 2007, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.4.3.3 Step 3-Prediction: Prediction of TTR data for the period from September 1st, 2007 to August 31st, 2008 based on data from September 1st, 2006 to August 31st, 2007 based on a discrete distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at mine A during the time period from September 1st, 2007 to August 31st, 2008. Fitting result from @Risk® shows the Poisson probability distribution fits the predicted data set best. The mean of the Poisson probability distribution Lambda=3.4567.

Figure 5.14 shows a convergence graph comparison between the Raw Evaluation

Data and the Generated Data for the time period from September 1st, 2007 to August 31st, 2008. At a level of significance of 5%, t-test statistic is 0 with a degree of freedom of 785. Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

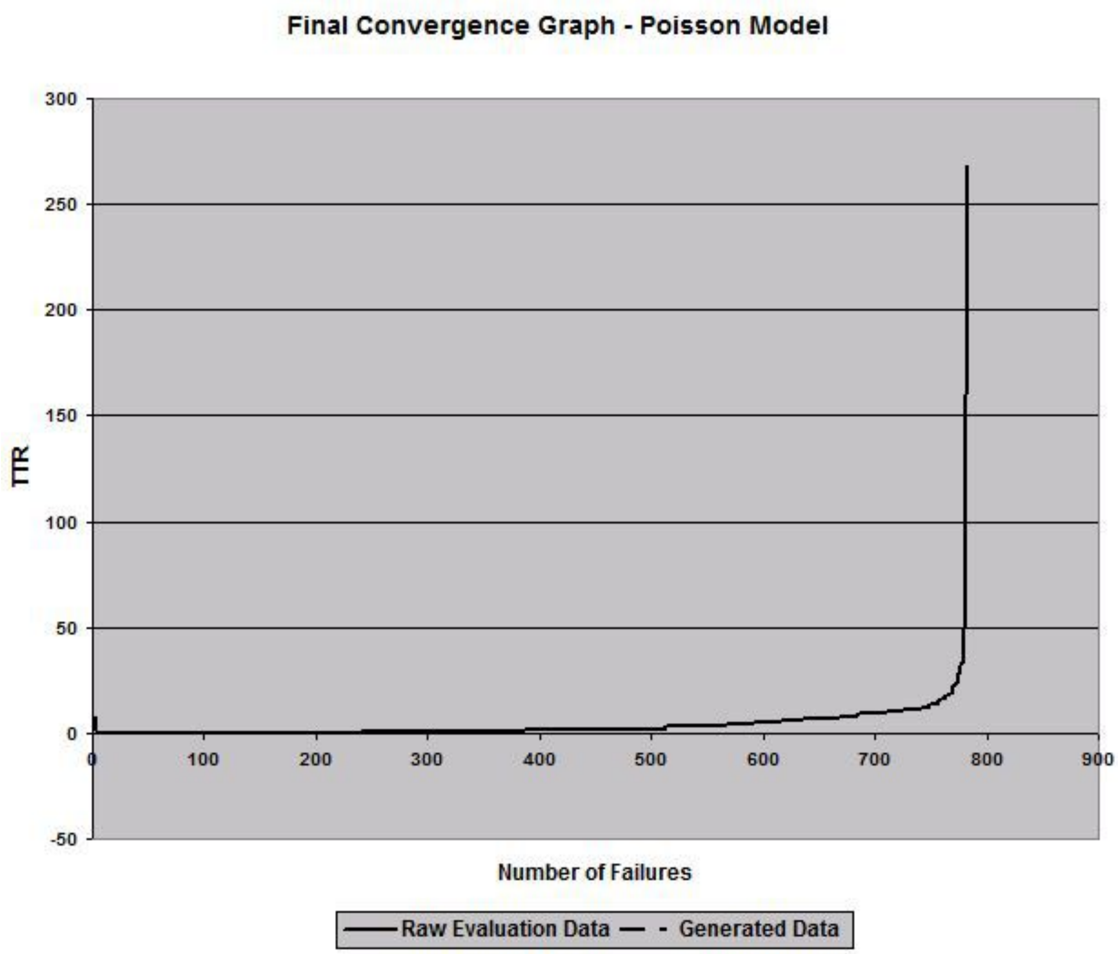

Figure 5.14 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from September 1st, 2007 to August 31st, 2008, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the Poisson cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.2):

$$M(T) = e^{-3.4567} \sum_{n=0}^{T} \frac{3.4567^n}{n!}$$

Following are some maintainability values based on TTR

TTR(Hours)	1	2	3	4	5	6	7	8
Maintainability M(T)	14.05%	32.89%	54.60%	73.36%	86.33%	93.80%	97.49%	99.08%
λ=3.4567								

5.4.3.4 Step 2-Verification: Continuous distribution fitting to verify the applicability of GenRel under this case study

The best fit of continuous distribution function is Exponential distribution for the Raw Input Data. Table 5.25 shows after one iteration GenRel yields a set of data within the pre-defined convergence limit.

Iteration	Sum of Raw Evaluation Data parameters	Upper Evaluation Limit Based on Convergence Limit of GA	Lower Evaluation Limit Based on Convergence Limit of GA	Parameter Deviation of Generated Data	Accepted Convergence?
1	4.06153	0.2030765	0	0.06333	yes

Table 5.25 iteration results of TTR data from September 1st, 2006 to August 31st, 2007, Mine B

Based on the above, It is suggested that GenRel is applicable to analyze the set of TTR data under this case study.

5.4.3.5 Step 3-Prediction: Prediction of TTR data for the period from September 1st, 2007 to August 31st, 2008 based on data from September 1st, 2006 to August 31st, 2007 based on continuous distribution function

After one iteration, GenRel returns a set of TTR data as the final prediction of failures on the hoist system at mine A during the time period from September 1st, 2007 to August 31st, 2008. Results from @Risk® show that the Exponential probability distribution fits the predicted data set best. The parameters of

Exponential probability distribution are β =3.1824 and shift=0.49582.

Figure 5.15 shows a convergence graph comparison between the Raw Evaluation Data and the Generated Data for the time period from September 1st, 2007 to August 31st, 2008. At a level of significance of 5%, t-test statistic is 0.77 with 1543 degrees of freedom . Based on the result of the t-test, it is concluded that there is no significant difference between generated data set and Raw Evaluation Data set in terms of mean at a given level of significance of 5% (Appendix D).

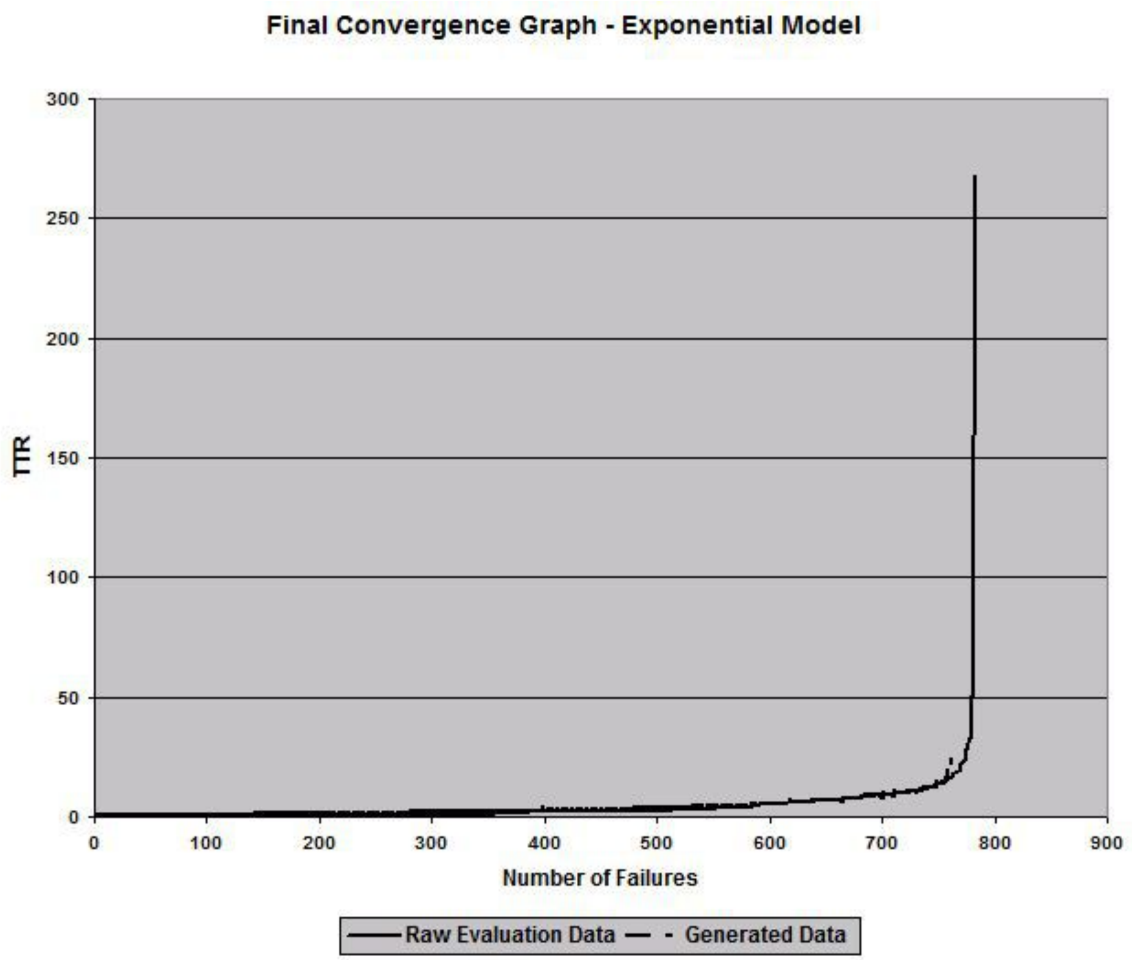

Figure 5.15 Convergence comparison between Raw Evaluation Data and Generated Data for the time period from September 1st, 2007 to August 31st, 2008, Mine B

Combining the definition of maintainability (see 1.3.1) and applying the

Exponential cumulative distribution function, the maintainability equation can be expressed (for detailed calculation, see Appendix B.4):

$$M(T) = 1 - e^{-\frac{T - shift}{\beta}}$$

where

t	is time
shift	is the location parameter,
β	is the scale parameter

Following are some maintainability values based on TTR

TTR(Hours)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Maintainability M(T)	27.26%	47.08%	61.51%	72.00%	79.63%	85.18%	89.22%	92.16%
β=3.1824 and shift=0.49582								

5.5 Remarks

There are three groups of case studies in this chapter, three months, six months and one year. For all case studies, the Poisson probability distribution was found to be the best fit for the Raw Input Data in the discrete probability distribution fitting pool. In the case studies of three month periods, six month periods and a one year period, the size of the Raw Input Data ranges from 166 to 762 and the fitness function value falls within the user-defined convergence limit after one iteration run in GenRel. In the fitting of the Poisson probability distribution, all of the prediction results for three month periods have a significant difference between the generated data set and the Raw Evaluation Data set in terms of mean at a given level of significance of 5%. Furthermore the data size of the Evaluation Data Set for prediction is less than half compared to the Input Data Set (see Table 6.2). It should be mentioned here that Planned Maintenance represents a high percentage of the input failure data (see Table 4.11), and thus, during or after this routine maintenance period, the number of failures may decline rapidly.

In the case study of continuous probability distribution fitting, one failure in verification step occurred per each case study group. The Lognormal probability distribution was found to be the best fit for prediction for the first two case studies in the three month period and the first case study in the six month period. However, the Exponential probability distribution was also found to be the best fit for prediction in the case study of one year period (with input data from 1st September 2006 to 31st August 2007). There are four successful case studies in the three case study groups. Input data size ranges from 166 to 762.

Chapter 6 Discussion

Five groups of case studies have been analyzed for verifying the applicability of GenRel, two groups for Mine A, for three month and six months period and the other three groups for Mine B, with three months, six months and one year time periods. In all case studies same user based input parameters have been set in GenRel. The maximum number of iteration was 15, the convergence limit was 0.05 and the probability of mutation was 0.05.

Table 6.1 shows a summary of all case studies that a discrete probability distribution was selected for testing for best fit. Table 6.2 shows a summary of all case studies that a continuous probability distribution was selected for testing for best fit.

Discrete Distribution Fitting										
Input Data Set		Iteration		Prediction		Evaluation Data Set		Value of t-test	Sig	Name of Function
Time period	Size	S / F	Times	Time period	Size	Time period	Size			
Hoist System at Mine A										
Three month Case Studies										
1st Sep06- 30th Nov06	230	S	1	1st Dec06 -28thFeb07	230	1st Dec06- 28th Feb07	178	1.76	Yes	Poisson
1st Jan07- 31st Mar07	148	S	1	1st Apr -30thJun07	148	1st Apr07- 30th Jun07	258	2.12	Yes	Poisson
1st Sep07- 30th Nov07	78	S	1	1st Dec07 -28thFeb08	78	1st Dec07- 28th Feb08	118	2.41	Yes	Poisson
Six month Case Studies										
1st Sep06- 28th Feb07	409	S	1	1st Mar -31stAug07	409	1st Mar07- 31st Aug07	331	1.96	Yes	Poisson
1st Nov06- 30th Apr07	396	S	1	1st May -30thOct07	396	1st May07- 30th Oct07	270	0.21	No	Poisson
1st Jan07- 30th Jun07	136	S	1	1st July -31stDec07	136	1st July07- 31st Dec07	110	3.54	Yes	Poisson

Hoist System at Mine B										
Three month Case Studies										
1st Mar-31st May06	170	S	1	1st Jun06 -31st Aug06	170	1st Jun06-31st Aug06	73	7.61	Yes	Poisson
1st Sep-30th Nov06	166	S	1	1st Dec06 -28th Feb07	166	1st Dec06-28th Feb07	73	6.15	Yes	Poisson
1st Mar-31st May07	237	S	1	1st Jun07 -31st Aug07	237	1st Jun07-31st Aug07	73	7.97	Yes	Poisson
Six month Case Studies										
1st Mar06-31st Aug06	242	S	1	1st Sep06 -28thFeb07	242	1st Sep06-28th Feb07	342	0.71	No	Poisson
1st July06-31st Dec06	256	S	1	1stJan07- 30thJune07	256	1st Jan07-30th June07	459	2.97	Yes	Poisson
1st Apr07-30th Sep07	411	S	1	1st Oct07 -31stMar08	411	1st Oct07-31st Mar08	477	1.31	No	Poisson
One year Case Studies										
1st Mar06-28th Feb07	649	S	1	1st Mar07 -28thFeb08	649	1st Mar07-28th Feb08	871	4.85	Yes	Poisson
1st Sep06-31stAug07	762	S	1	1st Sep07 -31stAug08	762	1st Sep07-31st Aug08	783	0.00	No	Poisson
S/F Stand for Success/Fail of the verification results, Sig means significance of t-test (Yes/No)										

Table 6.1 Summary of the case studies at Mine A and at Mine B (discrete distribution fitting)

Continuous Distribution Fitting										
Input Data Set		Iteration		Prediction		Evaluation Data Set		Value of t-test	Sig	Name of Function
Time period	Size	S/F	Times	Time period	Size	Time period	Size			
Hoist System at Mine A										
Three month Case Studies										
1st Sep06-30th Nov06	230	S	3	1st Dec06-28th Feb07	230	1st Dec06-28th Feb07	178	1.62	No	Lognormal
1st Jan07-31st Mar07	148	F		1st Apr07-30th Jun07		1st Apr07-30th Jun07				
1st Sep07-30th Nov07	78	S	1	1st Dec07-28th Feb08	78	1st Dec07-28th Feb08	118	1.71	No	Lognormal

Six month Case Studies										
1st Sep06- 28th Feb07	409	S	1	1st Mar07- 31st Aug07	409	1st Mar07- 31st Aug07	331	0.32	No	Lognormal
1st Nov06- 30th Apr07	396	S	1	1st May07- 31st Oct07	396	1st May07- 31st Oct07	270	0.7	No	Lognormal
1st Jan07- 30th Jun07	136	S	1	1st July07- 31st Dec07	136	1st July07- 31st Dec07	110	3.45	Yes	Lognormal
Hoist System at Mine B										
Three month Case Studies										
1st Mar06- 31st May06	170	S	1	1st Jun06- 31st Aug06	170	1st Jun06- 31st Aug06	73	0.42	No	Lognormal
1st Sep06- 30th Nov06	166	S	1	1st Dec06- 28th Feb07	166	1st Dec06- 28th Feb07	73	0.84	No	Lognormal
1st Mar07- 31st May07	123	F	15	1stJun07- 31st Aug07		1st Jun07- 31st Aug07				
Six month Case Studies										
1st Mar06- 31st Aug06	242	S	1	1st Sep06- 28th Feb07	242	1st Sep06- 28th Feb07	342	1.63	No	Lognormal
1st July06- 31st Dec06	256	S	1	1st Jan07- 30th Jun07	256	1st Jan07- 30th Jun07	459	2.84	Yes	Expon
1st Apr07- 30th Sep07	411	F	15	1st Oct07- 31st Mar08		1st Oct07- 31st Mar08				
One year Case Studies										
1st Mar06- 28th Feb07	649	F	15	1stMar07- 28thFeb08		1st Mar07- 28th Feb08				
1st Sep06- 31st Aug07	762	S	1	1stSep07- 31st Aug08	762	1st Sep07- 31stAug08	783	0.77	No	Expon
S/F Stand for Success/Fail of the verification results, Sig means significance of t-test (Yes/No) Expon means Exponential										

Table 6.2 Summary of the case studies at Mine A and at Mine B (continuous distribution fitting)

Both of these tables include the time period and data size of the Input Data, Evaluation Data and the predicted data sets, the results of the verification and the number of iteration runs in GenRel.

Based on the collected input data, the remarks in chapters 4.4, 5.5 and the tabulation of output in Tables 6.1 and 6.2, the following table (Table 6.3) has been created to display which type of failure has the highest percent of occurrence within the Input Data Set per each case study.

Input Data Set		Continuous Probability Fitting		Discrete Probability Fitting		Type of Failure with the highest percent of occurrence (from the Input Data Set)		Type of Failure with the second highest percent of occurrence (from the Input Data Set)	
Time period	Size	Veri S/F	Pred S/F	Veri S/F	Pred S/F	Name	%	Name	%
Hoist System at Mine A									
Three month Case Studies									
1stSep06-30thNov06	230	S	S	S	F	OI	33.84	MP	32.80
1stJan07-31stMar07	148	F	N/A	S	F	MP	45.57	OI	41.87
1stSep07-30thNov07	78	S	S	S	F	MP	61.24	OI	31.13
Six month Case Studies									
1stSep06-28thFeb07	409	S	S	S	F	MP	38.83	OI	35.41
1stNov06-30thApr07	396	S	S	S	S	MP	43.37	OI	35.21
1stJan07-30thJun07	136	S	F	S	F	MP	47.41	OI	30.46
Hoist System at Mine B									
Three month Case Studies									
1stMar06-31stMay06	170	S	S	S	F	MP	49.46	OI	31.29
1stSep06-30thNov06	166	S	S	S	F	MP	55.22	OI	26.19
1stMar07-31stMay07	123	F	N/A	S	F	MP	49.16	OI	16.47
Six month Case Studies									
1stMar06-31stAug06	242	S	S	S	S	MP	47.80	OI	29.11
1stJuly06-31stDec06	256	S	F	S	F	MP	56.54	OI	22.31
1stApr07-30thSep07	411	F	N/A	S	S	MP	50.79	OI	18.78
One year Case Studies									
1stMar06-28thFeb07	649	F	N/A	S	F	MP	53.36	OI	25.22
1stSep06-31stAug07	762	S	S	S	S	MP	54.10	OI	21.17
S/F Stand for Success/Fail, Veri means verification, Pred means prediction MP means Planned Maintenance and OI means Operator Planned Inspection N/A means Not Applicable									

Table 6.3 Type of Failure with highest percent of occurrence within the Input Data Set per each case study

From Table 6.3 (page 125),for both mines we know the two highest percentage failures are Planned Maintenance (MP) and Operator Planned Inspection (OI). From Table 5.20 (page 111) and Table 5.23 (page 115), the other significant failures for mine B are Electrical Down (ME) and Operator Repairs (OP).

Overall, GenRel was developed to demonstrate whether it can be used as an independent method for estimating the maintainability of equipment systems. Based on the available data from the case studies the following observations were made:

- **In the Verification Step:**

➢ Discrete probability distribution succeeded in all case studies in this step.

➢ Continuous probability distribution failed three times:

For Mine A, failed once in three months case study.

For Mine B, failed once in three months case study and once in six months case study.

- **In the Prediction Step:**

For Mine A:

➢ For three months predictability: Not applicable

(Continuous probability distribution succeeded twice, failed once. Discrete probability distribution failed 3 times)

➢ For six months predictability: May be applicable

(Continuous probability distribution succeeded twice, failed once. Discrete probability distribution succeed once, failed twice)

For Mine B:

➢ For three months predictability: Not applicable

(Continuous probability distribution succeeded twice, failed once. Discrete probability distribution failed 3 times)

- For six months predictability: May be applicable

 (Continuous probability distribution succeeded once, failed twice. Discrete probability distribution succeed twice, failed once)

- For one year predictability: May be applicable

 (Continuous probability distribution and discrete probability distribution succeeded once, failed once respectively.)

The computational approach based on Genetic Algorithms and adopted in GenRel should not be considered as a self proven approach that can substitute existing reliability/maintainability probabilistic methods. It can be used as a supplement to current practices and further investigation is suggested.

No significant impact of the data size on the applicability of GenRel was observed. Considering the maintainability analysis of the hoist system at Mine B as an example, discrete distribution fitting was successful in all case studies with data sets size varying from 242 to 762 samples. In the continuous distribution fitting, at the same mine, a successful application case was described in Section 5.2.3, with the Raw Input Data set covering the period from September 1st, 2006 to November 30th, 2006 with data size of 166. In the successful application of GenRel in the one year case study, as described in Section 5.4.3, the Raw Input Data Set has a data size of 762. Despite of three failures at data sets with size of 256, of 411 and of 649 for continuous distribution fitting, GenRel demonstrates its capability of predicting future failure data with data size ranging from 166 to 762.

6.1 Limitations of the Applicability of GenRel

Overall, the case studies indicated to a degree the applicability of discrete probability distribution fitting for the hoist systems at Mine A and Mine B. In the prediction of three months period at Mine B, it was found that there is a significant difference between the generated data set and the Evaluation Data set in terms of mean at a given level of significance of 5%. These three months case studies at Mine B cover the period from March 1st, 2006 to May 31st, 2006 (Section 5.2.2), from September 1st, 2006 to November 30th, 2006 (Section 5.2.3) and from March 1st, 2007 to May 31st, 2007 (Section 5.2.4). In these cases it was considered that the historical data was independent and identically distributed, even though apparent concavity can be observed in the trend test curves (Appendix C). The reason for concavity might be related to the annual maintenance of equipment. For the hoist at Mine B, annual maintenance is usually carried out in a specific time period (e.g. from June to August), and thus during or after this annual maintenance, the number of failures may decline rapidly.

6.2 Future Direction

It must be mentioned that the above remarks and conclusions of the applicability of GenRel are based on statistical results using a specific set of field data. Furthermore, the discussion in the previous sections indicate potential future research directions.

Future Work:

1. Apply GenRel using data for other types of mining machinery to expand the knowledge and understanding.
2. Through the case studies, it was shown there are limitations of GenRel in continuous probability distribution fitting. Since we only have 5 out of 20 theoretical probability distributions (see Palisade Corporation, 2005), adding other continuous distribution functions in the GenRel's continuous distribution pool

could reduce the limited applicability of continuous distribution fitting of the Input Data Set.

3. A further study on the relationship between the time periods of annual maintenance and the level of applicability of GenRel is suggested.

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Appendix A

Source Code of Improvement of GenRel

-------Poisson Inverse Transform Technique

```
Function PoissonInv(p As Double, lamda As Variant)
Dim i, j, k As Integer
If p < 0 Or p > 1 Then
    MsgBox ("P value is negative. Please double check the input.")
    GoTo ExitFunction
End If
If lamda < 0 Then
    MsgBox ("Lamda is negative. Please double check the input!")
    GoTo ExitFunction
End If
k = 1
On Error GoTo ExitFunction
While Application.WorksheetFunction.Poisson(k, lamda, True) < p
    k = k + 1
Wend
PoissInv = k
ExitFunction: End Function
```

------- Poisson Model (fitness)

```
Function fitness_poisson(raterange As Range, ratelambda As Variant, rc As Integer)   ' fitness function for poisson model --> Xiangxi Wu
    Dim fitInfo As RiskFitType
    Dim fitTabName$
    Dim displayString$

    rc = RiskFitGetDefaults(fitInfo)
    If rc <> 0 Then GoTo fail
    Set fitInfo.DataRange = raterange
    fitInfo.Discrete = True

    fitTabName = fitInfo.fitTabName

    'Actually fit the data...
    rc = RiskFitDistributions(fitInfo)
    If rc <> 0 Then GoTo fail
   rc = RiskFitGetFunction(fitTabName, RiskNoStatistic, thefunction, RiskFormatDisplay, displayString)
    If rc <> 0 Then
    b = RiskFitDeleteTab(fitTabName)
    End If
    If rc <> 0 Then GoTo fail

   P1 = InStr(displayString, "(")
   P2 = InStr(displayString, ")")
```

```
  ratelambda = Mid(displayString, P1 + 1, P2 - P1 - 1)

    'Get rid of the fit tab...
    rc = RiskFitDeleteTab(fitTabName): If rc <> 0 Then GoTo fail

    'Fitting brings the @RISK-Model application forward.   Bring myself forward
again...
    AppActivate Application.Caption

fail:
If C <> 0 Then
rc = 1
End If

End Function
```

------- Poisson Model (main code)

```
Private Sub Poisson_model()
Dim i, k, p As Integer
Dim j As Integer
Dim inputrange As Range
Dim raterange As Range
Dim ratelambda As Variant
Dim rankrange As Range
Dim r(6) As Integer
Dim rc As Integer

Worksheets("Iteration Data").Range("a3:r300").ClearContents
Worksheets("simulation").Range("a1:z1000").ClearContents
Set inputrange = Worksheets("Input Menu").Range("g9:g1000")

Lambda = Worksheets("Model Selection").Range("d23")
Count = Application.WorksheetFunction.Count(inputrange)
k = 0
For j = 2 To 12 Step 2
repeat:
k = k + 1
For i = 1 To Count
Worksheets("Simulation").Cells(i, j) = PoissonInv(Worksheets("Random
Numbers").Cells(i, j), Lambda)
Next i
Set raterange =
Worksheets("Simulation").Range(Worksheets("Simulation").Cells(1, j),
```

```
Worksheets("Simulation").Cells(Count, j))
Call fitness_poisson(raterange, ratelambda, rc)
If rc <> 0 Then GoTo repeat
Worksheets("Simulation").Cells(1, j - 1) = "lambda"
Worksheets("Simulation").Cells(2, j - 1) = ratelambda
Worksheets("Simulation").Cells(3, j - 1) = "Cost:"
Worksheets("Simulation").Cells(4, j - 1) = Abs(Lambda - ratelambda)
Next j
Worksheets("simulation").Cells(1, 20) = Worksheets("simulation").Cells(4, 1)
Worksheets("simulation").Cells(2, 20) = Worksheets("simulation").Cells(4, 3)
Worksheets("simulation").Cells(3, 20) = Worksheets("simulation").Cells(4, 5)
Worksheets("simulation").Cells(4, 20) = Worksheets("simulation").Cells(4, 7)
Worksheets("simulation").Cells(5, 20) = Worksheets("simulation").Cells(4, 9)
Worksheets("simulation").Cells(6, 20) = Worksheets("simulation").Cells(4, 11)
Set rankrange = Worksheets("simulation").Range("t1:t6")
r(1) = Application.WorksheetFunction.Rank(Worksheets("simulation").Cells(4, 1),
rankrange, 1)
r(2) = Application.WorksheetFunction.Rank(Worksheets("simulation").Cells(4, 3),
rankrange, 1)
r(3) = Application.WorksheetFunction.Rank(Worksheets("simulation").Cells(4, 5),
rankrange, 1)
r(4) = Application.WorksheetFunction.Rank(Worksheets("simulation").Cells(4, 7),
rankrange, 1)
r(5) = Application.WorksheetFunction.Rank(Worksheets("simulation").Cells(4, 9),
rankrange, 1)
r(6) = Application.WorksheetFunction.Rank(Worksheets("simulation").Cells(4, 11),
rankrange, 1)
```

```
rankrange.ClearContents
Worksheets("simulation").Range("m1:z1000").ClearContents
Worksheets("simulation").Range(Worksheets("simulation").Cells(1, 11 + r(1) * 2),
Worksheets("simulation").Cells(1000, 12 + r(1) * 2)).Value =
Worksheets("simulation").Range("a1:b1000").Value
Worksheets("simulation").Range(Worksheets("simulation").Cells(1, 11 + r(2) * 2),
Worksheets("simulation").Cells(1000, 12 + r(2) * 2)).Value =
Worksheets("simulation").Range("c1:d1000").Value
Worksheets("simulation").Range(Worksheets("simulation").Cells(1, 11 + r(3) * 2),
Worksheets("simulation").Cells(1000, 12 + r(3) * 2)).Value =
Worksheets("simulation").Range("e1:f1000").Value
Worksheets("simulation").Range(Worksheets("simulation").Cells(1, 11 + r(4) * 2),
Worksheets("simulation").Cells(1000, 12 + r(4) * 2)).Value =
Worksheets("simulation").Range("g1:h1000").Value
Worksheets("simulation").Range(Worksheets("simulation").Cells(1, 11 + r(5) * 2),
Worksheets("simulation").Cells(1000, 12 + r(5) * 2)).Value =
Worksheets("simulation").Range("i1:j1000").Value
Worksheets("simulation").Range(Worksheets("simulation").Cells(1, 11 + r(6) * 2),
Worksheets("simulation").Cells(1000, 12 + r(6) * 2)).Value =
Worksheets("simulation").Range("k1:l1000").Value
Worksheets("simulation").Range("a1:l1000").Delete
MaxIterations = Worksheets("model selection").Range("d20")
Convergence = Worksheets("model selection").Range("d21")
para_sum = Abs(Lambda)
para_dev_upper = para_sum * Convergence
para_dev_lower = 0
p = 1
```

```
Call Copy_Initial
Do While p <= MaxIterations
Call crossandmutation((p))
Call rankwhole
gpara_dev = Abs(Worksheets("simulation").Range("a2") - Lambda)
Worksheets("Iteration Data").Cells(p + 2, 1).Value = p
Worksheets("Iteration Data").Cells(p + 2, 2).Value = para_sum
Worksheets("Iteration Data").Cells(p + 2, 3).Value = para_dev_upper
Worksheets("Iteration Data").Cells(p + 2, 4).Value = para_dev_lower
Worksheets("Iteration Data").Cells(p + 2, 5).Value = gpara_dev
Worksheets("Iteration Data").Cells(p + 2, 6).Value = "no"
If gpara_dev < para_dev_upper And gpara_dev > para_dev_lower Then
    Worksheets("Iteration Data").Cells(2, 7).Value = "Convergence Criteria
Satisfied"
    Worksheets("Iteration Data").Cells(p + 2, 6).Value = "yes"
    Exit Do
End If
p = p + 1
Loop
If gpara_dev > para_dev_upper Or gpara_dev < para_dev_lower Then
Worksheets("Iteration Data").Cells(2, 7).Value = "Convergence Criteria Not Met.
Try Again."
Call Copy_Final_Population
Call Sort_Final_Data
Worksheets("Data Statistics").Cells(2, 10).Value = "Poisson"
Worksheets("Iteration Data").Cells(1, 8).Value = "Poisson"
Worksheets("Iteration Data Graph").Cells(2, 16).Value = "Poisson"
```

```
With Worksheets("Iteration Data Graph").ChartObjects(1).Chart
        .HasTitle = True
        .ChartTitle.Text = "Comparison of the Parameter Deviation versus the
Number of GA Iterations - Poisson Model"
End With
Worksheets("Final Iteration Results").Cells(2, 15).Value = "Poisson"
Worksheets("Final Convergence Graph").Cells(2, 16).Value = "Poisson"
With Worksheets("Final Convergence Graph").ChartObjects(1).Chart
        .HasTitle = True
        .ChartTitle.Text = "Final Convergence Graph - Poisson Model"
End With
If Worksheets("Input Menu").Cells(1, 17).Value = True Then YAxis = "TBF"
If Worksheets("Input Menu").Cells(1, 17).Value = False Then YAxis = "TTR"
Worksheets("Final Convergence Graph").ChartObjects(1).Activate
        With ActiveChart.Axes(xlValue)
        .HasTitle = True
                With .AxisTitle
                        .Caption = YAxis
                End With
        End With
Application.ScreenUpdating = True
Worksheets("Model Selection").Activate
MsgBox "Work complete!"
End Sub
```

Appendix B

Combination the Definition of Maintainability and Probability Distribution Function

B.1 Definition of maintainability and applying the Poisson cumulative distribution function

For cumulative function, the maintainability function is defined

$$M(T) = F_r(t \le T)$$

where

$M(T)$ is the maintainability function,

T and t are time,

$F_r(T)$ is the repair time cumulative distribution function

applying the Poisson cumulative function

$$M(T) = \sum_{k=0}^{T} \frac{e^{-\lambda} \lambda^k}{k!}$$

Where,

The random variable X denotes the number of successes in the whole interval.

λ is the mean number of successes in the interval

k is an discrete integer and no less than one(Palisade, 2002)

Formula of combination

$$M(T) = \sum_{k=0}^{T} \frac{e^{-\lambda} \lambda^k}{k!}$$

B.2 Definition of maintainability and Beta cumulative distribution function

For cumulative function, the maintainability function is defined

$$M(T) = F_r(t \le T)$$

where

$M(T)$	is the maintainability function,
T and t	are time,
$F_r(T)$	is the repair time cumulative distribution function,

Beta cumulative function

$$F(t) = \int_0^x \frac{(t-\min)^{\alpha 1-1}(\max - t)^{\alpha 2-1}}{B(\alpha 1, \alpha 2)(\max - \min)^{\alpha 1+\alpha 2-1}} dt$$

where,

F	is the cumulative distribution function,
t	is time,
min	is the minimum value,
max	is the maximum value,
$\alpha 1$	is a shape parameter,
$\alpha 2$	is a shape parameter,
B	is the Beta function,

Formula of combination

$$M(T) = \int_0^x \frac{(t-\min)^{\alpha 1-1}(\max - t)^{\alpha 2-1}}{B(\alpha 1, \alpha 2)(\max - \min)^{\alpha 1+\alpha 2-1}} dT$$

B.3 Definition of maintainability and Lognormal cumulative distribution function

For cumulative function, the maintainability function is defined

$$M(T) = F_r(t \le T)$$

where

$M(T)$	is the maintainability function,
T and t	are time,
$F_r(T)$	is the repair time cumulative distribution function,

Lognormal cumulative function

$$F(t) = \int_0^t \frac{1}{\sigma'(x-\theta)\sqrt{2\pi}} e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2} dx$$

with

$$\sigma' \equiv \sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu' \equiv \ln \frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

where

θ	is a shift,
σ	is the mean of associated Normal distribution,
μ	is the standard deviation of associated Normal distribution,

Formula of combination

$$M(T) = \int_0^T \frac{1}{\sigma'(x-\theta)\sqrt{2\pi}} e^{-(\frac{1}{2\sigma'^2})(\ln(x-\theta)-\mu')^2} dx$$

with

$$\sigma' \equiv \sqrt{\ln(1+(\frac{\sigma}{\mu})^2}. \qquad and \qquad \mu' \equiv \ln \frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}$$

B.4 Definition of maintainability and Exponential cumulative distribution function

For cumulative function, the maintainability function is defined

$$M(T) = F_r(t \leq T)$$

where

$M(T)$	is the maintainability function,
T and t	are time,
$F_r(T)$	is the repair time cumulative distribution function,

Exponential cumulative function

$$F(t) = 1 - e^{-\frac{t-shift}{\beta}}$$

where

t	is time
shift	is the location parameter,
β	is the scale parameter

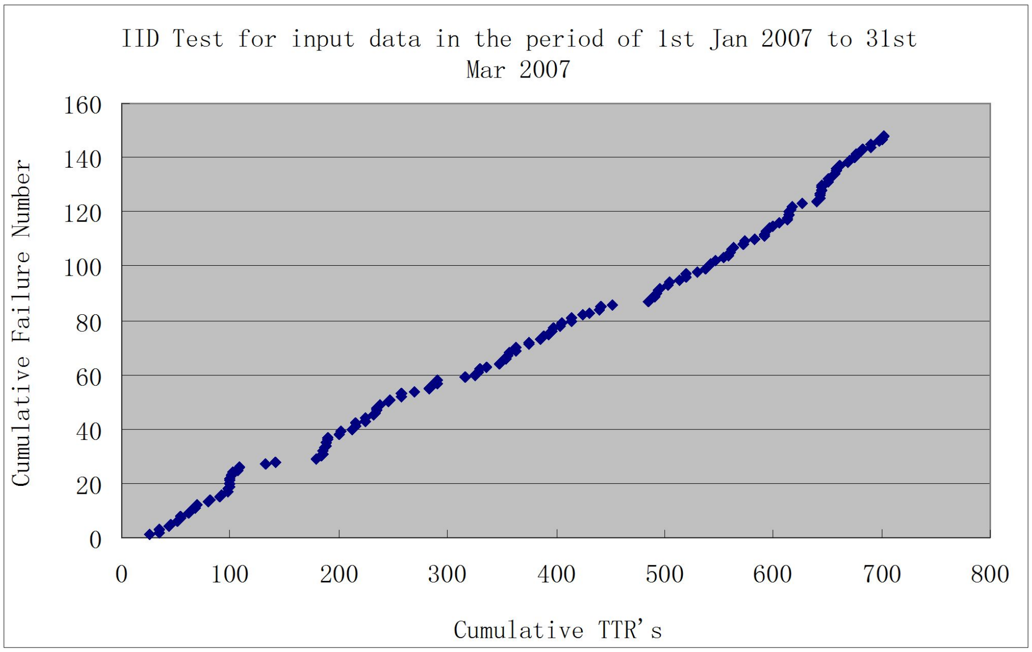
Formula of combination

$$M(T) = 1 - e^{-\frac{T-shift}{\beta}}$$

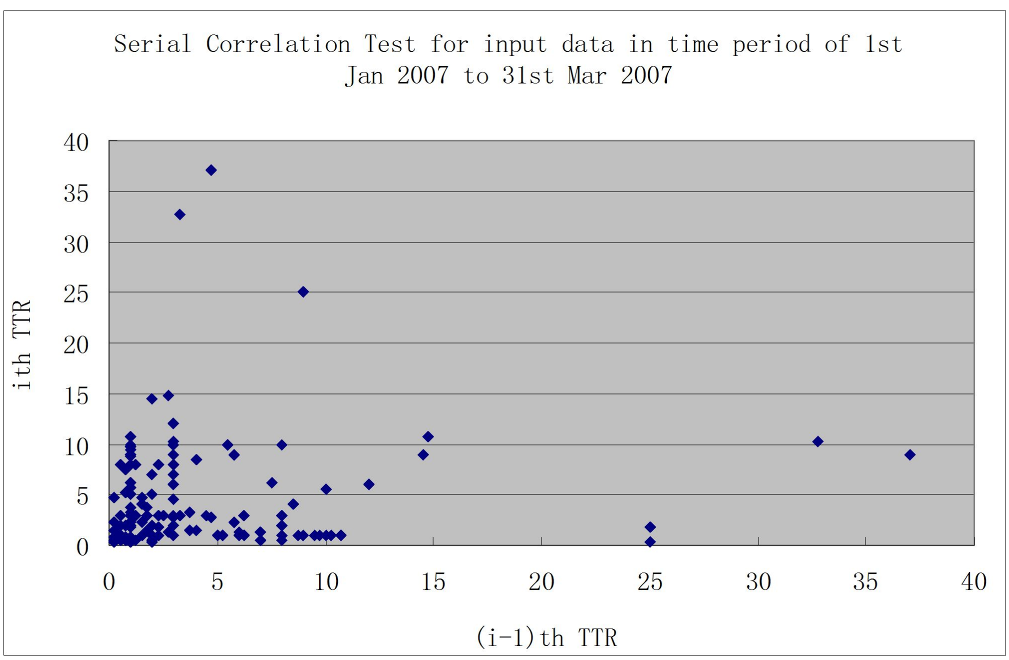
Appendix C

Trend test and serial correlation test

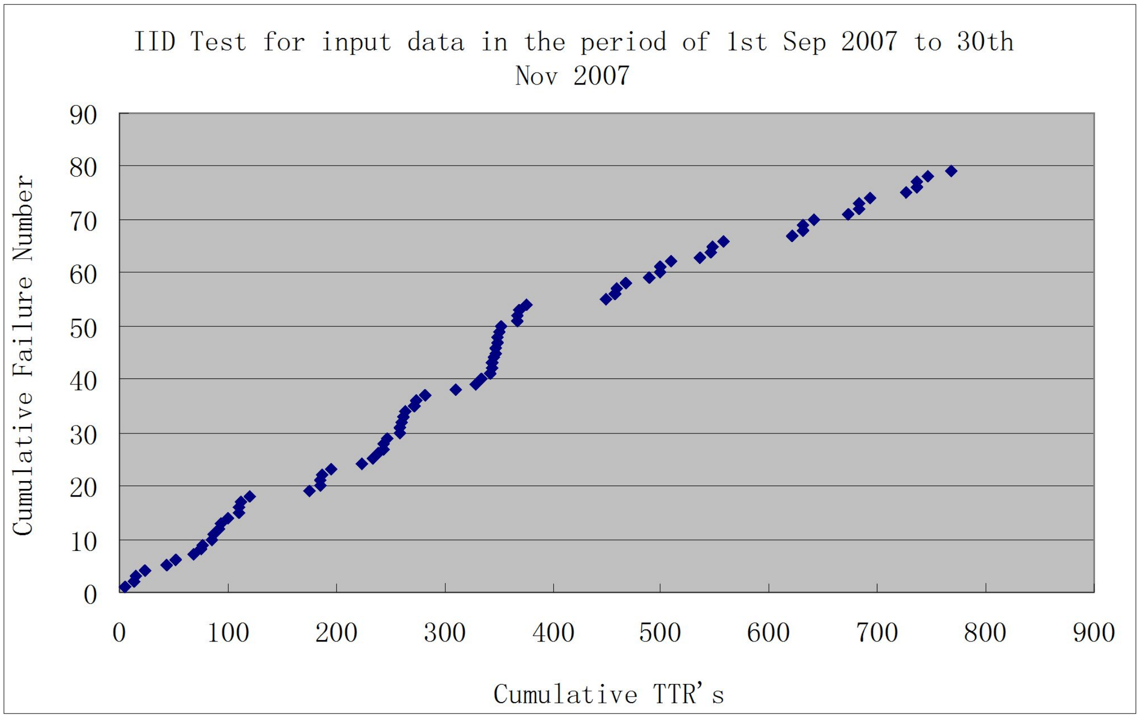
1. Mine A



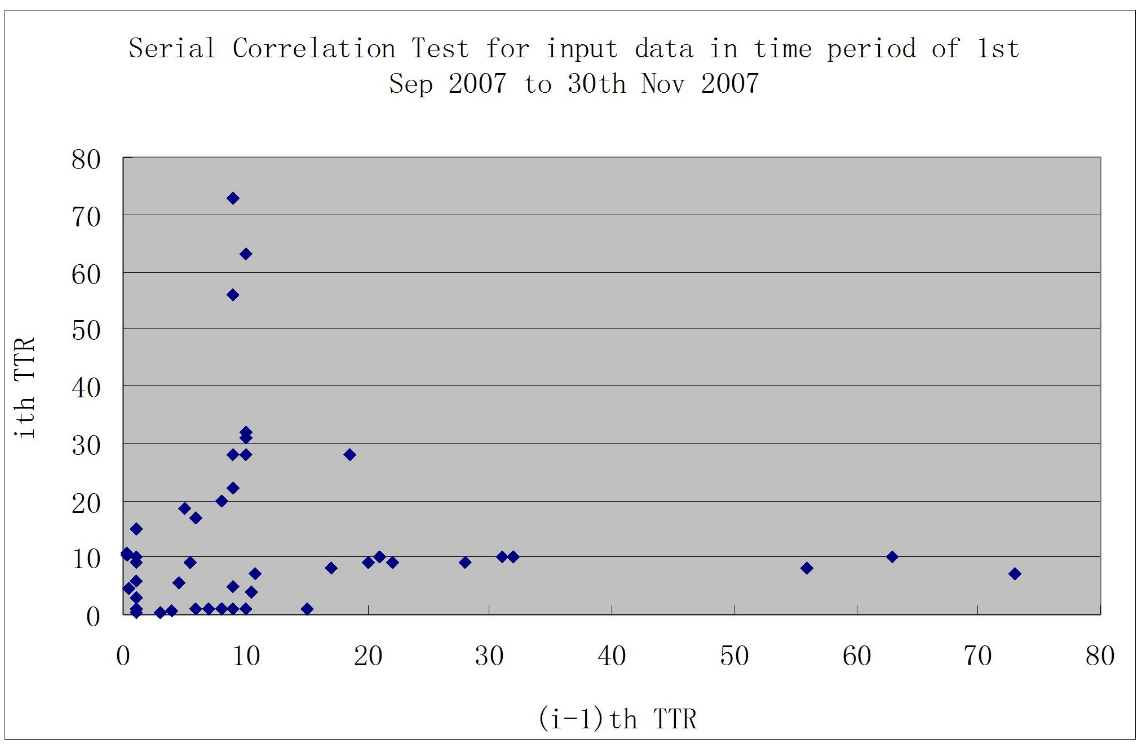
Trend test of TTR data for the period from January 1st to March 31st, 2007, Mine A



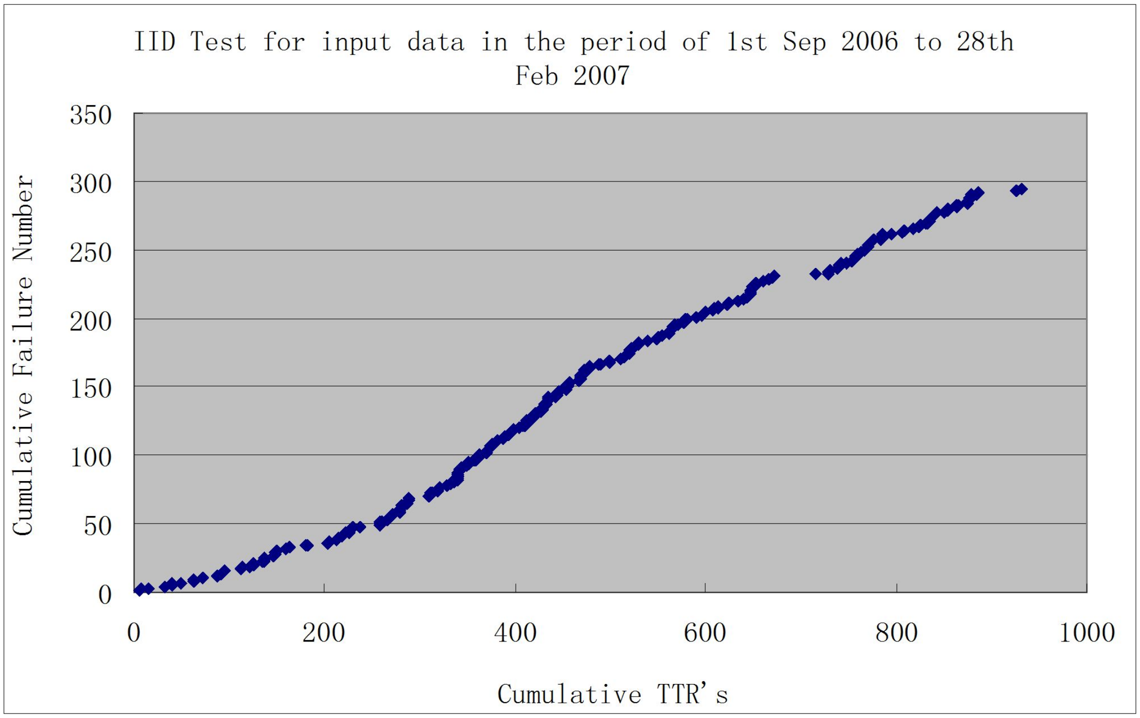
Serial correlation test of TTR data from January1st to March 31st, 2007, Mine A



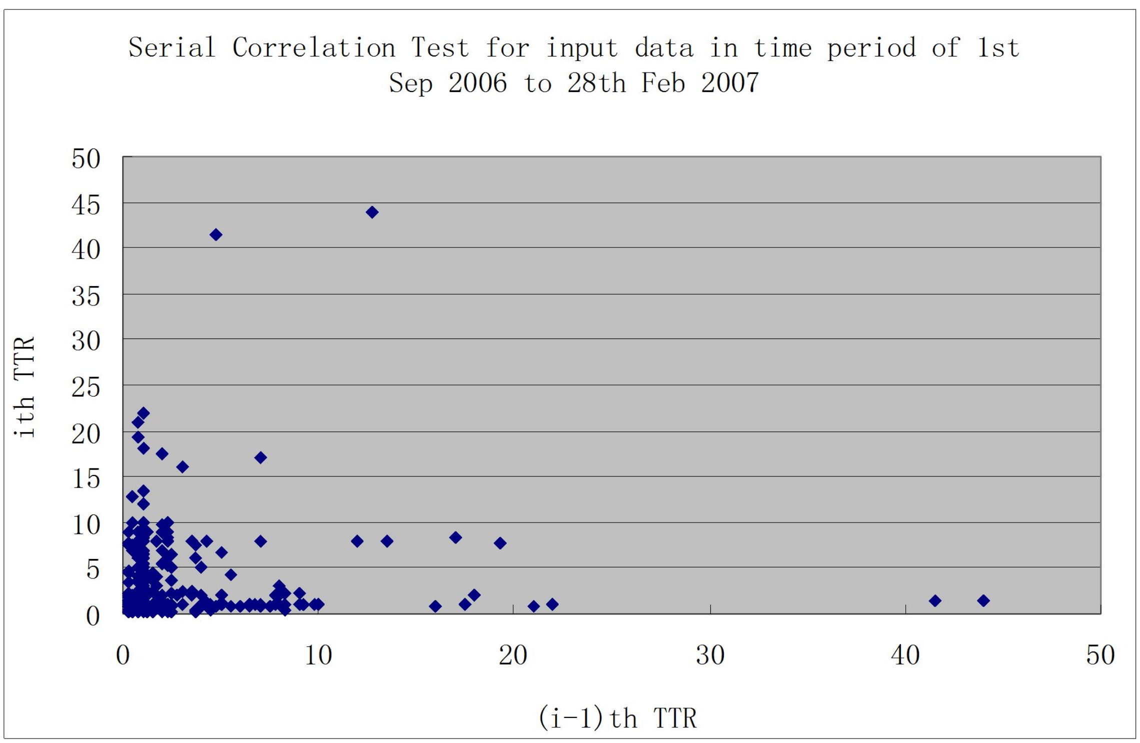
Trend test of TTR data for the period from September 1st to November 30th, 2007, Mine A



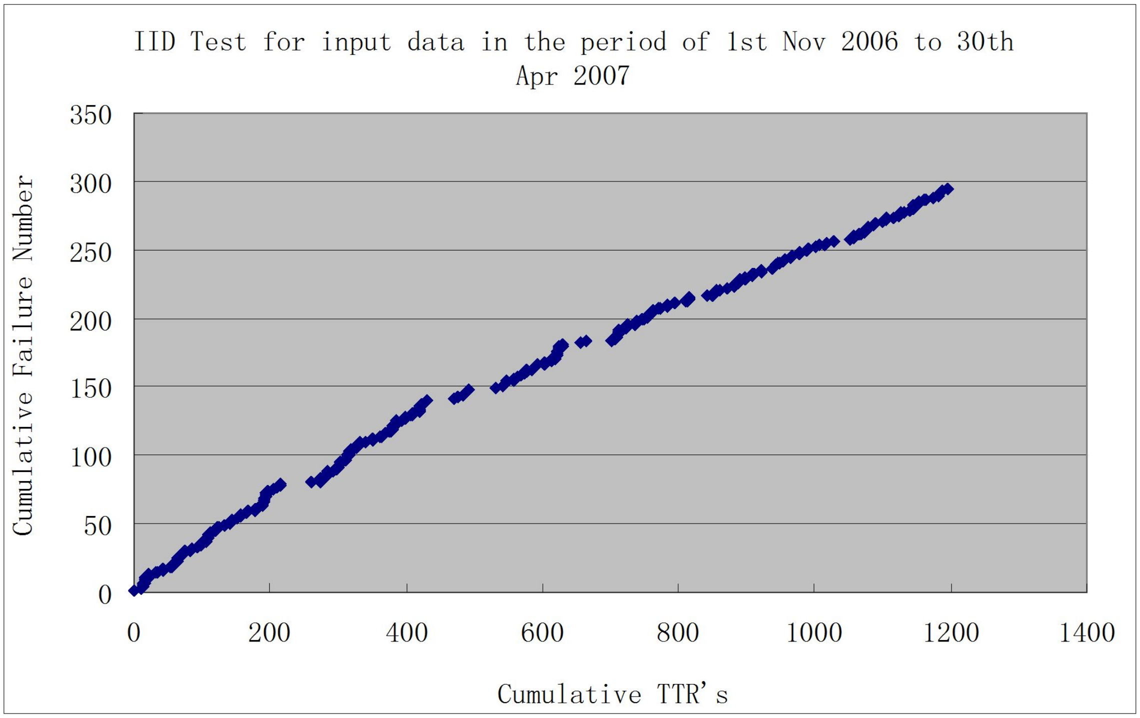
Serial correlation test of TTR data for the period from September 1st to November 30th, 2007, Mine A



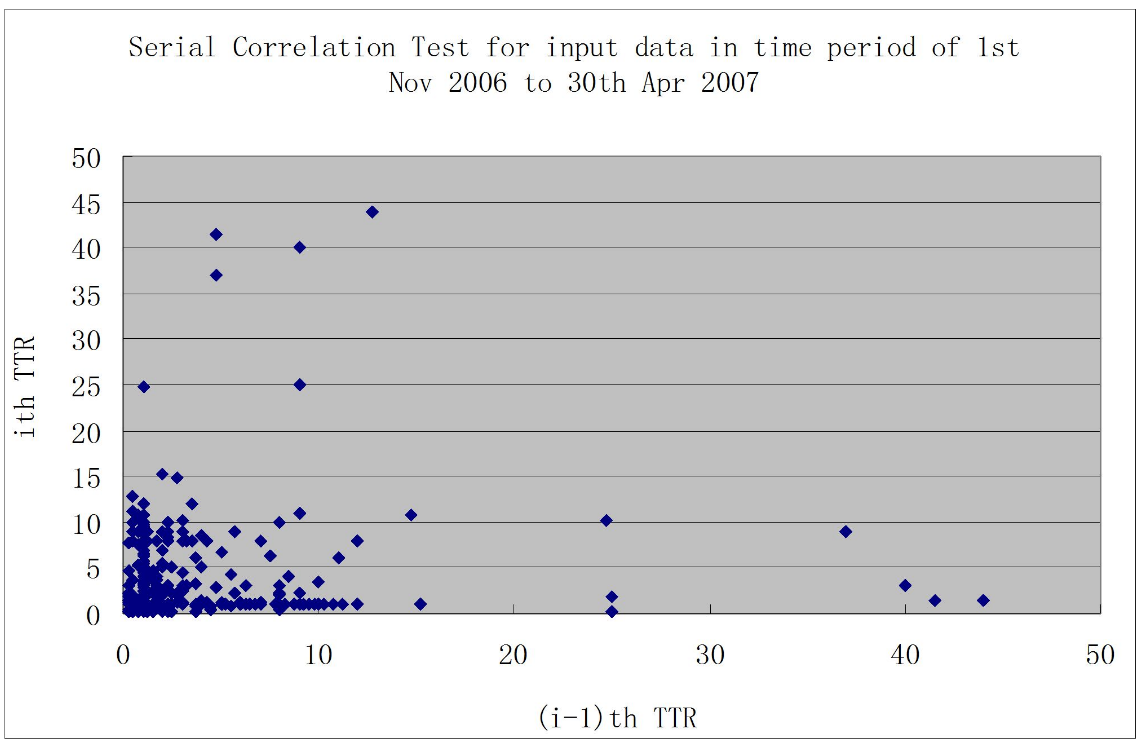
Trend test of TTR data for the period from September 1st, 2006 to February 28th, 2007, Mine A



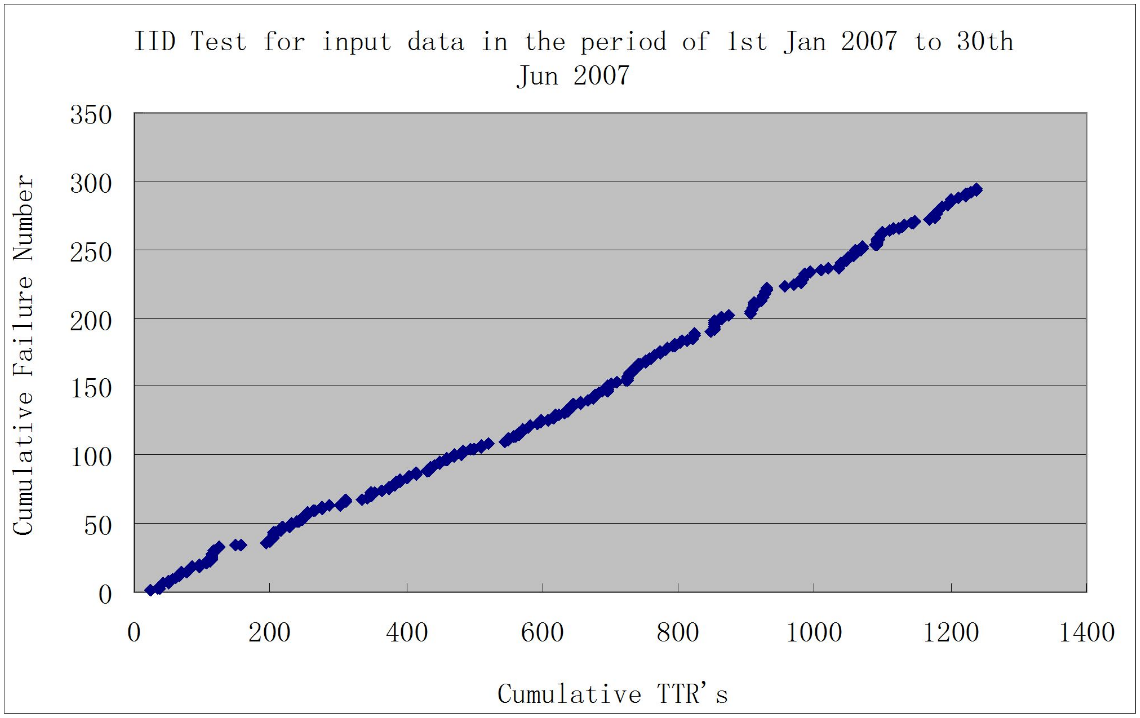
Serial correlation test of TTR data for the period from September 1st, 2006 to February 28th, 2007, Mine A



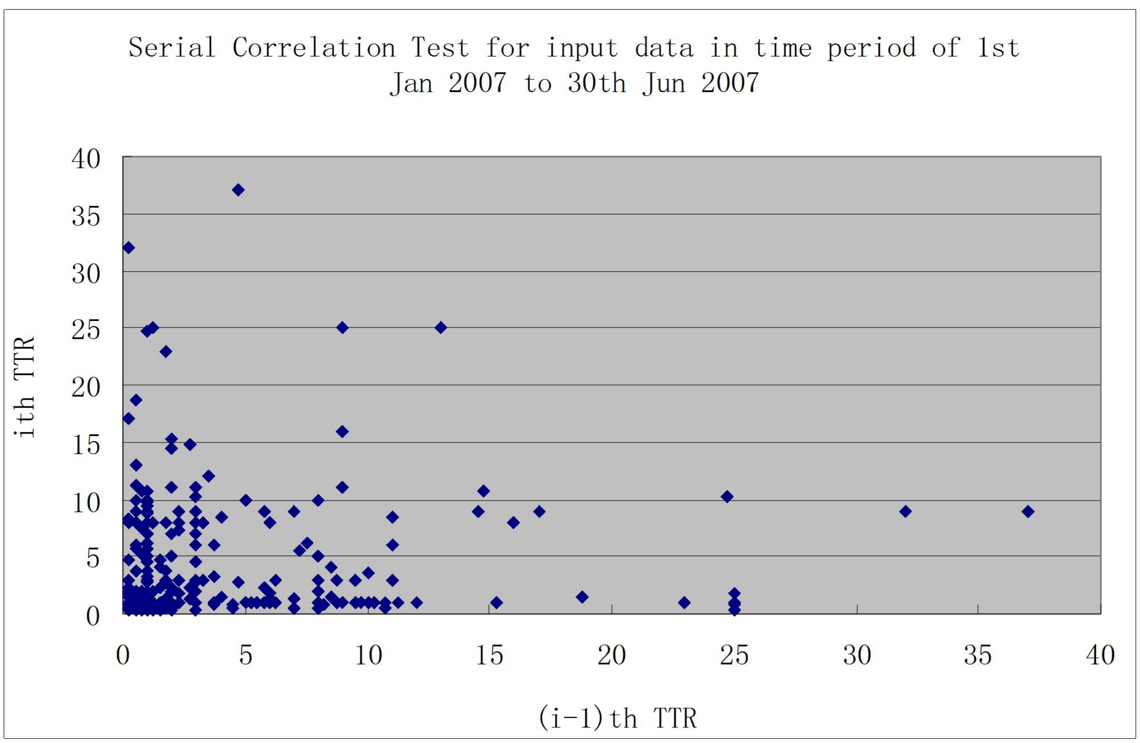
Trend test of TTR data for the period from November 1st, 2006 to April 30th, 2007, Mine A



Serial correlation test of TTR data for the period from November 1st, 2006 to April 30th, 2007

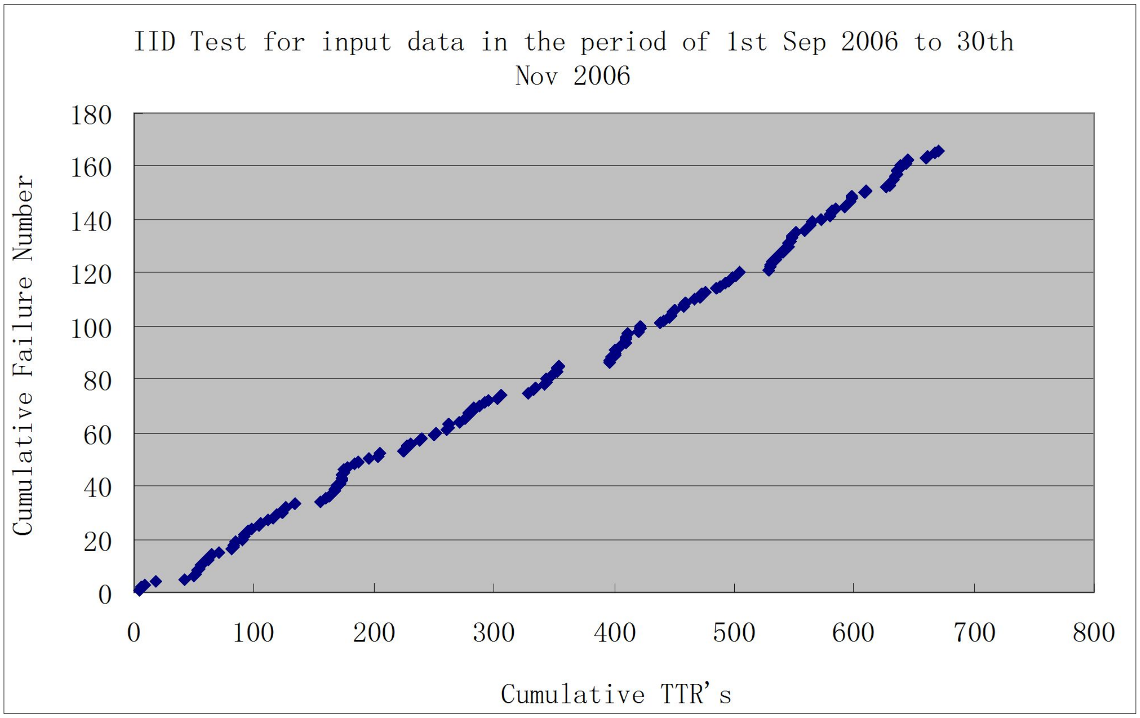


Trend test of TTR data for the period from January 1st, to June 30th, 2007, Mine A

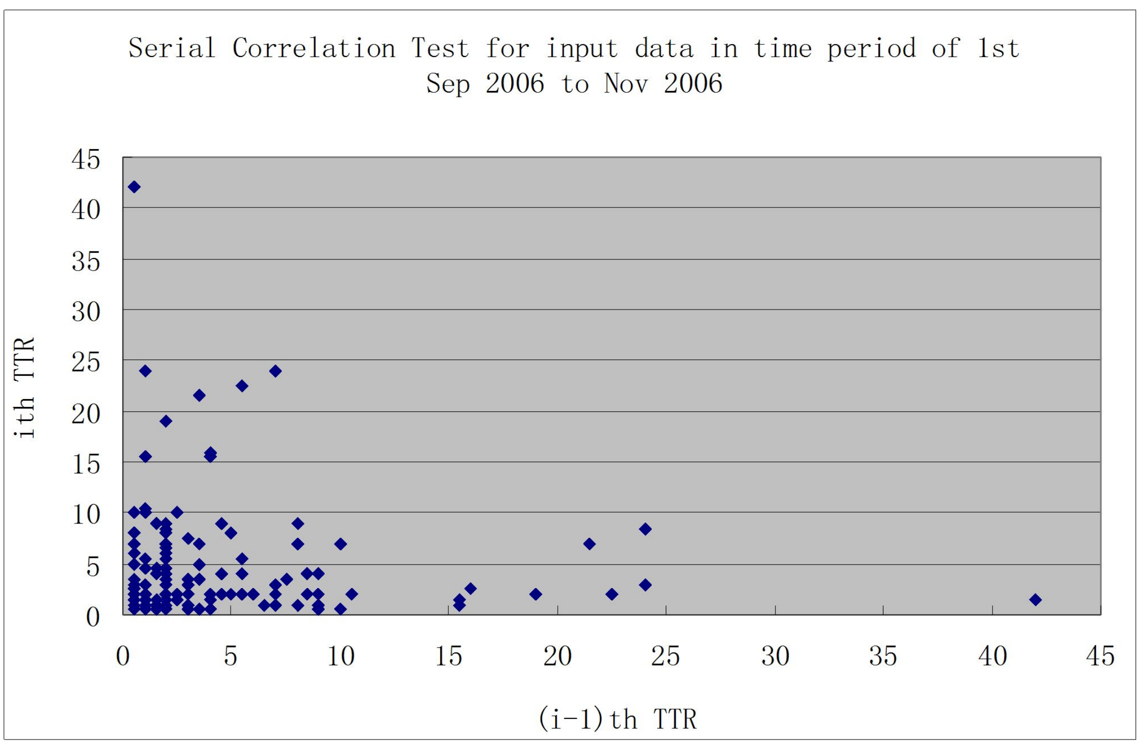


Serial correlation test of TTR data for the period from January 1st to June 30th, 2007

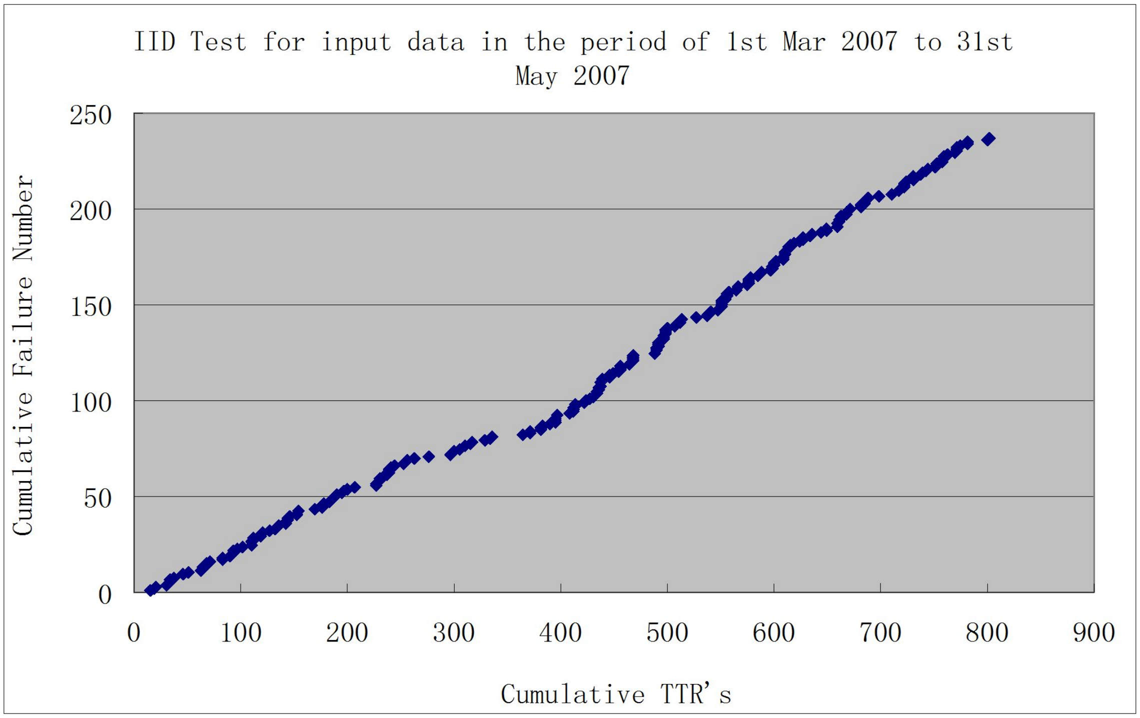
2. Mine B:



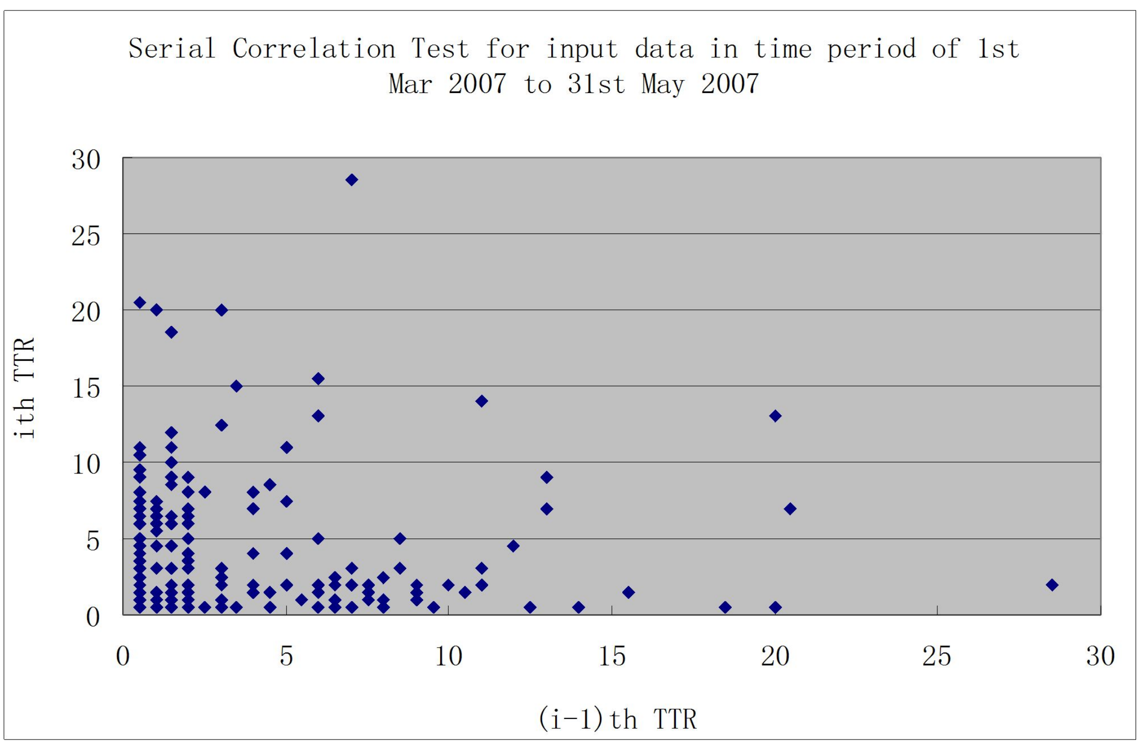
Trend test of TTR data for the period from September 1st 2006 to November 30th, 2006, Mine B



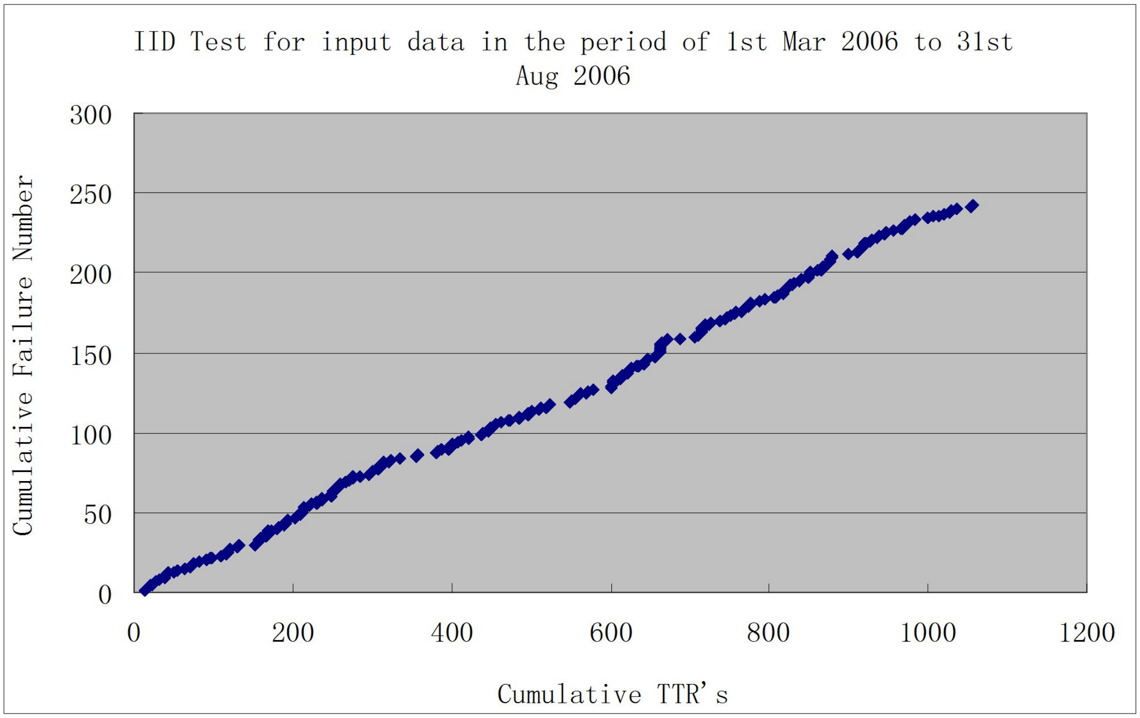
Serial correlation test of TTR data from September 1st, 2006 to November 30th, 2006, Mine B



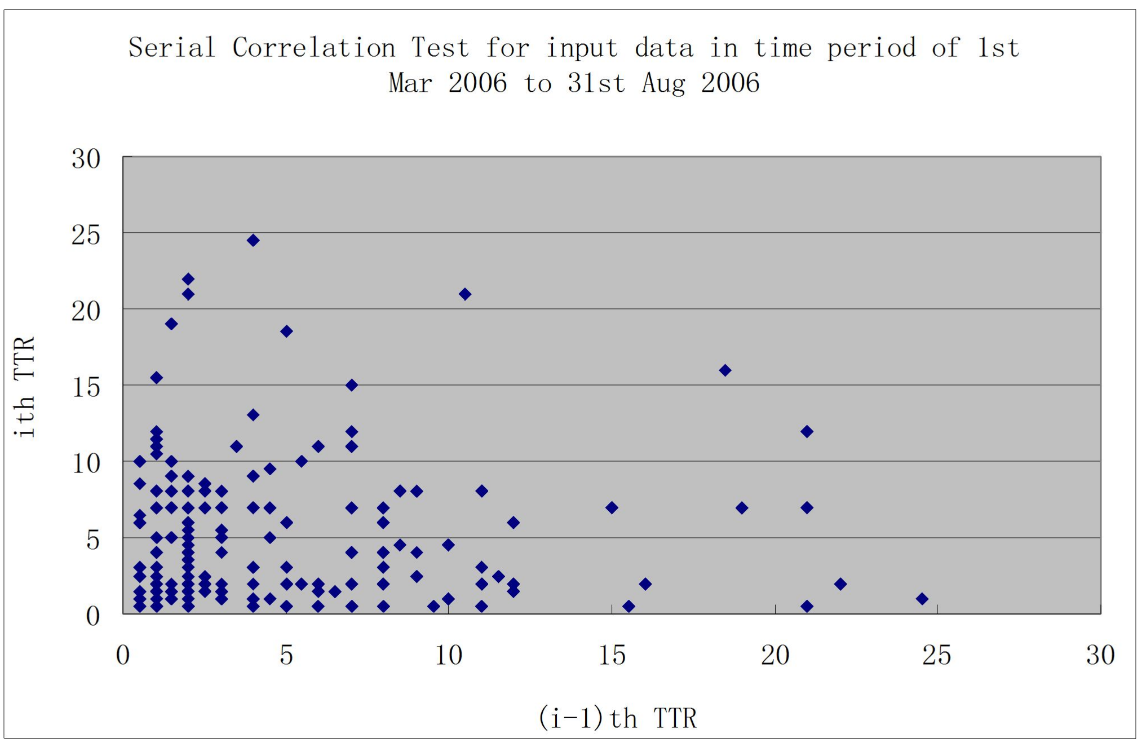
Trend test of TTR data for the period from March 1st, 2007 to May 31st, 2007, Mine B



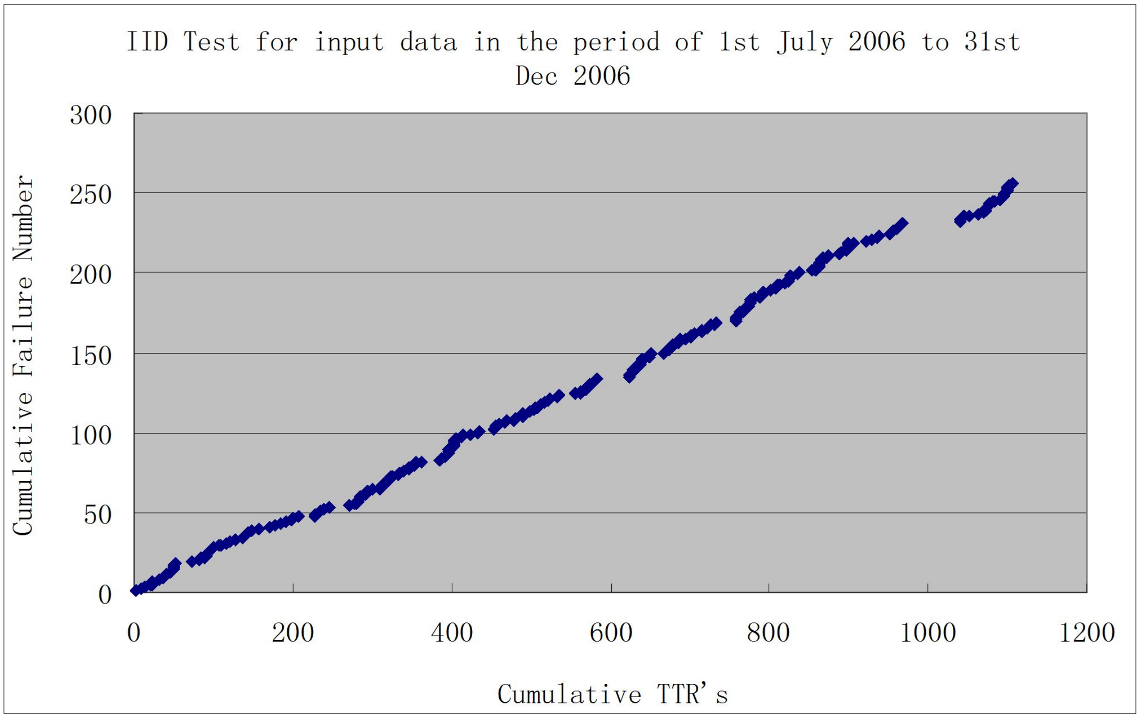
Serial correlation test of TTR data for the period from March 1st 2007 to May 31st, 2007, Mine B



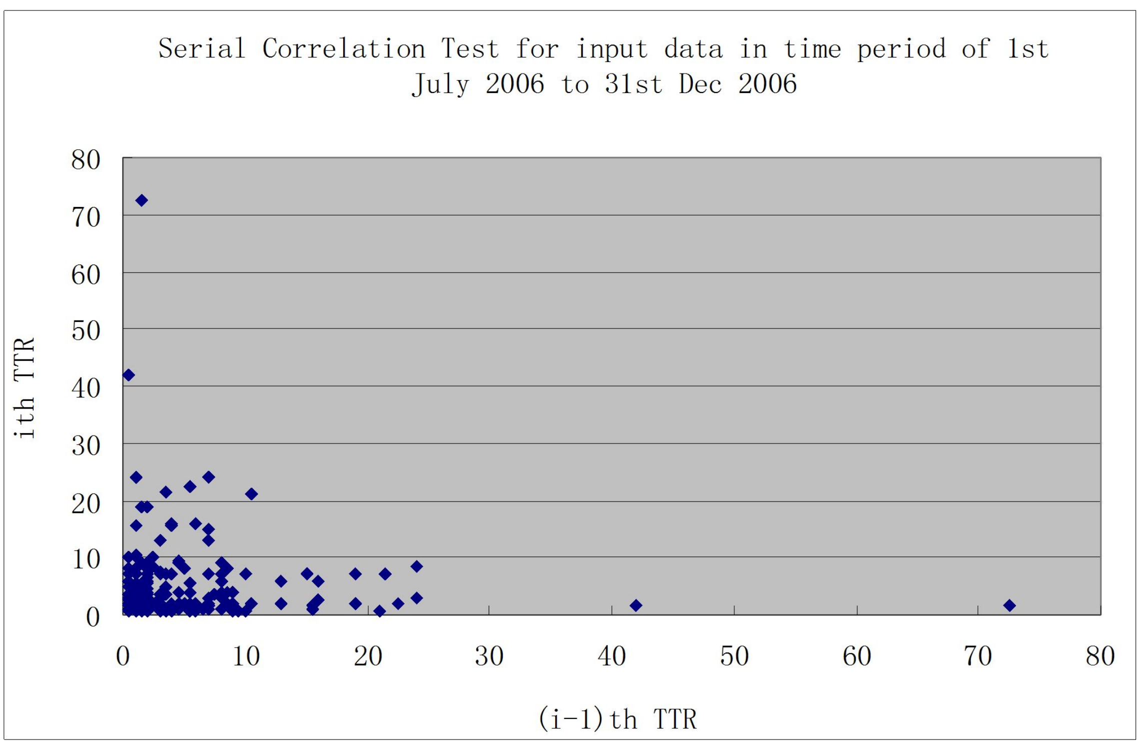
Trend test of TTR data for the period from March 1st to August 31st, 2006, Mine B



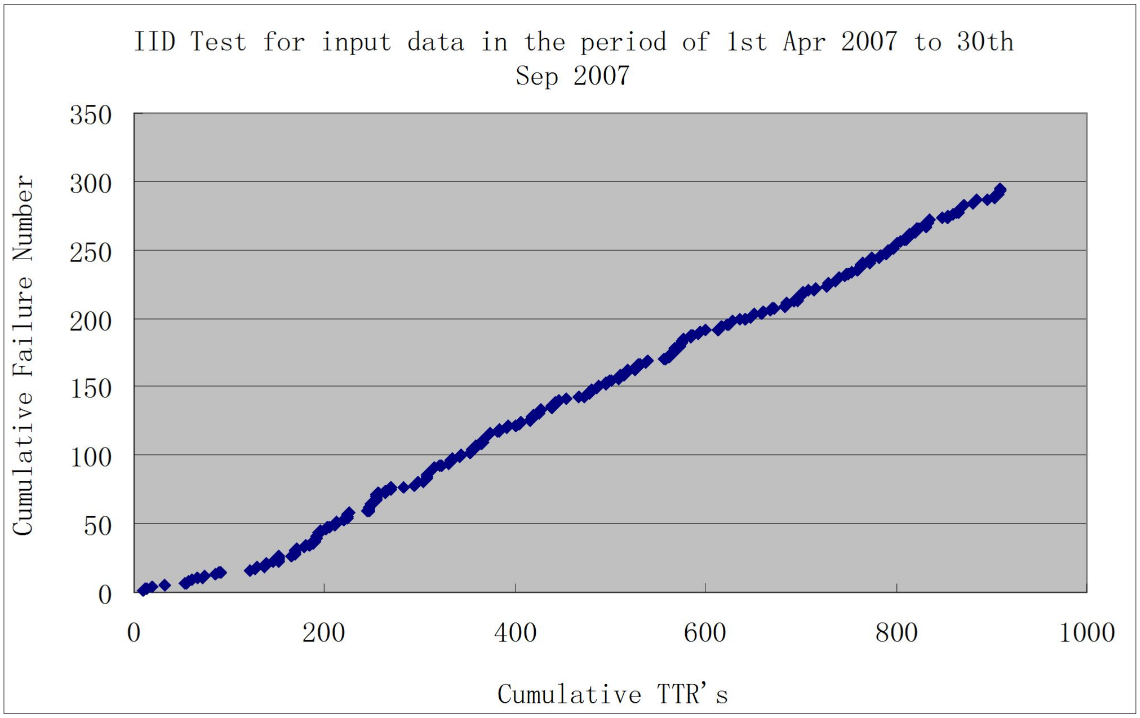
Serial correlation test of TTR data for the period from March 1st to August 31st, 2006, Mine B



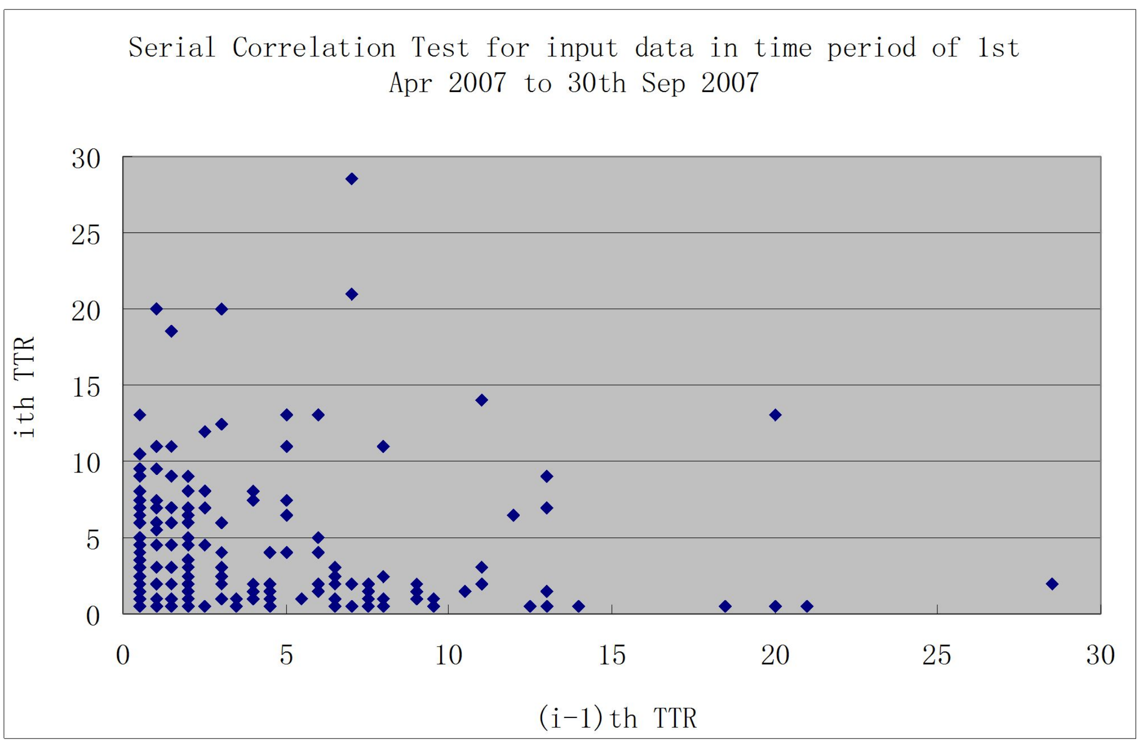
Trend test of TTR data for the period from July 1st, 2006 to December 31st, 2006, Mine B



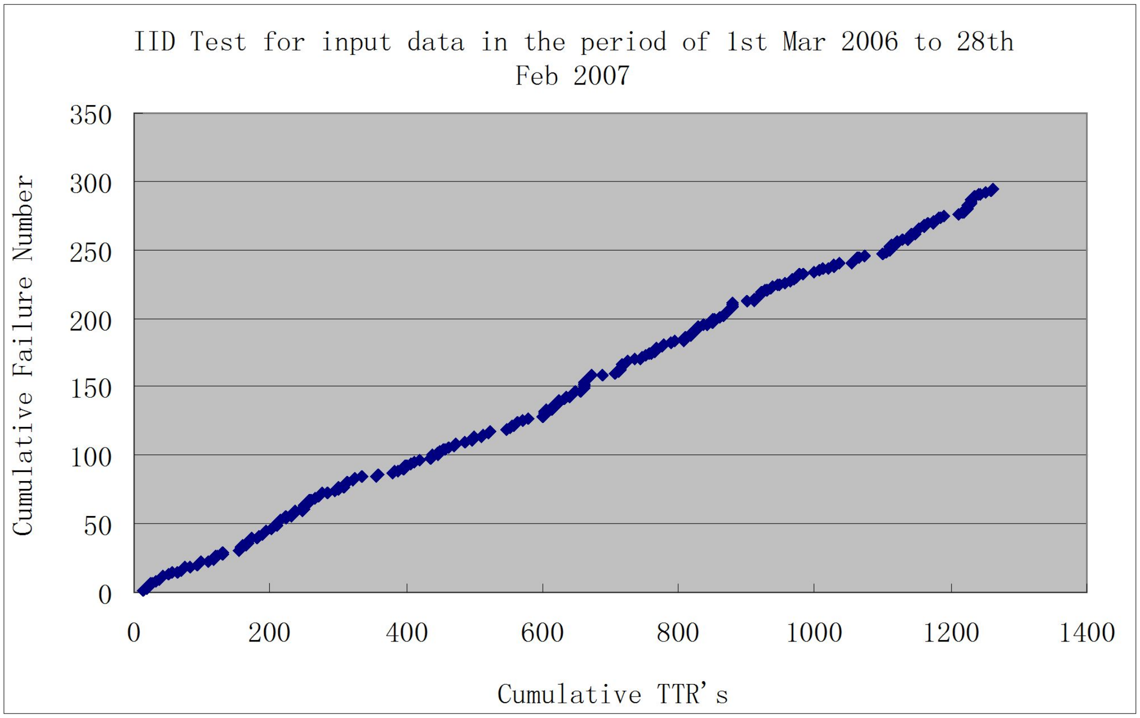
Serial correlation test of TTR data for the period from July 1st, 2006 to December 31st, 2006, Mine B



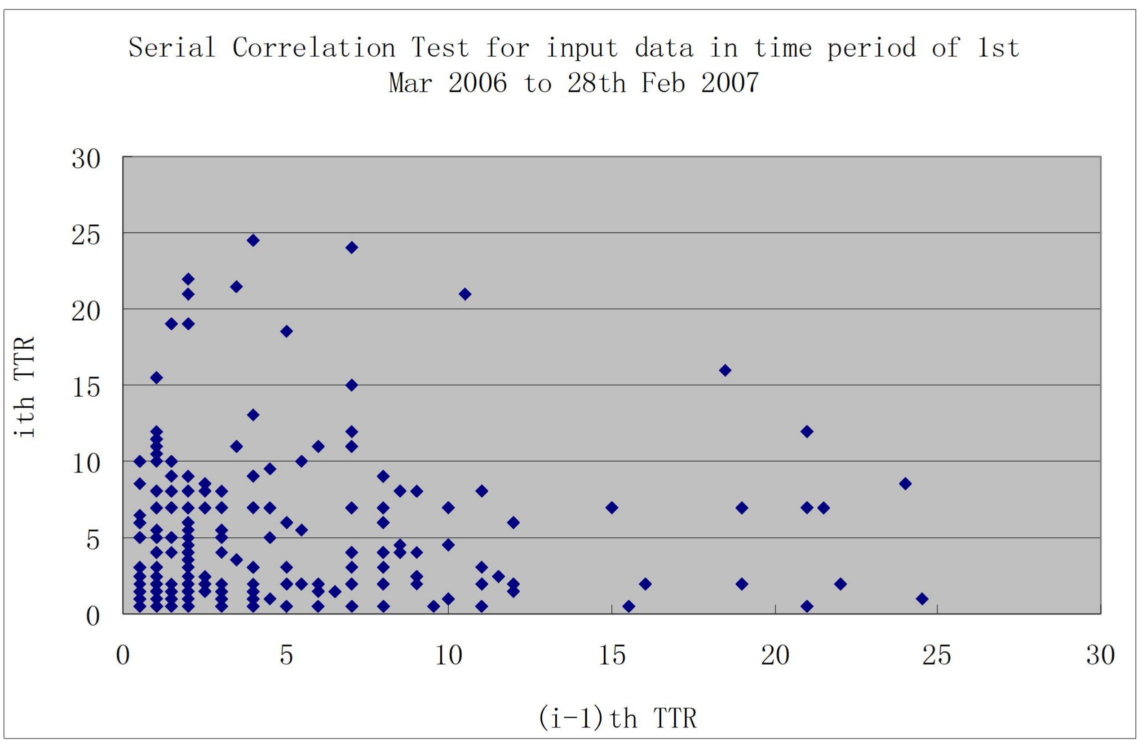
Trend test of TTR data for the period from April 1st 2007 to September 30th, 2007, Mine B



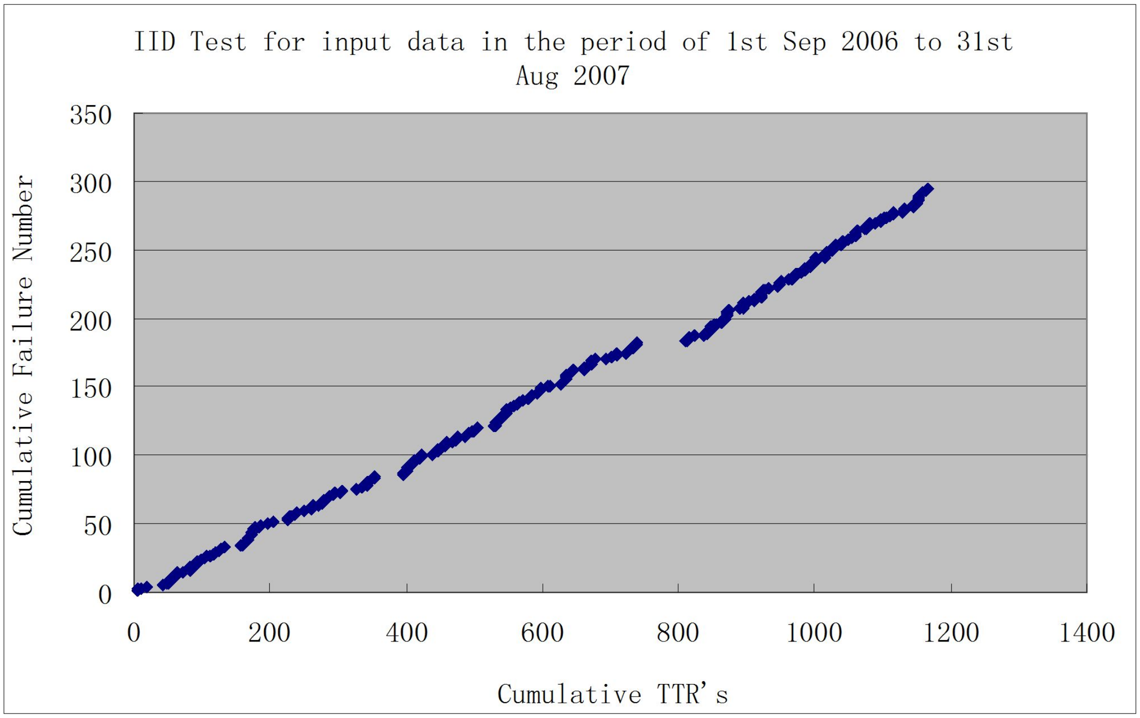
Serial correlation test of TTR data for the period from April 1st, 2007 to September 30th, 2007, Mine B



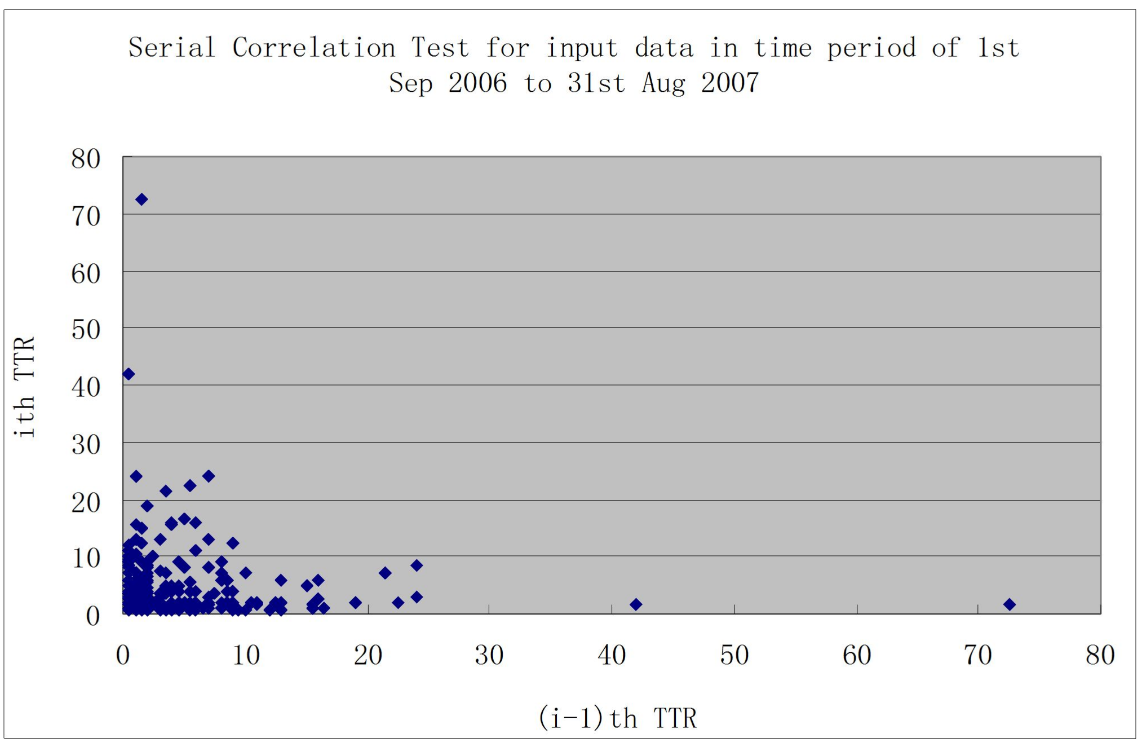
Trend test of TTR data for the period from March 1st 2006 to February 28th, 2007, Mine B



Serial correlation test of TTR data for the period from March 1st, 2006 to February 28th, 2007, Mine B



Trend test of TTR data for the period from September 1st 2006 to August 31st, 2007, Mine B



Serial correlation test of TTR data from September 1st 2006 to August 31st, 2007, Mine B

Appendix D

Table D.1 shows critical values of the t-Distribution at levels of significance of ɑ= 0:05, ɑ= 0:025, ɑ= 0:01, ɑ= 0:005 and ɑ= 0:0005.

ν	Level of significance α				
	0.10	0.05	0.025	0.01	0.005
1	3.078	6.314	12.706	31.821	63.657
2	1.886	2.920	4.303	6.965	9.925
3	1.638	2.353	3.182	4.541	5.841
4	1.533	2.132	2.776	3.747	4.604
5	1.476	2.015	2.571	3.365	4.032
6	1.440	1.943	2.447	3.143	3.707
7	1.415	1.895	2.365	2.998	3.499
8	1.397	1.860	2.306	2.896	3.355
9	1.383	1.833	2.262	2.821	3.250
10	1.372	1.812	2.228	2.764	3.169
11	1.363	1.796	2.201	2.718	3.106
12	1.356	1.782	2.179	2.681	3.055
13	1.350	1.771	2.160	2.650	3.012
14	1.345	1.761	2.145	2.624	2.977
15	1.341	1.753	2.131	2.602	2.947
16	1.337	1.746	2.120	2.583	2.921
17	1.333	1.740	2.110	2.567	2.898
18	1.330	1.734	2.101	2.552	2.878
19	1.328	1.729	2.093	2.539	2.861
20	1.325	1.725	2.086	2.528	2.845
21	1.323	1.721	2.080	2.518	2.831
22	1.321	1.717	2.074	2.508	2.819
23	1.319	1.714	2.069	2.500	2.807
24	1.318	1.711	2.064	2.492	2.797
25	1.316	1.708	2.060	2.485	2.787
26	1.315	1.706	2.056	2.479	2.779
27	1.314	1.703	2.052	2.473	2.771
28	1.313	1.701	2.048	2.467	2.763
29	1.311	1.699	2.045	2.462	2.756
30	1.310	1.697	2.042	2.457	2.750
∞	1.282	1.645	1.960	2.326	2.576

Table D.1 Critical values of the t-distribution