SYSTEM DYNAMICS MODELING OF HUMAN ERRORS AT MINING OPERATIONS

by

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Abstract

There have been many studies about the causes of incidents in different industries, and the mining industry is no exception. From all of these studies, companies and researchers have concluded that the principal reason for incidents in a mining operation is due to human errors.

The aim of this research is to use system dynamics to devise a model of human errors leading to incidents. The model includes the modification of the rate of worker errors through *feedback* (experience and training) and the modification of the *learning or experience curve* when training programs are implemented. The combination of latent and worker errors leading to incidents is also modeled.

Since the errors, combinations of errors and changes due to training each occur at different frequencies, the model predicts some interesting interactions.

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To Papá y Mamá

1 INTRODUCTION

In the mining industry, *production* has always been the focus of investigations and research leading to significant developments in mining methods and equipment over the years. In the last 30 years, the protection of the environment has become one of the priorities for many mining companies. Nowadays, before deciding to start a mining operation, a mining company must present an entire plan that specifies how their operations will not damage the environment.

More recently, mining safety has become another important concern for most of the mining operations around the world. It is known that accidents and incidents are part of any mining production; for that reason, the commitment to safety and responsibility for safety from managers and workers are very important in the reduction of the consequences of any accident. Owing to the commitment to safety of people who work in mining operations, the mining industry is much safer than it was thirty to forty years ago.

According to the Department of Mineral Resources in Australia (2000), it is known that most mining incidents are caused by human errors on the part of workers, engineers involved in mine design, and mine managers. It is of interest whether these error occurrences, their interactions, and the effects of training can be modeled in a quantitative manner. Such a model would illustrate the dynamics of error occurrences and would be useful for understanding the effects of training, experience levels, safety management or safety policy changes.

A dynamic model of human error leading to incidents has been developed. This dynamic model includes the modification of incidents rate through *feedback* (experience and training) and the modification of the learning or experience curve when training is implemented. Moreover, since human errors occur randomly and interact with other errors caused by design or management, the dynamic model developed in this study exhibits some interesting features.

1.1 Statement of the Problem

Most managers of mining companies and researchers agree that mining safety has become one of the most important, if not the most important, aspects of any mining operation. It is the responsibility of every manager and worker in a mining company to keep the mining operation as safe as possible.

Many researchers have developed different tools to understand the causes of an incident. Most of these researchers have concluded that the main cause of any incident or accident is human error; however none of these researchers quantified the probability of occurrence of an error and hence the probability of an incident.

The central issue in this work is to present a quantitative dynamic model of mine safety which evaluates variables such as number of human error occurrences, experience, and training. Moreover, it is not only workers who commit errors; there are some design or organizational errors which contribute to some of the accidents in any mining operation. These errors are called *latent* errors since they often go undetected until there is an interaction between these errors and an error committed by a worker. For that reason, this research also intends to study the combination of worker and latent errors.

Finally, the system dynamics model will show how *feedback* through training and worker experience can change the incident rate in a mining operation.

1.2 Objectives

The principal objective of this research is to quantitatively model the incident rate at mining operations due to worker and latent errors, including the effects of training and experience. The goal is to demonstrate that it is possible to quantify and model errors and incidents at mining operations.

The use of system dynamics will allow us to formulate and to understand the complexity of human errors leading to incidents, and how these incidents can be reduced by the effort of managers and workers in a safe mining operation.

Finally, this research aims to study how the safety commitment and experience of each worker at mining operations can change the incident rate. In order to validate this model, data from three different mining companies will be used; one is located in BC Canada and two in South America.

1.3 Limitations of this Study

- Due to the lack of information available on error occurrences at mine sites, a particular random occurrence of human error and incidents has been assumed.

- It was the intention of this research to quantify the number of human errors, as well as the number of incidents at a mining operation; however, this quantification can not be generalized to all mining operations around the world.

- This is an empirical study that can not be applied to all mining operations. Furthermore, this study does not predict human errors and, hence, incidents in the mining industry.

1.4 Contributions of the Thesis

The main contributions of this thesis are:

- The extension of the study of mining safety through the modeling of human error, experience, training and incident rate.

- The use of system dynamics to model safety in order to model how worker experience and training can change the incident rate in a mining operation.

- To model the occurrence of incidents due to the combination of worker errors and latent errors.

1.5 Organization of the Work

This study is organized in four chapters. Chapter 1 presents a brief introduction, the statement of the problem, the objectives, and the contributions of this research. Chapter 2 presents the concepts used in this study, as well as works from different authors explaining the causes of incidents in any industry. Chapter 3 explains the principal causes of incidents in mining operations which are human errors. Also, this chapter explains how different human errors can lead to incidents and how the combination of latent errors and worker errors also lead to incidents. Finally, this chapter also explains the dynamic systems used for the development of the safety model. Chapter 4 presents the results of the simulations, as well as the discussion of the results. The last chapter presents the conclusions and recommendations resulting from this work.

2 REVIEW OF CONCEPTS AND MINING SAFETY

2.1 Introduction

Mining companies, through their managers and workers, have been trying to reduce the incident rate. For that reason, a large amount of research has been done on the causes of industrial accidents resulting in a considerable amount of descriptive data; and in order to explain this data, several models of accident occurrence have been developed.

It is well known that one of the reasons why incident rates have been reduced in the mining and other industries is the commitment and the responsibility that each manager and worker has in their mining operations (Rundmo, et al. 2003). After a number of investigations and observations of the causes of accidents, different models of accident occurrence have been developed during the years. Most of these models are graphical and seek to explain the main causes of incidents and accidents. Due to these models and studies, the reduction of incident rates has been possible.

2.2 Review of Concepts

2.2.1 Incident & Accident

The definitions of what is an incident and what is an accident are:

Incident:

Cooke (2003) defines *incident* as "*an unplanned event that may or may not result in undesirable consequences*". For the purpose of this research an *incident* will be considered as an occurrence which can cause minimal personal injury, property and environmental damage. In other words, an *incident* will be any event that includes "near-miss" or "near-hit" situations.

Accident:

Different authors such as Holmes, et al. (1997; 2002) and Whittingham (2004) define *accidents* as a mishap which can cause injury or death. On the other hand, Cooke (2003) defines an *accident* as "*an incident with actual negative consequences*". In this research an *accident* is considered as any event that causes serious personal injuries, environmental damage, or property damage.

2.2.2 Mining Safety

According to The Mining Association of BC (2005) the mining industry has become the safest heavy industry in the province. The following graph shows that the mining injury rate[1] was 6 per 100 person years in 1996; and it has been reduced to 1.3 per 100 person years in 2005. In other words, the mining injury rate was reduced 78% within a ten year period. The decrease in mining activity may have influenced the accident rate, but it could only have achieved a small portion of this result. The safety efforts of mining companies, government and other organizations must be given most of the recognition.

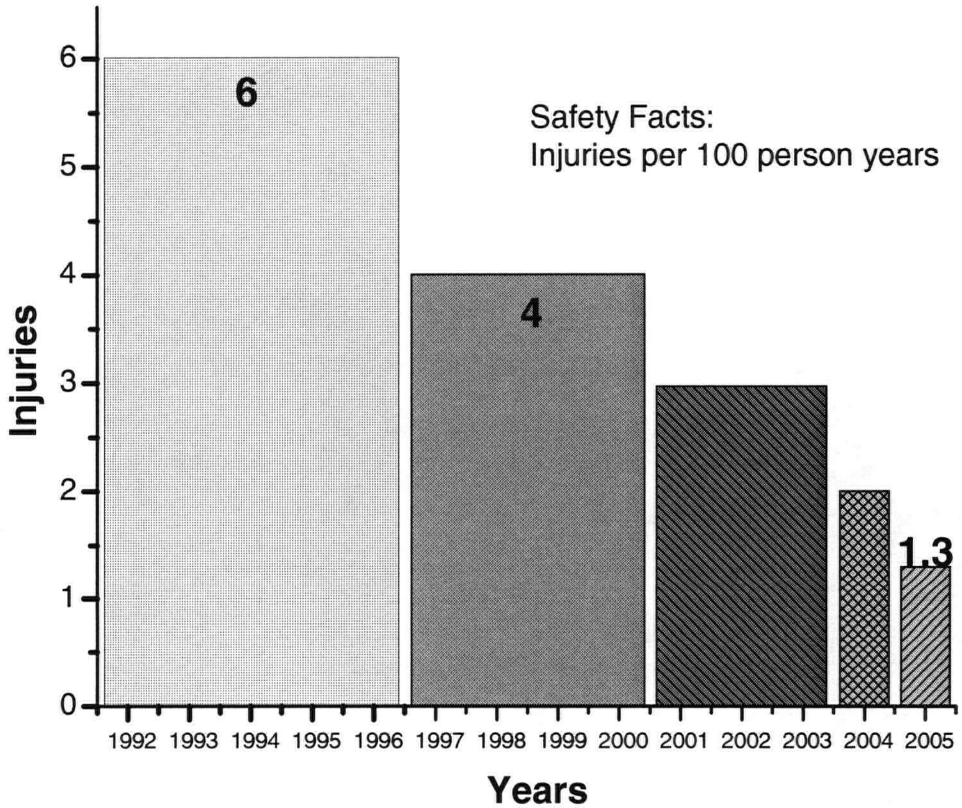

Figure 1 - Mining Injuries in BC. *After The Mining Association of BC* (2005)

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[1] The injury rate is determined by the number of "time-loss accidents." A "time-loss accident" is any injury that causes a worker to take time off work. Injuries can range from miner cuts and bruises to major impairments including death. (The Mining Association of British Columbia 2005)

In order to reduce the injury rate in the mining industry in BC, most of the mining companies began in the early 1990's to implement new safety programs and procedures. Also, awards have been implemented gradually for the safest mining operation in BC. All these initiatives and implementations have changed the safety culture of workers and managers in the industry. However, according to The Mining Association of BC (2005) to keep these low records of injury rates will be a challenge because of the high demand for minerals, which increases production pressure in all mining companies. For that reason, they conclude that it is responsibility of each mining company and each miner to keep the injury rate as low as possible.

On the other hand, countries in South America also have been working on reduction of the number of incidents and accidents in mining operations. Peru, one of the most important mining countries in South America, has also put a lot of effort in order to improve the safety culture in most of the mining operations. The following graph presents an example of how a change of ownership of a mining operation can lead to changes in the incident rate.

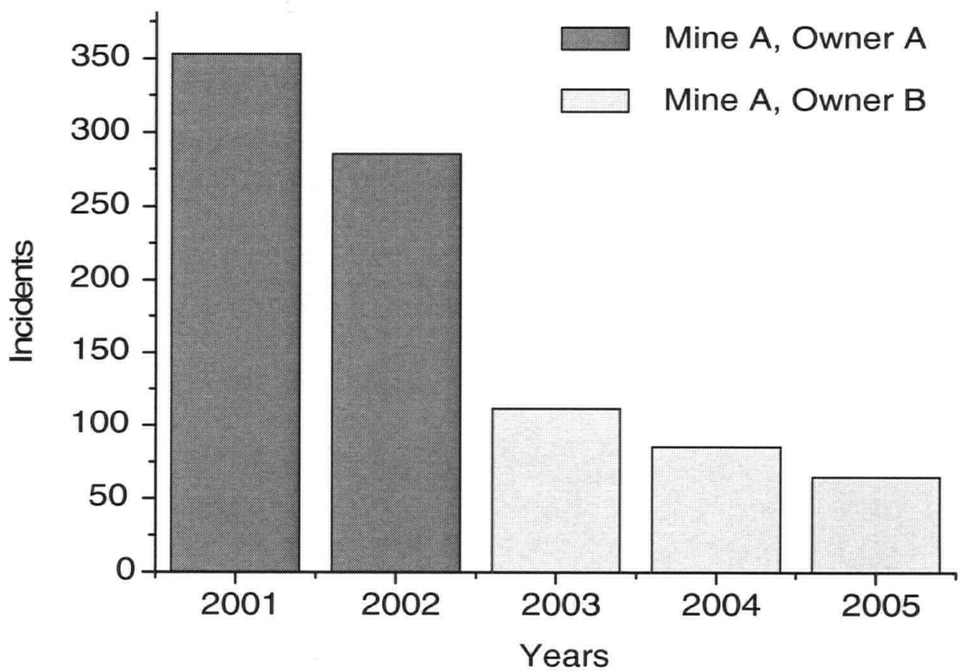


Figure 2 - Number of incidents with two different mining companies.

The mining operation was owned by company "A" for more than eight years. According to one of the workers at the mining operation, who has been working for more than twenty years, company A doubled the production of the previous owner in less than three years. Company A put most of the effort into production and less effort into safety. With the increase of production, Company A hired more people –most of them with low experience in mining-, which increased the number of incidents per year. In 2001, Company A had four fatal accidents, 25 accidents where workers could not work for more than six months and three accidents where workers could not work anymore in a mining operation.

In September 2002, Company B became the owner of the mining operation. This company arrived with a new work culture and approach to safety and implemented training programs for all the workers without exception, increasing the number of hours per worker of safety and technical training. As it can be appreciated in the previous graph, the number of incidents was reduced since company B started to run the mining operation. The increase of training hours was accompanied by other measures for making this operation safer. One of these measures was the implementation of a new culture to all workers focusing on safety at work. Moreover, this new company wanted to make some changes in the management and working areas of the mining operation, for that reason five managers from different areas and 5% of workers were reallocated, and in some cases fired.

After three years of running the mining operation, company B has had only one fatal accident and three accidents where workers had to be at home for months. This example clearly shows how the change of culture at a mining operation and the efforts put in different areas can make the mining operation safer. Nowadays, company B has extended the mining operation, hiring more workers and trying to keep the incident rate as low as possible.

It was mentioned, different mining companies around the world are working extremely hard to make mining operations as safe as possible for workers. For that reason, it can be said that the safety commitment of workers and managers has increased in the last twenty years.

2.2.3 Commitment to Safety

Management's attitude towards safety commitment shapes top and middle management decisions, while influencing the workers' individual decisions as well as the company's policies on safety. Accordingly, safety commitment *"is an attitude contributing to enhancing the safety, i.e. safe behavior and lowering the frequency of accidents and near-accidents."* (Rundmo and Hale 2003)

In some companies implementation of the safety plan is seen as the responsibility of the safety manager alone. However, all managers should be made aware of the importance of safety commitment in regards to the company's performance and growth. Rundmo et al (2003) state that studies developed by Mattila et al (1985) concluded that *"safety objectives seem to be reached more effectively when the management is committed to safety and actively involved in safety work"*. In other words, safety has to be integrated with other parts of the operation, such as production, maintenance.

Preventing incidents or accidents in the mining industry is a task that continues to draw the attention of occupational safety professionals, as well as miners and managers. A recent study, involving operators and miners in underground coal mining, found that a large percentage of the workforce believed that it was necessary to break the rules to get the job done. Laurence (2002) citing the Department of Mineral Resources (2000) states *"any mine that operates 100% within the rules will not produce a single ton of coal"*. This statement applies to most mining companies where miners and managers are committed to production in order to reach the goals set by the company for a particular period of time.

2.2.4 Manager's attitude towards safety

As human beings, nobody wants to see other people get hurt. For this reason, some managers have a very high concern for safety. They motivate the workers to do the right things on the job, and to always take care of themselves and their coworkers.

As previously stated, management commitment has a strong influence on the attitudes and behaviors of the workers in the company. It also influences other areas in a company such as the increase or decrease of safety and production rates, because of the decisions managers make based on their safety responsibilities.

Sometimes managers from small and large companies differ in their opinion about safety commitment. Managers from small companies believe that safety commitment depends on the information and knowledge they have about safety. Safety rules may be too complex for these managers to understand because they lack the expertise and the appropriate training. A study developed by Gillen, et al. (2004) says that *"for managers in large and small companies, the importance of management commitment to and support of safety practices has to be emphasized. The most successful managers were characterized as those who were involved, proactive, principled, innovative, and not afraid to take a stand."* This statement emphasizes that regardless the size of the company, the most important aspect is how strong the managers' commitment for safety is in order to minimize hazards for workers.

Baron, et al. (1999) say that operational knowledge and worker's personal decisions can be influenced by training policies and incentive systems established by mine managers. A study developed by The University of Washington (1998) concluded that employees noted the importance of good orientation programs, training, posting of safety procedures, and sharing of safety information with experts, because they can increase the knowledge and, consequently, the commitment about safety.

Some managers are very focused on production and become concerned about safety only when workers are hurt. A good manager must define the safety expectations for workers inside and outside (subcontractors) the company. One of the main responsibilities for managers is to enforce safety standards for workers, foreman and superintendents. Most company managers and workers agree that to be a successful manager, he or she has to, sometimes, make difficult decisions like shutting down unsafe worksites, even if it goes against the production objectives of the company.

Allocation of resources such as money, time and personnel play an important role in the management safety commitment. Managers are compelled to put more effort in those areas of production where safety and productivity can be more affected. The costs associated with safety will increase whenever work pressure increases; thus, Zohar, et al. (2003) mention that in order to maintain good supervisory practices, higher-level managers must communicate high safety priorities, even under increased work pressure

2.2.5 Worker attitude toward safety

Most workers in any industry would like to work in a safe environment. Logically, people do not want to get hurt or die while working, they work expecting that at the end of the day they will see their families. They are aware that their attitudes and conscientiousness during their jobs may avoid injuries, which could change their lives forever.

On the other hand, there are a proportion of employees that think they are self-sufficient, with the sense that incidents or accidents will not happen to them and who have a high resistance to being told what to do. In this case Rundmo, et al. (2003) said that 'misjudgment' of risk may cause inappropriate decisions as well as unsafe behavior and 'human error'. In other words, an excess of confidence in the job can increase the probability of having an incident.

Technical skills of miners are one of the most important factors associated with good results in the job. However, with the daily routine of the job, these skills can be reduced and the probability to have an accident increases. For that reason, constant training is required in order to keep those skills and improve them.

Miners who operate and inspect the mining operations, have a major effect on the productivity and safety of the mining company. Knowledge, skill level, responsibility, and commitment for safety from miners affect the whole operational system in the company.

Companies usually hire temporary workers or contractors to expand a mine. These workers are usually less experienced and trained than the regular miners, thus the probability of an incident in the mine site increases. Laurence (2005) established that there are studies that suggest that many of the accidents in the mine sites are caused by mineworkers who fail to follow procedures and rules implemented by the mining company. In other words, these workers are those who have low safety commitment or low training and knowledge.

2.2.6 Safety and Production

It was mention before that mining companies are putting a lot of effort toward mining and processing minerals without affecting the environment and without risking the lives of the workers. For that reason, nowadays miners and managers recognize that the mine sites are safer than they once were.

Keep high levels of safety and production are the primary objectives in most of the mining operations around the world. Starr et al. (1982) mentioned that accident avoidance and high productivity can be linked in the long term; however, in the short term there are often tradeoffs between immediate productivity and safety. In other words, in the short term the increase of production can affect the safety of the workers, owing to the pressure that they have in order to reach the goals of the mining company.

Rundmo et al. (2003) and Baron et al. (1999) agree that involvement in accident prevention is too time consuming, that some people are accident prone and consequently that accident prevention will not pay off, and that rules and safety instructions make it difficult to fulfill the production goals. Successful implementation of fully integrated safety function is difficult to achieve. It is difficult for management to espouse both goals of high productivity and high safety with credible enthusiasm. However, because production and safety are mutually dependent, it would make sense to manage these two important aspects of the mining industry simultaneously. Gillen, et al. (2004) mention that it is very often to have productivity records as models to see how is the company doing; however, it does not happen the same with safety records. But Gillen et al. (2004) also said that linking production and safety records receives good support from managers and workers.

According to different authors such as Laurence (2002) and Brown et al. (2000) there are three strategies to run the production in different companies: conservative, moderate and minimum required. These strategies can also be applied to mining companies.

The conservative strategy refers to the most conservative decision made in the mining project, with a very strong system design, to keep a regular preventive maintenance, have highly skilled operators, and maintain a cooperative relationship with the regulatory agencies including the sharing of information. This conservative strategy is very expensive to maintain in any industry especially for mining companies, because of the strong regulations for the mining operations.

A minimum required strategy is the other extreme of the conservative strategy, where the interruption of production occurs only by necessity; production continues as long as the machines can run, workers possess relatively low skill or knowledge for a specific task, and cooperation with regulatory agencies and any kind of outside inspection (i.e. safety regulators) is very restricted.

Production pressures are part of the industrial life, and for that reason, most of the time these pressures can affect safety through shortcuts that workers take to finish the job faster. However according to Gillen et al (2004), "there's no job so urgent or important that it can't be done in a safe way."

In the end, the responsibility for an accident lies with each mining company (managers). The attitude of the mining firm to safety often plays a visible role in accidents records. Most of the mining companies place safety as the higher priority, and some of these companies because they experienced accidents in the past. However, other companies still run with a "macho regard to production" (Safety May 2002), where everything (including safety) is sacrificed in order to reach the goal of production.

Productivity of mining operations where the top priority is production instead of safety may be high in the short term, however in the long term the shutdowns may be increase due to the frequent accidents on site. Thus, production time will be lost and productivity will be reduced. "While maximizing profit at the expense of safety may bring short-term gain, mining firms adopting good safety standards will probably profit in the long term, if not in heaven" (Safety May 2002).

2.2.7 Safety and Training

One of the major problems for managers of big and small companies is the lack of appropriate training. Many times, managers are encouraged to provide good training; however, they find workers who are not very committed to safety. These workers think that because they have been doing the same job for years, nobody can help them to improve and make it safer. Statements such as: "I've never worn a mask" or "it's my lung", are indicative of this attitude; however, with a good training program it can changed.

A study developed by the University of Washington (1998) established that employers, workers and government agencies all agreed that management and worker commitment were essential for an effective safety program. This is the reason that safety should be one if not the most important priority for managers, so they actively should direct a safety program in collaboration and assistance of people and institutions specialized in this issue.

There are big differences between big and small mining companies in terms of safety attitudes and perceptions. For big companies, avoiding incidents in the operation can be a positive motivator (i.e. company image), and therefore these companies invest a lot of time and money in safety personnel, equipment and training. On the other hand, small companies that do not have the resources (i.e. money, personnel, equipment) to implement safety measures and training have to emphasize most of their efforts in production, in order to keep the mine producing. However, Clifton (1998) states *"a company as a whole must work toward developing the key success factors. Every organization has the capability to create an effective safety process. When management is commitment to process and employee involvement is valued, safety becomes an integral part of the company culture."* In other words, with the participation of workers and managers to implement safety measures and avoid incidents, mine sites can be safety places to work.

Most of the times, safety has focused on the concept that accidents are caused by unsafe acts, and based in that fact, teaching workers how to act safely will lead to accident prevention. Cooke (2003) and the document presented by the University of Washington (1998) agree with employees' opinion that the best way management can train or guide any worker is by example. Moreover, Zohar et al (2003) mentioned that if supervisors do not give maximum attention to safety issues during interaction with subordinates, workers would also not behave safely on all occasions.

Many managers believe that the best training they can provide to workers is based on the feedback workers can give to managers. Due to the workers' experience in the job, they have the opportunity to share this experience with their coworkers and with managers. Workers will have the best ideas to make a very good training program, where managers should be able to support these ideas, because knowledge and skills from the workers can be translated into safety issues.

Even though companies put a lot of effort every year in safety, many workers still having accidents in the jobs, and the following explains this: *"Unfortunately the people at the* *top tend to go around giving lectures and saying how important safety is, and how no accident is acceptable and we must all pull together here. Unfortunately, no amount of pep talk is going to alter the way things are done. If you want to alter the way things are done, you have to go down to the grass roots level and find out how things are actually being done, and why they are being done, and why are these operators violating rules, as they often are. And there are always good reasons why they are violating rules. In this way you can find out what is needed to have them do the right thing. It's about changing systems and changing procedures. It is not about getting people to believe that safety is important, which is, unfortunately, so often the message that is conveyed"* (Safety_On-line 2001).

Many authors agree that a positive climate in an organization can be reached when:

- managers are personally involved in safety activities throughout training programs;
- safety issues are emphasized within the whole mining organization; and
- accident investigations are oriented toward problem solving and counseling.

2.2.8 Human Error

According to Kohn et al. (1999) an *error "is a failure of a planed action to be completed as intended (an execution error) or the use of the wrong plan to achieve an aim (a planning failure)".*

According to Reason (1990), human error is defined as: "*A generic term to encompass all those occasions on which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency.*" Also Einarsson (1999) states that Hollnagel (1993) defines human error as "*an action, which fails to produce the expected results and therefore leads to unwanted consequences.*"

Different authors such as Einarsson (1999) and Senders et al. (1991) agree that a human error could happen in everyday working life during a simple or complicated task, involving higher mental processes like creativity. Errors made by the workers are part of the learning process, and they have the constructive function of improving the workers' mental and physical capacities for more complex tasks in the future.

Feyer and Williamson (1998) mention that it has been estimated that up to 90% of all workplace accidents have human error as a cause. Most of the highly publicized accidents in recent memory including the mining industry have been a factor of the Human error. The Journal *World Mining Equipment* (May 2002) states that "*A large percentage of mine-site accidents are directly attributable to human error, rather than equipment failure*". In the mining industry, the human errors not only include the errors made for the personnel, but also errors made for managers (e.g. The Westray disaster 1992). It has been estimated that 60 to 75 percent of all mining accidents are avoidable and are the result of human error.[2]

According to different authors such as Sweeney (2003) and Green (2003), in order to have a better understanding of the human errors, these errors can be divided into Errors of Commission, Errors of Omission, Errors of Misperception, etc. These different kinds of human errors will be explained in more detail in Chapter 3.

2.3 Investigation Methodology

There are several existing graphical approaches for explaining accident causation. Graphic representations have been very important tools to understand the root causes of most of the accidents. These graphics help people to be aware and minimize the possible causes of an accident in order to reduce the consequences for workers and the companies.

2.3.1 Fault Tree Analysis (FTA)

Bandener (2005) defines fault tree analysis as "... *a technique to write down the conditions and events in a logical way that can lead to a single undesired event, such as*

[2] Microsoft® Encarta® Online Encyclopedia 2005, http://encarta.msn.com/encyclopedia_761575410/Mining.html

an accident or incident". This undesired event, which in FTA is called "the top event", is noted at the top of the fault tree as the root note. Below the "top event" there are spread many other events, also called *blocks",* which are connected to each other by logic gates. These logic gates are: "AND" & "OR".

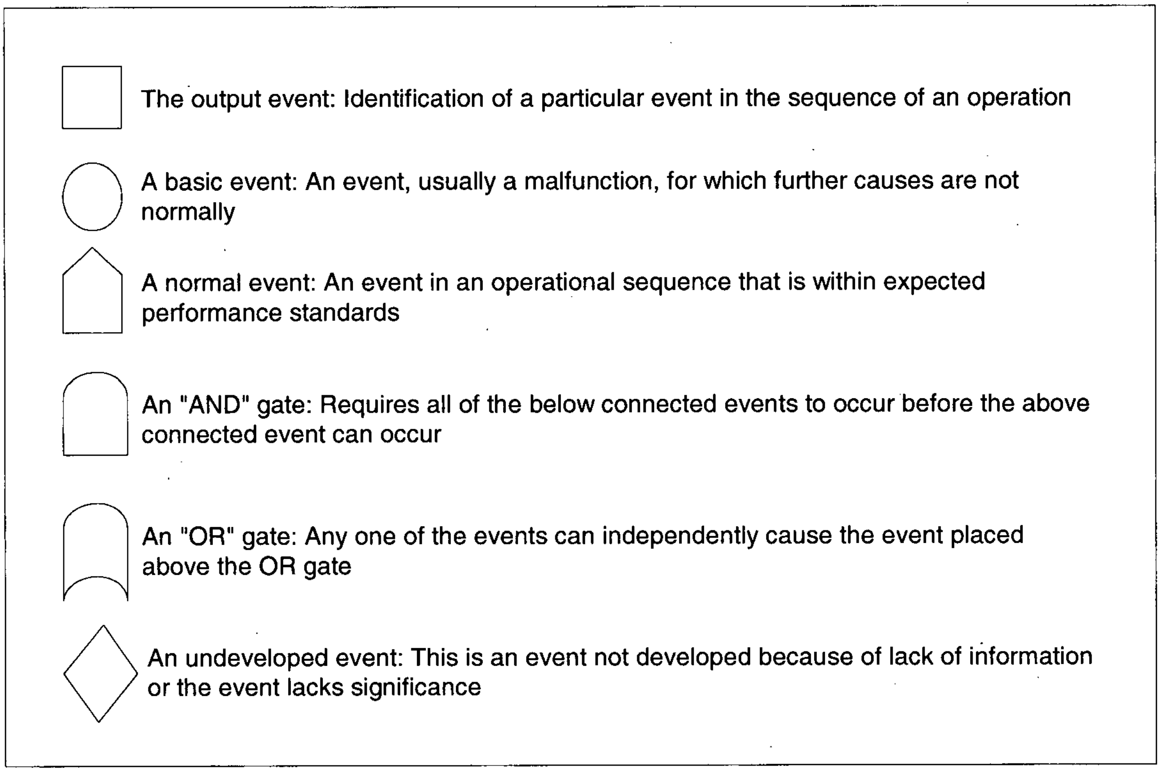


Figure 3 - A Key Fault Analysis Symbols. After (FAA 2000)

Fault Tree Analysis is well recognized worldwide as one of the most important tools for evaluating root causes of accidents. It has been used to translate the failure behaviour of a system into a visual diagram in the aerospace, nuclear and transportation industries. A fault tree represents a visual and concise representation of the possible combinations of occurrences that can lead to an undesirable event (accident). Many companies and authors such as Weber, et al. (2004) agree that fault tree analysis (FTA) is a tool that has been used more often to identify safety critical components which include the investigation of accidents and incidents. Moreover, FTA helps to display the causes and consequences of negative events, and also FTA helps to identify common-causes of failures in different working systems.

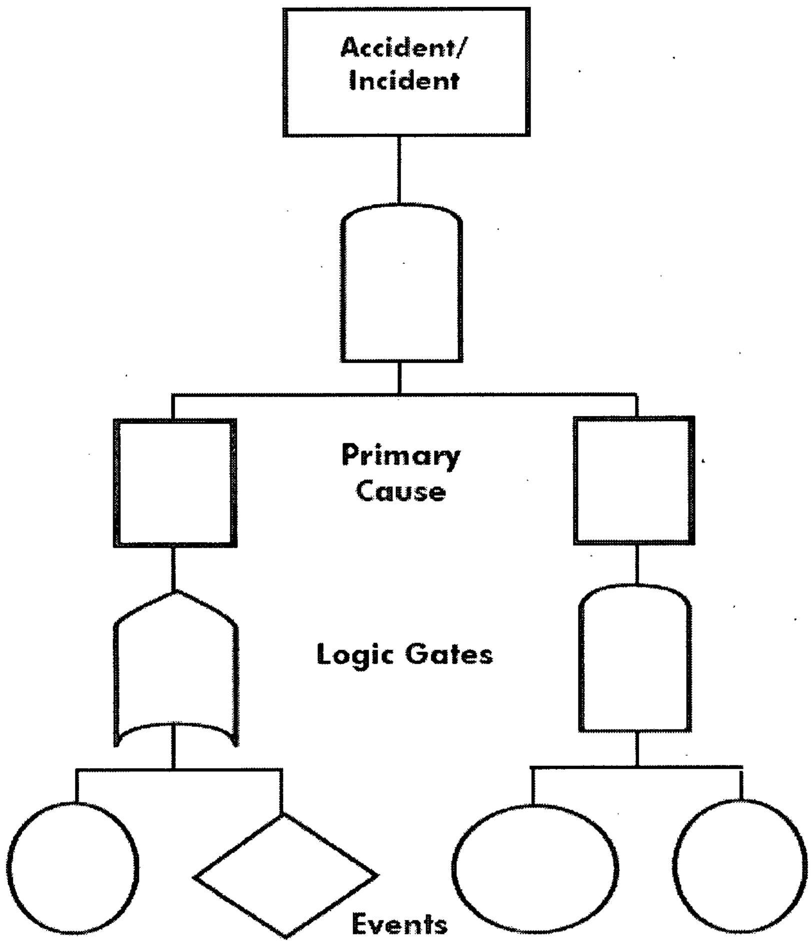


Figure 4 - Texas Workers' Compensation Commission (2005)

Although fault tree analysis is highly effective in determining how combinations of events and failures can cause incidents or accidents; Oh et al. (2005) and Weber et al (2004) established the following limitations:

- Fault tree analysis (FTA) examines only one specific accident of interest. To analyze other types of accidents, other fault trees must be developed.
- A limitation of the fault tree analysis is that the undesired event evaluated must be foreseen and all significant contributors to the failure must be anticipated.

2.3.2 *Failure Mode and Effects Analysis (FMEA)*

Failure Mode and Effects Analysis (FMEA) and Failure Modes, Effects and Criticality Analysis (FMECA) are methodological analyses designed to recognize and classify possible hazards from process or making products. According to the Society of Automotive Engineers (SAE) (2000), FMEA and FMECA are tools that help to evaluate the risk associated with failure modes. Also, these tools facilitate the classification of possible failures and rank them in order to carry out corrective actions to minimize or eliminate potential hazards.

The FMEA and FMECA are tools that can contribute to improved designs for products and process, resulting in higher reliability, increasing safety and reducing costs. (Weibull.com 2005) mention that FMEA and FMECA *"provide a knowledge base of failure mode and corrective action information that can be used as a resource in future troubleshooting efforts and as training tool for new engineers"*.

The following graph shows a sample of a Process FMEA in the Automotive Industry Action Group FMEA-3 format.

POTENTIAL
FAILURE MODE AND EFFECTS ANALYSIS
Front Door L.H.

System 1 - Automobile

Subsystem 2 - Closures

X Component 3 - Front Door L.H.

Model Year(s)/Vehicle(s) 199X/Lion 4dr/Wagon

Core Team A. Tate Body Engrg, J. Smith - OC, R. James - Production, J. Jones - Maintenance

Process Responsibility Body Engineering

Key Date 3/31/2003

FMEA Number 1450

Page 1 of 1

Prepared By J. Ford - X6521 - Assy Ops

FMEA Date (Orig.) 3/10/2003 (Rev) 3/21/2003

Item / Process Function/Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/Mechanism(s) of Failure	Occur	Current Process Controls Prevention	Current Process Controls Detection	Detec	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken: Actions Taken	Actions Taken: Sev	Actions Taken: Occ	Actions Taken: Det	Actions Taken: RPN
3 - Front Door L.H.																	
Manual application of wax inside door. To cover inner door, lower surfaces at minimum wax thickness to retard corrosion.	Insufficient wax coverage over specified surface.	Deteriorated life of door leading to: - Unsatisfactory appearance due to rust through paint over time. - Impaired function of interior door hardware.	7		Manually inserted spray head not inserted far enough.	8		Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	280	Add positive depth stop to sprayer.		Stop added, sprayer checked on line.	7	2	5	70
					Spray head clogged - Viscosity too high - Temperature too low - Pressure too low.	5		Test spray pattern at start-up and after idle periods, and preventive maintenance program to clean heads.	3	105				7	1	3	21
					Spray head deformed due to impact.	2		Preventive maintenance program to maintain heads.	2	28				7	2	2	28
					Spray time insufficient.	8		Operator instructions and lot sampling (10 doors/shift) to check for coverage of critical areas.	7	392				7	1	7	49

Figure 5 - Process FMEA (PFMEA) Automotive Action Group (AIAG) FMEA-3 format. (Weibull.com 2005)

2.3.3 The Management Oversight and Risk Tree (MORT)

The development of nuclear energy technology was the birthplace of MORT the Management Oversight and Risk Tree. MORT is the result of an ambitious plan to create a comprehensive best-practices safety management program for the nuclear energy industry. Currently, MORT has grown into a generic tool which can be used for analyzing accidents that occur in any area which needs safety management. According to studies developed by Bandener (2005), MORT is no longer coupled to the nuclear industry. It is also used in various areas such as building industry or other engineering industries.

MORT diagrams are similar to Fault Tree Analysis; however FTA differs from MORT because, in FTA, a new fault tree is modeled for each analyzed accident. Thus, the events modeled in those fault trees are very specific regarding the considered accident. On the other hand, the MORT diagram is already filled out for the user (a defined fault tree, called a MORT chart), allowing a person to identify the contributory factors for a given undesirable event. One of the main advantages of using MORT diagrams is that MORT is very detailed; thus a person can identify most of the basic causes for almost any type of event. A simple MORT diagram contains over 300 blocks (events), and some charts may contain up to 10,000 blocks. However, according to the Federal Aviation Administration (FAA 2000) a very detailed MORT diagram becomes a limitation because it is time-consuming and very costly.

The top event of the MORT chart is called *Losses* which can be losses of human life, of health or monetary values. Figure 6 shows the top part of the MORT chart.

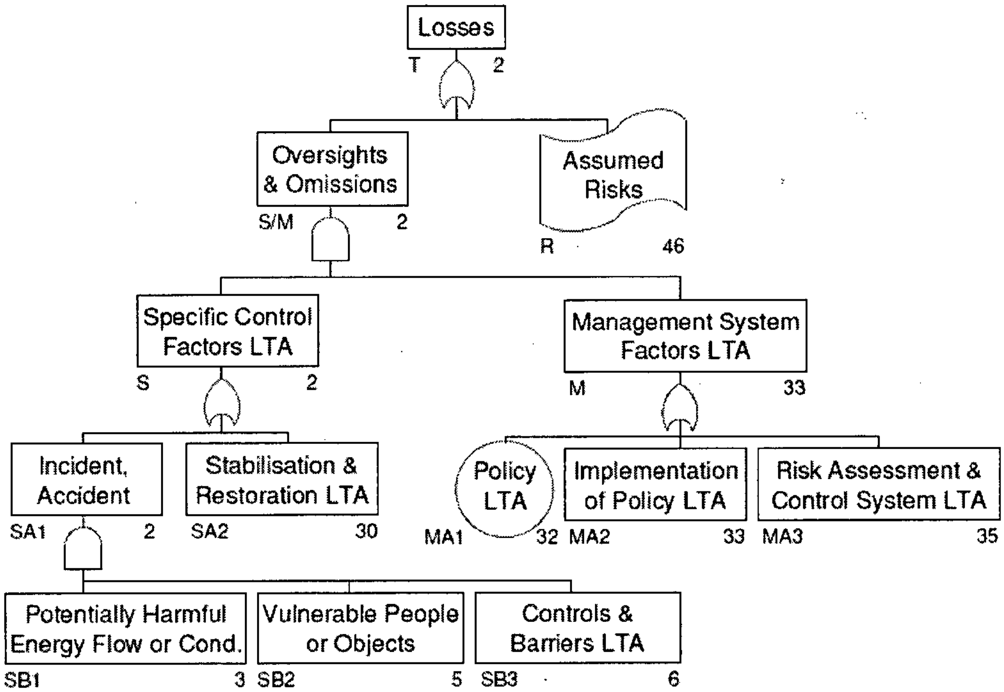


Figure 6 - The top of the MORT chart. After (Bandener 2005)

2.3.4 Swiss Cheese Model

When it comes to understanding incidents and accidents, many authors agree that the "Swiss Cheese Model" developed by James Reason (1990) has become one of the most important tools. According to Luxhøj, et al. (2003), the "Swiss Cheese Model" or the Reason Model is a general model that traces the root causes of an accident to organizational errors arising these causes to the upper levels of any organization. This model is very helpful because it allows explanations of accidents to be based upon more than just individual operator performance.

James Reason made a key distinction in his model between "*Active errors*" and "*Latent Errors*". The active errors, also called operational errors, are the unsafe acts associated with the performance of the 'front-line' operators (pilots, medical doctors, miners, etc) of a complex system. On the other hand, the latent errors, also called organizational errors, are those that people who are not in the front-line, such as managers, commit in their jobs. Reason (1990) states that "*systems accidents have their primary origins in the* *fallible decisions made by designers and high-level (corporate or plant) managerial decision makers*" (p. 203). In other words, the primary causes of many accidents occur in the upper- level of the organization.

Figure 7 shows the "Swiss Cheese Model" as developed by Reason (2000).

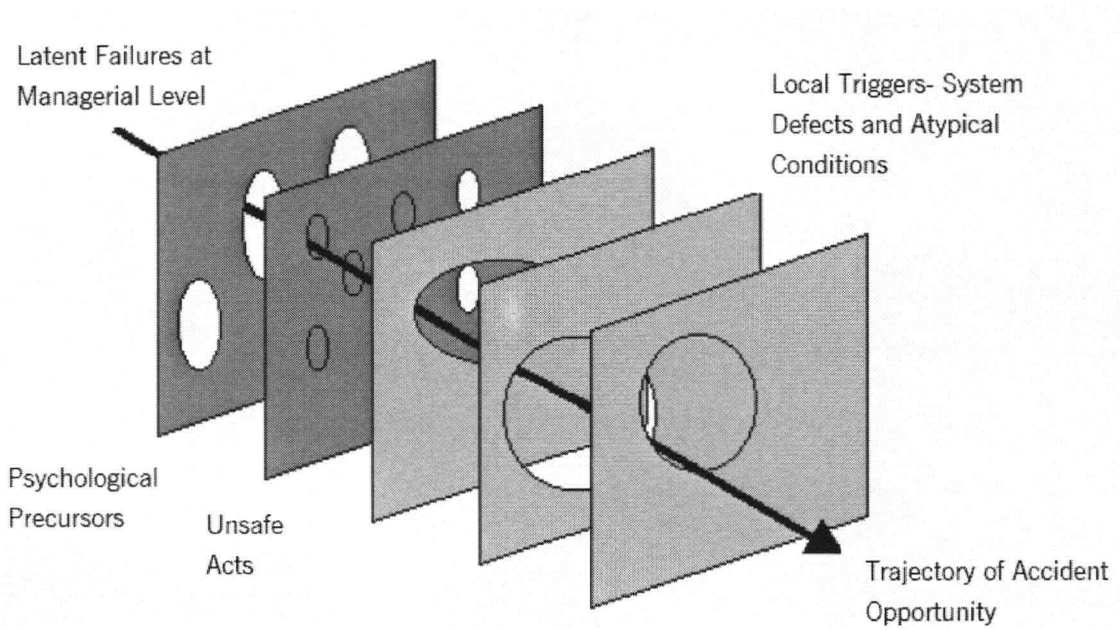


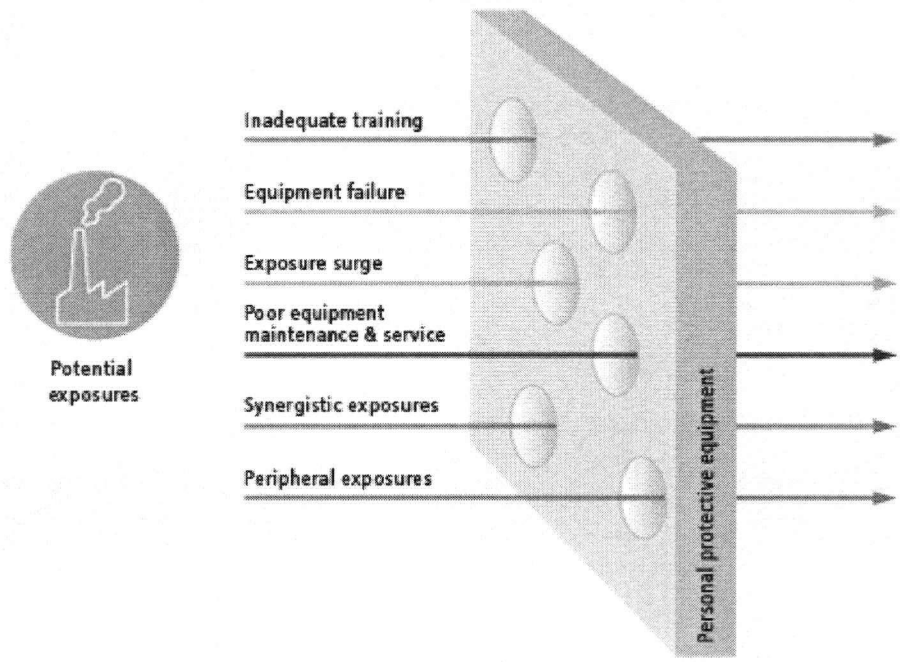
Figure 7 - The Swiss cheese model of accident causation. After (Reason 2000)

> *The figure shows a trajectory of accidents opportunity and its penetration through several types of defensive system. The combined chances of an accident occurring are very small, as the holes in the various defense systems must all line up. Some are active failures of human or mechanical performance, and others are latent conditions, such as management factors or poor system design. However, it is clear that if steps are taken in each case to reduce the defensive gaps, the overall chance of accident will be greatly reduced. Organizational planning can reduce the latent failures at the managerial level, psychological failings can be reduced by*

paying attention to the types to task that are required of workers and unsafe acts can be reduced by good interface design. (Reason 2000)

When Reason developed the image of "The Swiss Cheese Model", he intended to explain the occurrences of system failures in nuclear plants. However, according to Roberts (2001) this model has been used for many researchers in order to study causes of accidents in medical practice and in the US Armed Forces

BHP Billiton proposed the Swiss Cheese Model concept to reduce employee health exposures in mining operations. Figure 8 shows their version of the Swiss Cheese model.



There may be many reasons why personal protective equipment alone may not be sufficient to protect against potential exposures.

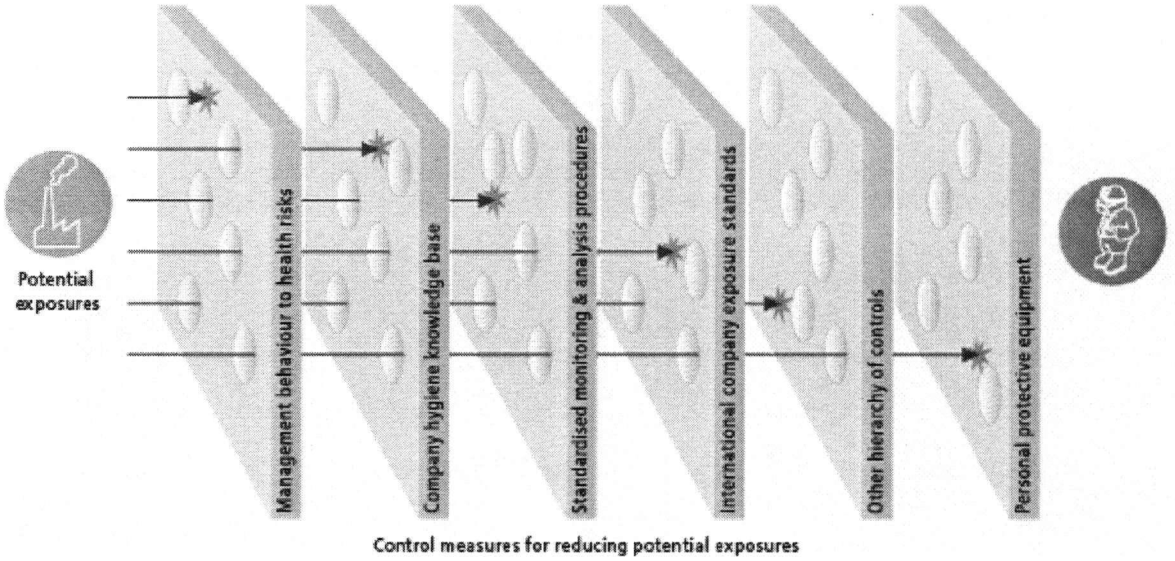


Figure 8 - Swiss Cheese Model – Reducing Employee Health Exposures (BHP-Billiton 2005)

Even though many researchers use "The Swiss Cheese Model" to explain and study the causes of an accident or incident in a complex system, Luxhøj, et al. (2003) established that the main disadvantage of this model is that it does not account for detailed interrelationships among causal factors. Without such detailed interrelationships the use of other tools such as MORT and FTA diagrams is necessary in order to evaluate the causes of an accident.

3 HUMAN ERRORS AND SYSTEM DYNAMICS

3.1 Human Error

Mistakes are part of our daily life. The simplest way to define a Human Error is that "anyone makes a mistake". Green (2003) mentions that over thousands of years, "*to err*" has been part of being human, and he gives for examples of that:

- *ERRARE HUMAN UM EST*; to err is human. (Probably a variation on Plutarch, Morals, c 100 AD)
- "I presume you're mortal, and may err." (Shirley, The Lady of Pleasure, 1635)
- "To err is human; to forgive divine." (Pope, Essay on Criticism 1711)
- "To err is human; to forgive is against company policy." (Senders, various, 1978)

The above says state that errors will be made by any person, even though he or she wants to avoid them. When errors lead to accidents, many companies make responsible of the entire accident to the "front-line" workers (e.g. miners, operators, doctors, pilots, etc), who committed the last error in the whole system.

However, nowadays many companies are working with the "*no-blame*" culture. Managers from different companies believe that errors which lead to accidents are not only the responsibility of the person who is doing the job. For this reason, an incident may be caused by different errors occurred in different parts of the company such as at a management, administrative or operational level, even due to a failure machine.

Authors such as Reason (2000) and Whittingham (2004) agree that in order to improve safety in any industry, the analysis of the error which lead to an incident should be focused on a system and not on people.

3.2 Taxonomies of Errors

Hyland et al (2005) says that *"most usability testing for errors is done from a pragmatic point of view i.e. identifying errors in a system and eliminating them. Such pragmatic testing is seldom based on any theoretical understanding of the causes of errors. The use* *of a well-researched taxonomy of errors in such testing provides additional insight into the causes of errors and so improves the "fixes" required by software developers"*. In other words, the identification and elimination of an error is not enough if the causes of that error have not been found.

Errors have been sub-divided for researchers into slips, lapses and mistakes. Slips and lapses are errors which take place during the execution of a task, and as a consequence the desired outcome from a specific action is not achieved. Errors which take place into a higher level (planning) are classified as 'mistakes'.

Slip, lapse and mistake are define for Whittingham (2004) as follows:

- *Slip*; is a failure in the execution of an action as planned.
- *Lapse*; is an omission to execute an action as planned due to a failure of memory or storage.
- *Mistake*; is an error in planning an action irrespective of whether the action is carried out correctly.

Even though slip, lapse and mistake are terms used for many researchers, for the development of the dynamic model presented in this research we are going to apply the nomenclature used by Sweeney (2003) who defined three kind of errors: Errors of commission, errors of omission and errors of mistaken belief. These errors are decisions made for people that lead to a *critical event* (incident or accident).

3.2.1 Errors of Commission (EOC)

These type of errors are those which the actor or worker is completely aware of the job conditions. This worker is fully cognizant of the consequences of any decision he makes during the job he is doing.

An example of error of commission is presented by Sweeney (2003) in which he explains an scenario where a driver is driving a haul truck with a speed limit of 60 km/hr. This driver observing the road conditions and the good shape of the machine decides to drive over the speed limit (e.g. 70 km/hr). The decision of the driver was made consciously due to different reasons (e.g. finish the job earlier). The actor (driver) knows about the possible consequences of his/her decision. This decision may or may not lead to an accident. However, the decision of increasing the speed limit from 60 to 70 km/hr, also increases the probability of losing control and, thus causing an undesired event.

Through the above example, we can understand that the driver does not intend to harm anybody or cause any damage that could affect the operational integrity of the company.

The possible causes of these types of accidents are:

- The individual is a senior or very mature worker that has learned to do the task without following the rules or standards provided by the company. This worker is not willing to change his or her way of doing the job.
- Some unionized workers refuse to work to standard as they believe that these rules are made by management to deny liberties to them.

3.2.2 Errors of Omission (EOO)

Errors of omission are characterized by the absence of a conscious decision by the worker when he or she is doing a job. This worker intends to do his/her job as well as possible following all the safety rules. However, due to external causes (e.g. fatigue) which are out of his/her consciousnesses, the actor proceeds to do the job without having full knowledge of all external conditions, which can change the normal procedure of his/her job.

Following the example presented by errors of commission, in this case the scenario is the same where a driver is driving a haul truck with a speed limit of 60 km/hr. However, as a result of lack of attention, over stimulation or just fatigue, the driver increases the speed of the truck to 70 km/hr unconsciously. Excessive speed increases the probability of losing control of the truck leading to an accident or incident.

One of the most important differences between errors of commission and omission presented, is that in errors of omission the worker does not know or is not conscious that he/she is in a risky situation; therefore, his/her reaction will be slower if something wrong happens with the road or the machine.

Some of the causes of errors of omission are:

- Fatigue, over stimulation, time pressure, competing priorities
- Work shift too long
- Badly designed control room enunciation
- Workers under the influence of drugs/alcohol
- Too much work demand
- Pressure from fellow workers or the supervisor

3.2.3 Errors of Mistaken Belief (EMB)

Errors of mistaken belief or honest mistakes are those where a decision is taken by the actor (worker) based on a mistaken or false information. These errors occur when the worker may or may not be fully aware of the hazards of the job he/she is doing. These errors may occur due to inadequate training. In the absence of clear knowledge, the worker makes assumptions and based on that he/she makes decisions that may lead to an accident.

To complete the example presented for errors of commission and omission, in this particular case, the driver who is driving the haul truck exceeding the speed limit (60km/hr) by 10km/hr thinks that he/she is actually driving at the speed limit. The increase of the speed could be possible because the odometer is reporting a wrong speed, or because the driver thinks that the speed limit of 60km/hr is only for night shifts.

The different aspects that can cause this type of errors are:

- Workers not being trained
- Young workers in entry level positions
- Workers who are not competent for the assigned tasks
- Workers who are filling in for others

- Workers who have not had any refresher training when new technology is applied
- Workers who are intellectually unequal to the decision making requirements of the work

3.3 Latent errors

The three type of errors described above refer to those errors committed by workers. However the errors which lead to accidents are not only committed by workers, managers also commit errors which lead to incidents or accidents.

Latent errors may be design errors committed by engineers responsible for design and/or construction of mine. Such errors may be discovered by design checks, but are otherwise difficult to detect. Latent errors may be committed by managers and supervisors responsible for operational decisions. Such errors are also difficult to detect and eliminate until an incident occurs. According to the safety data obtained from two mining companies and the definition of errors mentioned before, it is possible to classify latent errors as errors of omission (EOOm) or errors of mistaken belief (EMBm).

3.3.1 Latent Errors of Omission (EOOm)

As described before, these types of errors are characterized by the absence of a conscious decision. In this case the manager who intends to perform a good and safe job fails to do so due to external causes (e.g. time pressure, too much work demand).

An example of this kind of error is when a blasting process is programmed in any mining operation; all machines have to be placed far enough from the blasting area. However due to the time consuming activity of moving the shovel from one point to the other, the manager responsible for the loading and hauling of the mineral decides not to move the shovel to the safety place required by the mine policy. He decides to move the shovel a shorter distance from the blasting area assuming that nothing will happen to the machine. Nevertheless at the time of blasting one rock flies and hits the radiator of the shovel putting it out of service for some hours and delaying the whole process.

3.3.2 Latent Errors of Mistaken Belief (EMBm)

As described before, these errors are those when the decision made by the person is based on false information or misinterpretation. EMBm occurs when a new manager responsible for a part of any process in the mine operation fails to give good instructions to workers due to his experience.

An example given by a manager of a Peruvian company is that when a new manager arrives in the mine, he/she is not familiar with the weather conditions in the mine. Due to this inexperience, the new manager fails to order workers to make an inspection of all the pipes in the mine. When the raining season arrives and a landslide occurs, some pipes broke down, thus making the mining process to stop. This lack of prevention is due to the inexperience and lack of information that the new manager has with this type of weather.

3.4 Combination of worker errors and latent errors

The mine errors that are studied in this research will be treated as latent errors. For the purposes of this study it will be assumed that *latent errors* (Reason 1990) do not lead to an accident unless a combination with active errors occurs.

As explained before, in the mining industry errors of omission and errors of mistaken belief are not only made by workers. The mine through its managers also commits these kinds of errors. Errors such as lack of maintenance planning, lack of personal safety equipment and lack of specific mechanical tools are the responsibility of the mine.

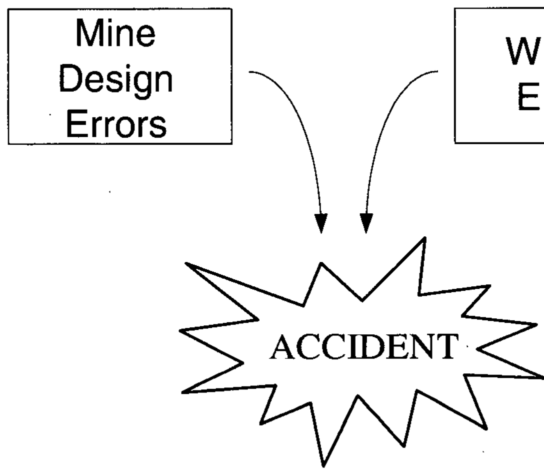


Figure 9 - Combination of errors leading to an accident

3.5 The Swiss Cheese Model and combination of errors

In order to have a better graphical understanding of what is intended to do with the system dynamics model, an example is presented in Figure 10.

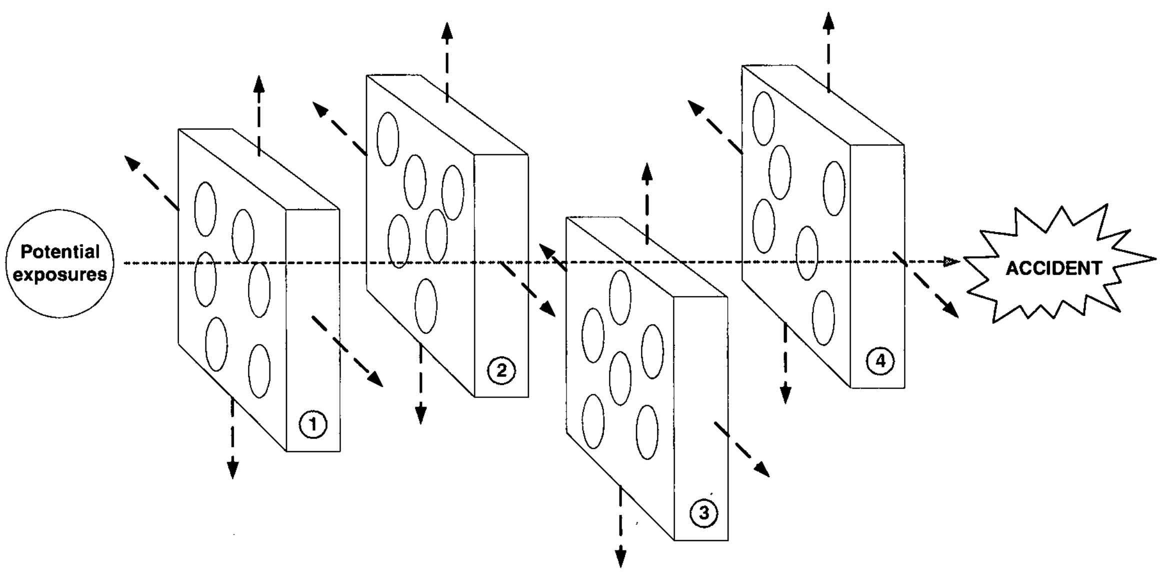


Figure 10 - Defenses against errors

In the above figure, we can see four walls that represent the defenses that any error has to pass in order to turn into an accident. In the system dynamic model proposed in this research, each "wall" or defense represents the safety measures that a company (managers) or workers take in order to avoid an accident. Each of these defenses is independent from each other. However if an error passes through all these defenses, an accident is inevitable.

Likewise, in Figure 10, it is seen four different walls with arrows in each of the sides of the walls. These arrows mean that the "walls" or defenses can move in different directions with different probabilities. The probability of how much each wall moves and how often it moves is different for the four of them. If the probability of having an error is high, it will mean that the "wall" or defense is moving very fast. However, if the probability of having an error is low, it will mean that the wall is moving slowly.

Finally, the arrow represents that an error could pass through all these defenses in a certain point, only if the holes of each wall are aligned.

From the example presented in chapter two where a driver certainly commits errors during his job, the four "walls" are: Driver training, Truck maintenance, Transit and road conditions, and Driving. These are discussed below.

Driver Training

The training that any worker receives before driving a truck is the entire responsibility of the mine company. The mine through its driving instructors provides the drivers with the knowledge and skills to drive a truck safely. Due to training and experience, any driver will improve his skills in driving a truck as safe as possible, avoiding possible hazards that can lead to an accident.

The probability of bringing a bad driver training program from the mine is very *low*. It is assumed that due to the experience of the instructors, they will try to provide any driver with the knowledge necessary to operate a haul truck or any machine as good and safe as possible.

Truck Maintenance

Truck maintenance is other defense against an accident. All the trucks which are operating in any mining operation might have a maintenance program in order to ensure the good operation of the machine at any time. For that reason, the maintenance inspectors must check and guaranty that the machine is in optimum conditions to be operated.

In any mining operation, the most common practice after the personnel from maintenance checked or repaired the machine is to test it. Not only people who repaired the machine check that it is working in perfect conditions, but also the maintenance inspectors verify the conditions of the machine before it is sent to continue its operation. Due to the fact that the maintenance of any machine is checked by different people and more than once, the probability of having a maintenance error is *low*.

Transit and road conditions

It is responsibility of the mining company and drivers to make sure that transit and road conditions are optimum to guaranty the safest conditions to drive into the mine site. Inspectors in the mine site are the people who check and inspect constantly how the road conditions are. It is also responsibility from people in charge of dispatching to ensure the fluid transit of the haul trucks, with the purpose of avoiding congestion and possible crashes. Drivers are also very responsible for the transit and road conditions of the mine site. Drivers have to report if the road conditions are not the appropriate to drive in order for the inspectors to fix the problems.

The probability of having an error due to transit or road conditions is higher than the probability of having an error in driver training or truck maintenance. The good condition of the road will also depend on the weather conditions. There are mine sites where weather conditions make the roads extremely dangerous for any driver. For that reason, the probability of having an accident increases.

Driving

The "walls" or defenses are part of the safety measures that must be taken to avoid a haul truck accident. However, it is believed that driving is the most import aspect in order to minimize the possibilities of having an accident which can also have terrible consequences. The possibility of having an accident is the exclusive responsibility of the driver. The worker due to his her experience and commitment to safety will take more or less precautions when operating a machine.

The probability of having a driving error will depend on the experience and safety commitment of the driver. The probability could be *high* if the driver is new in the job, or if he has a high excess of confidence, or if his commitment to safety is very low. However, the probability of having an error that can lead to an accident will be *low* if the worker has a high driving experience, takes all the precautions to avoid any hazard and if his commitment for safety is very high.

As mentioned before, safe driving is the most important defense against any truck accident. It is possible that there would be errors in driver training, truck maintenance, and transit and road conditions; however if the driver is committed to perform his job and to drive his truck assuming all the responsibilities that this job involves, the probability of having an accident with terrible consequences could be minimized.

The example presented above gives an idea of how an error can lead to an accident if measures against human errors are not taken. The model that is being developed for this research will try to dynamically represent how human errors can lead to an accident, and how from the occurrence of an accident people can learn and try to minimize the errors which lead to undesired events.

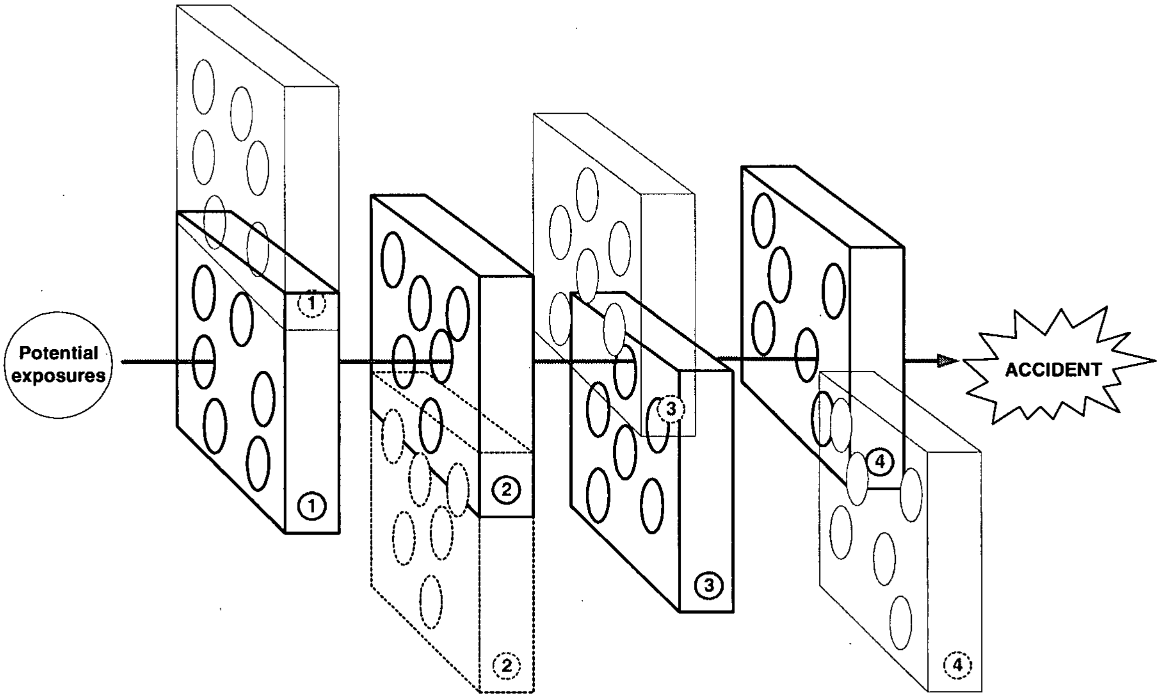


Figure 11 - Errors pass through the defenses

3.6 Formulation of Human Error Model Leading to Incidents

3.6.1 Bernoulli Random Variables

Devore (2004) defines a Bernoulli random variable as "*any random variable whose only possible values are 0 and 1*". For this research, it has been used the Bernoulli random variable in order to determined the occurrence of human errors. As was established before, human errors are very difficult to predict and they can occur any time during the performance of a job. For that reason, it can be said that human errors occur randomly.

The occurrence of an error is modeled as a Bernoulli process. Let E be a Bernoulli random variable where $E = 1$ indicates that an error has occurred ("success") and $E = 0$ indicates that no error occurred ('failure"). If $P(E=1)=p_1$ the procedure used to generate random human errors is:

$$\text{Generate } r \sim U[0,1]$$
$$\text{if } r < p_1, E=1, \text{else } E=0$$

where $U[0,1]$ denotes a random number uniformly distributed between 0 and 1.

Incidents are also assumed to be a Bernoulli random variable. Let I be a Bernoulli random variable where where $I = 1$ indicates that an incident has occurred as a result of human errors and $I = 0$ indicates that no incident occurred. If $P(I = 1) = p_{INC}$, the procedure used to generate incidents is the same as for human errors:

$$\text{Generate } r \sim U[0,1]$$
$$\text{if } r < p_{INC}, I = 1, \text{else } I = 0$$

3.6.2 Human Error Probability (HEP)

In this regard, many authors such as Reason (1990), and Senders, et. al (1991) made many studies in how human errors can lead to an accident. Reason (1990) through his Swiss Cheese model explained the difference of latent errors and active errors. However, none of these authors quantified the combination of these errors. Whittingham (2004) proposes the quantification of the combination of errors through the dependency that they have on each other.

Gertman (1992), and Gertman, et. al (1994) divided the decisions made by workers that could lead to an error into four main categories. Each of these categories presented in Table 1 were subdivided by the same authors in 20 decisions. On the other hand, from the decisions shown in Table 1, each decision was categorized as EOC, EOO or EMB, according to the error definitions given by Sweeney (2003). Note the significant difference between the low and upper bounds of the human error probability (HEP).

	Source Categories for Decision-based Errors	Upper Bound	Lower Bound	Type of Error
I. Action consequences				
1	Circumvent procedure with potentially catastrophic consequences	7.50E-02	6.00E-05	EMBm
2	Circumvent procedure with a minor consequences	8.60E-02	3.30E-04	EMBm
II. Attitude leading to circumvention				
5	Violate procedure and reconfigure equipment	8.30E-02	5.50E-04	EOCw
6	Violate procedure and devise own formula	4.70E-02	1.60E-03	EOCw
8	Common mode: failures due to poor safety culture	2.00E-01	4.60E-03	EOCw
III. Crew response set				
9	Misdiagnosis given like symptoms, capture sequences based stimuli	1.80E-01	1.30E-02	EMBw
10	Right diagnosis, wrong response, capture sequences based on response set; right conclusions but wrong action pathway selected	2.20E-01	3.90E-03	EMBw
12	Symptoms noticed but incorrect interpretation	1.00E-01	4.20E-03	EMBw
IV. Resource dependencies				
15	Insufficient resources/instrumentation provided by management	2.40E-01	7.40E-02	EOOm
17	Inadequate communication results in improper actions	2.00E-01	3.30E-03	EOOm
18	Excessive task demands result in poor judgment	2.90E-01	2.90E-02	EOOw

Table 1 - Source Categories of Action Consequence, Attitude, Response Set, and Resources and Estimates of HEP Upper and Lower Bounds for Decision-based Errors.

After (Gertman 1992)

From the table above, it can be appreciated that each decision has been divided into worker errors and latent errors. The assignment of each EOC, EOO, or EMB was made with the collaboration of different managers with more than ten years of experience working in the mining industry, and with whom the author of this research had personal contact.

3.6.3 Probability of Human Error Leading to an Incident

The probability of a human error leading to an incident was determined with a personal contact with Sweeney (2003) and four safety managers in Peruvian and Canadian mining companies, who concluded that 40% of the incidents occur for EOC, 25% for EOO, and 35% for EMB. For the formulation of incidents generated by human errors in the dynamic model proposed in this research, the percentages mentioned before have been used.

3.6.4 Dependency of Human Error and Latent Error

Whittingham (2004) proposed five levels of dependency of errors that can lead to an accident. He mentions that latent errors exist in all companies, and only when active errors take place an accident may occur. But how does the interaction of these errors lead to an accident? Whittingham classified a rule dependency with these errors. High dependency is when a worker is carrying out two tasks which are dependents on each other and the time period to perform the two tasks is less than one minute. On the other hand, a low dependency is when a worker carried out two tasks which are almost independent of each other and the time period to do these tasks is longer. For High, Medium and Low Dependency of an error a depending on an error b having probability P_b, the probability formulas developed by Whittingham are:

$$P_{a|b}^{HD}(a|b) = (1 + P_b)/2$$
$$P_{a|b}^{MD}(a|b) = (1 + 6P_b)/7$$
$$P_{a|b}^{LD}(a|b) = (1 + 19P_b)/20$$

The dependency of latent errors on worker errors is very low. It is known that a design or organizational error can remain latent for a long time until a combination with a worker error (active error) occurs. Due to the time between one error and the other, the *low dependency* error is used for the development of the model proposed in this research.

3.7 Experience and Human Error

Since the studies of human errors began, it has been difficult to separate human error from system failures. According to Duffey, et al. (2004) more than 60% of incidents or accidents in any industry are caused by human error. There have been many authors who developed many studies in human errors; some of these authors conclude that human beings learn from their own mistakes.

Humans learn from their mistakes is a fact that many authors use when they explain the different models of learning. The basic learning process is represented in the following graph.

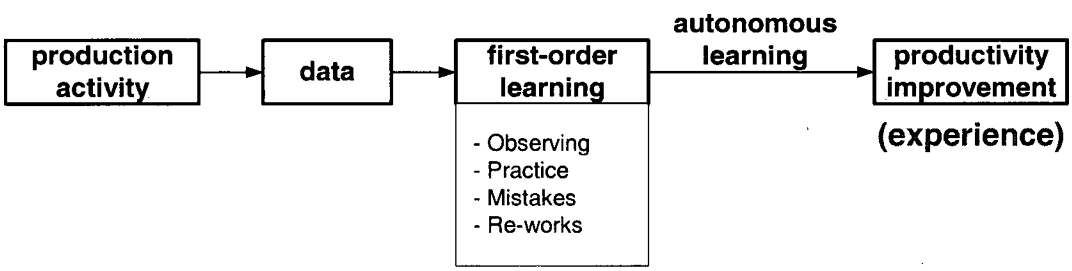


Figure 12 - The Basic Learning Process Model. After (Adler and Clark 1991)

Figure 12 shows how experience increases productivity of any worker with time. When a new worker begins a job, it is expected that his performance or productivity will be low. But it is also expected that this new worker will learn and improve his/her job performance with time. Adler, et al. (1991) established that the best way for a worker to gain experience is through his/her own self-learning or autonomous learning.

When beginning a new job most workers, observe how their coworkers perform their jobs. After a time of observation, they start doing the job and through practice they will get better in the job. It is well known that when a person is doing a job, it is possible to make mistakes and sometimes do the job again (re-work). However, every time a worker makes a mistake; he or she learns from it and tries to avoid similar mistakes in the future. To conclude, observation, practice in the job, learning from mistakes, and re-works make the workers gain more skill and performance. For that reason, after a certain length of time, it is expected that his/her job will be performed with high productivity because this worker is not considered anymore a "new" worker; he/she is considered an experienced worker.

As it was mention before, the self-learning or autonomous learning is the most important aspect to gain experience (skill and knowledge); but is not the only one. There are other aspects (external) that help workers gain experience faster than doing by their own learning.

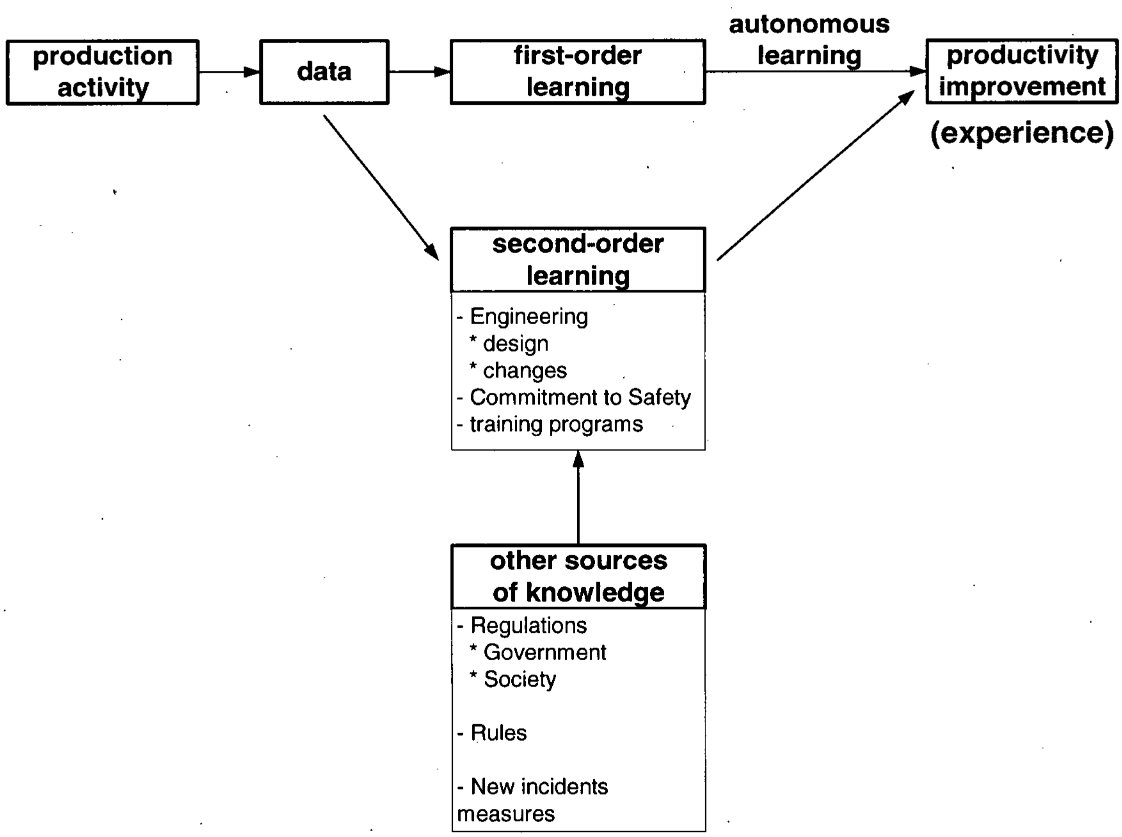


Figure 13 - The Learning Process Model. After (Adler and Clark 1991)

As errors occur, Managers, Society and Regulators introduce new measures (Rules, Procedures and Systems) to attempt to minimize or eliminate these errors. New measures are taken to try to control the incidents caused by worker error. Also the requirement for new safety rules increase according to the increase of human error occurrence.

Authors such as Adler et al (1991) and Helmreich et al (2000) establish the more the occurrence of workers errors, the developed for safety measures is more required. As the technology changes, also the process and design of operations change, which means that the workers must continue following training programs in order to work safely every time.

In other words, when workers make errors, companies respond with new safety measures; and the more new measures are implemented in the companies, the faster a worker get experience. However, the more experience a worker has, the probability of committing an error is reduced. For that reason, Duffey, et al. (2004) conclude that "human error probability is *dynamic* and evolves with experience".

In Figure 14 it is represented how errors increase the requirement for new measurements and how these measures help to get experience faster. Also, this figure represents the learning or experience curve increase during time. Duffey, et al. (2002) postulate that "*humans learn from their mistakes as experience is gained*".

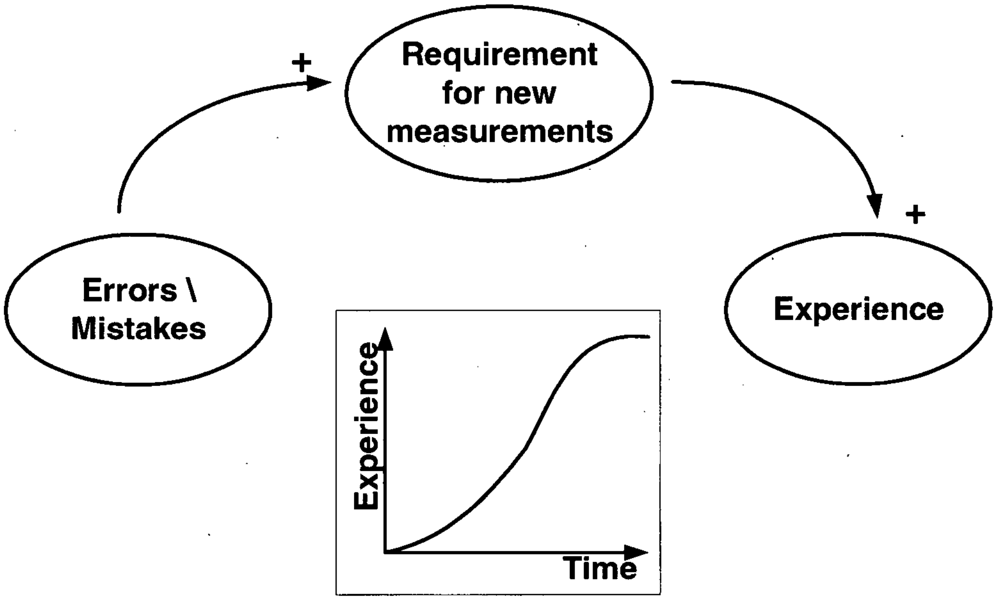


Figure 14 - Learning or Experience Curve

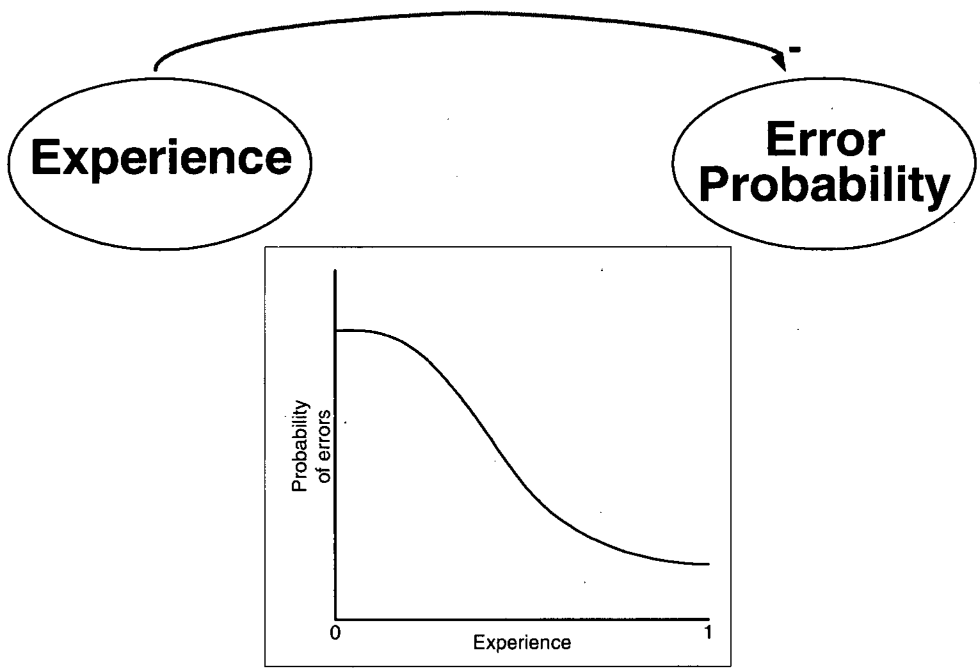


Figure 15 - Experience vs Error Probability. After (Duffey and Saull 2004)

From Figure 15, it is observed that the probability of errors reduce when workers gain more experience. From this figure it is also appreciated that the errors probability will never be *zero*. This is explained because there are no “zero defects” in any industry or process. In reality, errors have a random behavior and, for that reason, it is very difficult and sometimes impossible to distinguish or predict all the possible errors that can occur.

3.8 System Dynamics

A large amount of research has been done on the causes of industrial accidents resulting in a considerable amount of descriptive data. Several models of accident occurrence have been developed in an attempt to explain these data. Those models tend to be static or involve changes over a short time period (e.g. within a few minutes before an incident). In some industrial operations, particularly mining, the workforce conditions evolve physically; and in terms of labor and management personnel, they evolve knowledge and training. This suggests a more dynamic model is required to represent the safety conditions at the mine. For that reason system dynamics tools are used for the development of the simulation model presented in this research.

System dynamics is a methodology developed by Forrester (1961). This methodology was developed in order to study and manage complex feedback systems. System is a word that has been applied to many situations, however in system dynamics, *feedback* is the differentiating descriptor. The System Dynamics Society (2005) describes “feedback” *as the situation of X affecting Y and Y in turn affecting X perhaps through a chain of causes and effects. One cannot study the link between X and Y and, independently, the link between Y and X and predict how the system will behave. Only the study of the whole system as a feedback system will lead to correct results.*

The methods of system dynamics also called *systems thinking* provide important tools for better understanding complex systems. These tools help managers have a view or understanding of all the management problems. The approach of systems thinking is not looking at *event* and *causes* as independent events. With these systems, people have to look at any organization as a complete *system* which is made of interacting parts. The term *system* is defined by Kirkwood (1998) as an interdependent group of items forming a unified pattern.

This model will aid understanding of how human errors lead to accidents and of how such errors can be minimized through training. The model will also attempt to incorporate the effects of combinations of errors such as does due to workers and those due to management.

3.8.1 Feedback

According to Sterman (2000), the most important aspect of system dynamics modeling is the discovery and representation of feedback processes, which, along with stock and flow structures, time delays, and nonlinearities determines the dynamics of a system. In system where a transformation occurs, there are inputs and outputs. The inputs are the result of the environment's influence on the system, and the outputs are the influence of the system on the environment. Input and output are separated by duration of time, as in before and after, or past and present.

In every feedback loop, information about the result of a transformation or an action in the system is sent back to the input of the system in the form of input data. If these new data facilitate and accelerate the transformation in the same direction as the preceding results, they are termed positive feedback - their effects are cumulative. If the new data produce a result in the opposite direction to previous results, they are termed negative feedback - their effects stabilize the system. In the first case there is exponential growth or decline; in the second there is maintenance of the equilibrium.

For a better understanding of positive feedback and negative feedback, graphic representation made by Sterman (2000) will be used:

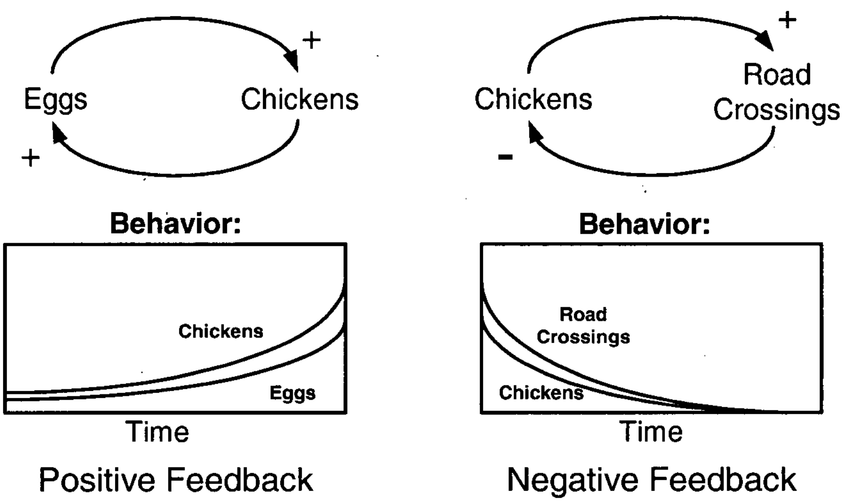


Figure 16 - Positive and negative feedback loops. After (Sterman 2000)

Positive feedback:	More eggs – more chickens (+)
	More chickens – more eggs (+)
Negative feedback:	More chickens – more chickens dead (road crossing) (+)
	More chickens dead (road crossing) – less chickens (-)

3.9 Formulation of the Dynamic Safety Model

As previously mentioned, system dynamics is an important tool in the development and understanding of complex systems. Due to variables such as human error, probability of errors leading to incidents, and training as feedback, system dynamics is applied in this research.

The dynamic model presented in this research attempts to model the worker errors (EOC, EOO and EMB) as independent errors which lead to incidents. Furthermore, this research aims at seeing the combination of errors between manager errors (mine) and worker errors that lead to incidents. Also, these errors will be reduced due to a feedback.

The software used for the development of the model proposed in this research is iThink ® (High Performance Systems, Inc.)

3.9.1 Worker Errors

As human beings, everybody is capable of making an error in their jobs. The mining industry is not an exception. There are three kinds of errors (EOC, EOO, and EMB) that any worker can make in his/her job. These kinds of errors were defined previously in chapter one. Also, it was mentioned before that workers get experience from autonomous learning and external learning.

The dynamic representation of errors leading to incidents and how these incidents affect the experience got by workers is presented in the following graph.

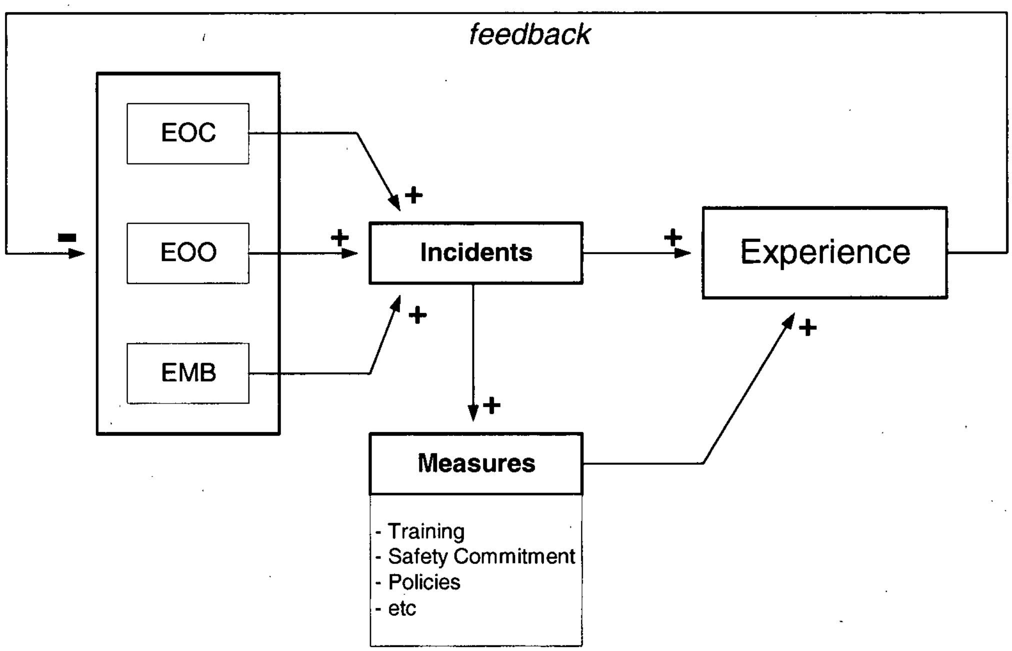


Figure 17 - Worker errors and Experience

From Figure 17 it is shown that the increasing number of worker errors will raise the number of incidents in the mine sites. As it was presented before, incidents will make mining companies put more effort in the current measures or implement new measures in order to analyze the cause of errors and reduce them.

On the other hand, the daily job makes a worker gain experience in what he/she does. However, every time an incident occurs or a new measure is implemented in the mining operation, the worker increases his/her experience faster than if these actions never happen.

The use of system dynamics modeling facilitates the representation of *feedback* in models with complex behaviors. It is shown in the previous graph that working experience increases with the number of incidents and measurements; and the increase in experience reduce the probability of having a worker error. To conclude, the more experience workers get, the more precaution they take in their jobs, and the more precautions taken in the job, the further the probability of committing an error is reduced.

The following graph represents all the variables used for the development of the dynamic representation of errors, experience and feedback in the model.

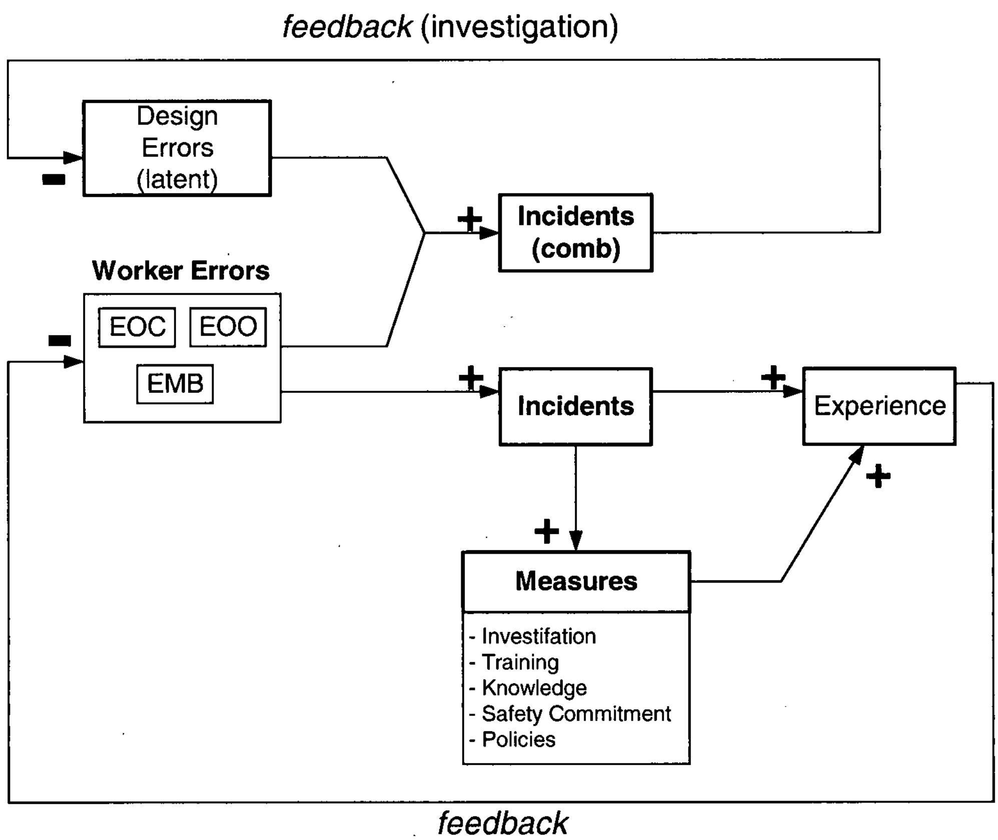


Figure 18 - Block diagram of the model

Description of Variables in the Model

- *EOC, EOO and EMB:*

Many researchers have been working and still working in studies trying to analyze the human mind in order to understand what patterns that human minds follow are. However, due to all the effort it has been impossible to study and analyze all the workings of the human mind. For that reason, all the possible errors that a worker can make are very difficult to predict; and the detection of these errors happen only when an incident occur.

Traditional approaches (e.g. investigate prior events, identify root causes, etc) have been trying to eliminate human errors; however, these approaches only reduce the errors but never eliminate them. In reality the elimination of an error is impossible because errors have *random* behavior; and as it was mentioned before errors follow a learning curve. Even though an error is detected, nobody will be able to guaranty the same error will not happen again in the future. Furthermore, the prediction and detection of all the possible errors that can occur in any mining operation is very difficult.

As explained before, workers errors of commission, omission, and mistaken belief will follow a random behavior in this model.

- *Total Worker Errors (Total Ew):*

The total worker errors are the sum of the total errors of commission, omission and mistaken belief during a time period.

$$\text{Total Ew} = \text{Total EOC} + \text{Total EOO} + \text{Total EMB}$$

The total worker errors will allow to analyze what was the change (reduction) from one period to another period of time.

- *Total Worker Incidents (Total Incidents Ew):*

  The total worker incidents represent the sum of all the incidents generated for the different errors committed by workers.

  Total Incidents Ew = Incidents EOC + Incidents EOO + Incidents EMB

  Not all the errors committed by workers became incidents in the mine sites. Most of the errors are hidden in the operations until an incident or accident happens and an investigation is concluded determining the causes of the incidents, which find the possible errors that lead to the undesired event. The total incidents will be another variable to see how the experience and training influenced in the reduction of these undesired events.

- *Working days:*

  The time frame used in this study is 4200 days. According to Duffey, et al. (2004) it is necessary to consider between one hundred to two hundred thousand working hours to evaluate *human* failure. The time frame of 4200 days in the model was considered assuming the 100 000 working hours proposed by Duffey, et al. (2004) and the data collected from two different open pit mines with 24 working hours per day. In other words the division of 100 000 working hours by 24 working hours a day, gives as a result 4166 working days which is approximately 4200 days. Thus, for the purpose of the model presented in this research 4200 days or 11.5 years are considered as the time necessary to evaluate *human* failures and accidents in the mine sites. Moreover, the data collected from different mining companies is up to ten years period. This is also the second reason why the model is base in 11 years in order to compare the simulated and the observed data.

- *Experience Multiplier:*

  The experience multiplier is a graphical function where is determined how the experience of the worker increase on time. The next figure gives an idea of how the experience multiplier graph is represented in the model.

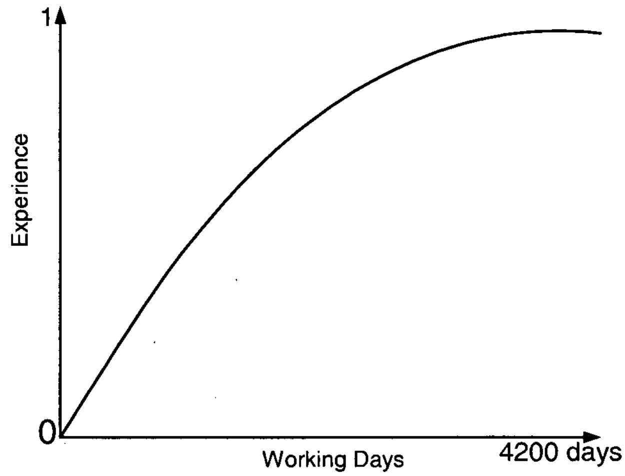


Figure 19 - Experience Multiplier

➢ *Training Multiplier:*

The training multiplier is another graphical function which is directly related to the number of errors and incidents occurring in the model. In other words, the more incidents happen, the bigger the training multiplier. Figure 19 shows how the training multiplier raises when incidents coming from human errors increase.

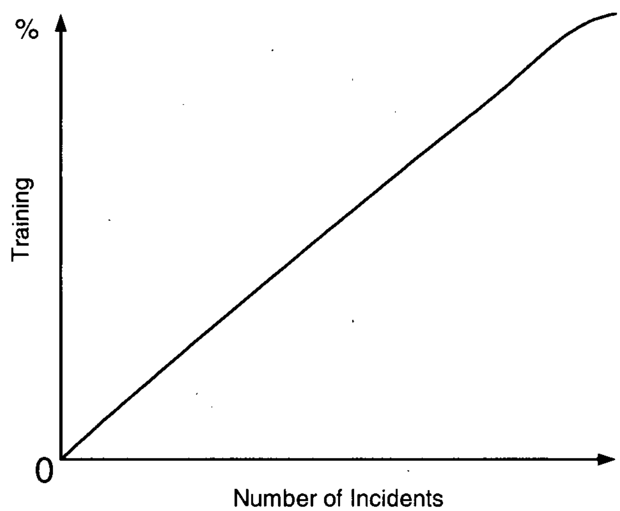


Figure 20 - Training Multiplier

From the graph above, it is seen that the training is represented in percentage. This percentage represents the number of hours invested in training compared with the total number of working hours during a period of time. From the data collected from different mines, it is observed that the maximum training goes up to 8%. For that reason, this model will use 10% as maximum training provided for the mining company to its workers depending on the number of incidents the occur at the mine site.

3.9.2 Combination of Errors

As mentioned in Chapter 2, not only workers make errors in a mining operation; there are also other errors which are bad decisions made by people who are in charge of the mine, these errors are called "latent errors". The difference between latent errors and worker errors is that the first ones are very difficult to detect unless an incident happen and an investigation determine the consequences. This type of errors is what Reason (1990) called latent errors.

It is assumed that a latent error does not lead to an incident by itself. But when this error is combined with a managerial (latent) error this combination necessarily leads to an incident. The occurrence of latent errors is difficult to quantify; for that reason, these kind of errors are assumed to follow a Bernoulli model similar to that of worker errors but with probability p_2 (see section 3.6.1)

Hence, the dynamic representation of combination of errors is shown in the following graph. It also shows the feedbacks necessary to reduce the number of management and worker errors.

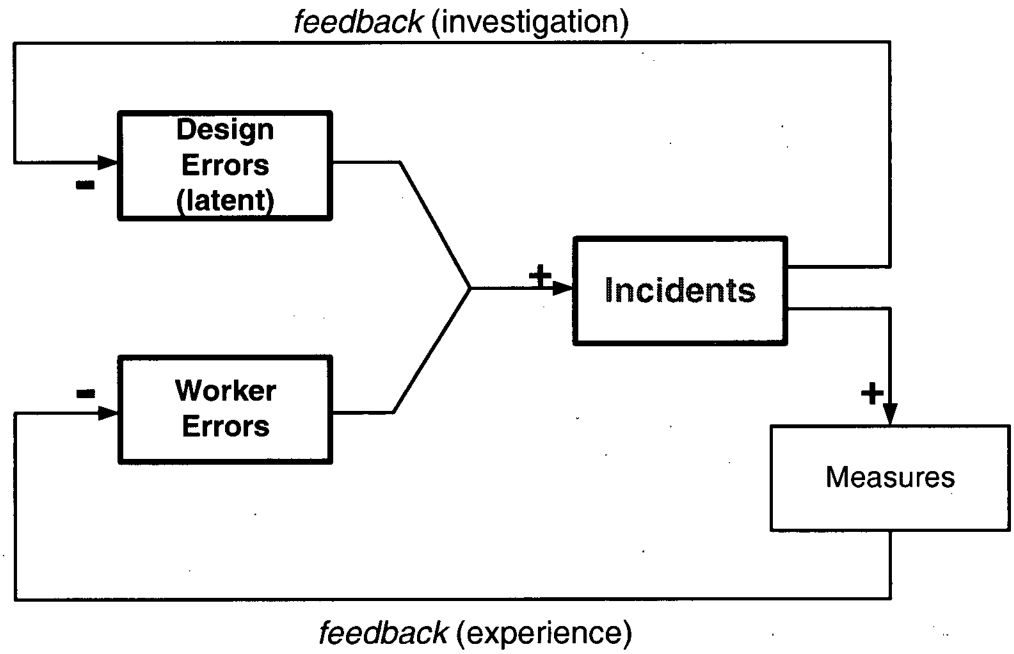


Figure 21 - Combination of errors leading to incidents.

From the previous figure it is observed that a management error combined with a worker error generate an incident. From the same graph it can be said that through feedback, management errors and worker errors can be reduced. However, in this case there are two different kinds of feedbacks with different frequencies.

The feedback for reducing management errors is the investigation that takes place after an incident. Once the consequences of the incident are determined, it is possible to correct the latent error and eliminate it from the total of latent errors that exist in the mining operation. The elimination of this error occur almost immediately after the cause of the incident is founded. Then, it can be said that the reduction of these errors is faster than those committed by workers.

On the other hand, the feedback for the reduction of worker errors is the same as explained in section 5.1.1. This reduction is through experience that workers get during a period of time. For this kind of feedback, there is a delay between the time the cause (error) of the incident in founded and the elimination of the worker error. This is because after the incident, the mining company has to implement new measurements to avoid the same kind of error, after that the managers have to let to know to all workers the new measurements and this can take some time.

The following graph represents all the variables used for the development of the dynamic representation of the combination of errors and feedback in the model. The complete model is presented in Appendix B of this study.

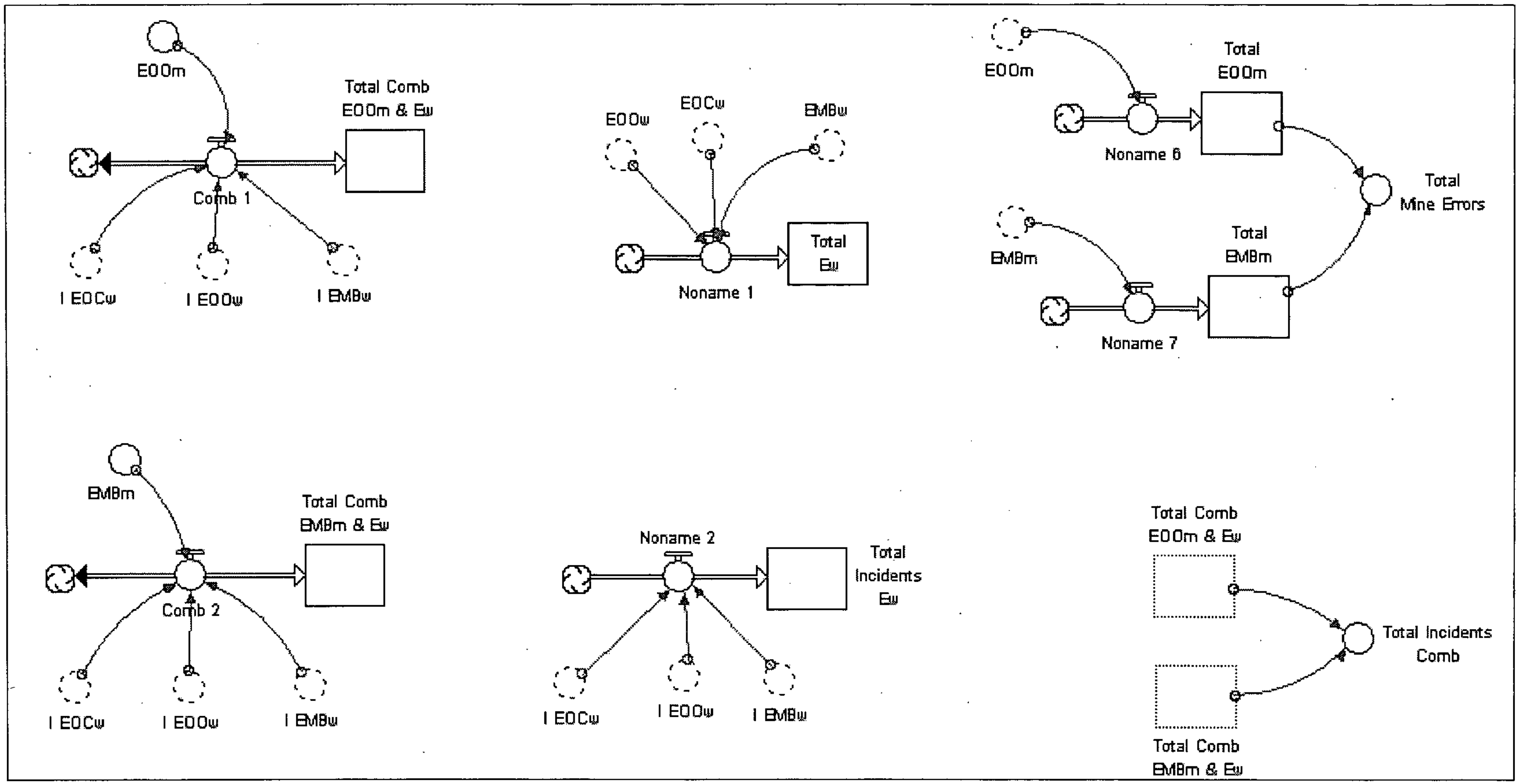


Figure 22 - Combination of errors

- *Management Errors (EOOm & EMBm):*

  It was mentioned before that there are two types of management errors: errors of omission mine and errors of mistaken belief mine. These errors have a random behavior and they are not discovered until an incident occurs.

  The management errors are combined with the three types of worker errors, with which they give the total combination (Total comb).

- *Total Combination (EOOm & Ew* and *EMBm & Ew):*

  The total combination is the sum of the combination of the two kinds of management errors with the three types of worker errors. This total combination will allow to determine how many latent errors were detected and eliminated; but it will not give much information about how many latent errors still in the mining operation.

The elimination or reduction of the management errors is very difficult to determine. When an incident happen, the error is corrected, thus the probability of committing the same error or similar is reduced and sometimes eliminated. However there is no possibility to find and eliminate all management errors.

For the development of this model it was assumed that the total management errors eliminated are equal to the total incidents generated by combination of errors.

$$\text{Total Combination of errors} = \text{Total incidents}$$

In other words, one latent error combined with one worker error necessarily leads to an incident.

4 SIMULATION, RESULTS AND DISCUSSION

4.1 Data Collection

In Chapter 2 it was mention that three mining companies provided the data for this research. The characteristics of these mines are that the three of them are open pit mines with five hundred workers each. Two of these mines produce gold and one of them produces copper. The data obtained from these companies are:

- Number of Incidents
- Number of Training hours
- Type of incidents
- Causes of incidents

The data was presented in tables as shown in Appendix D of this research. After that the author of this research has to determinate or codifies the type of errors that leaded to each incident (Appendix B). After that process of codifying, all the information was sent back to managers in the mining operations to validate if the type of error assigned for each incident was the correct. The process to obtain, codify and validate data took approximately six months.

4.2 *Simulation*

Banks (1998) defined simulation as *"the imitation of a real-world process or system over time"*. Simulation involves the generation of an artificial history in order to draw and represent the real characteristics of a real system. Simulation is often used to represent, describe, and analyze the behavior of simple or complex systems. Furthermore, simulation allows the representation of real and conceptual systems using "what if" questions.

Based on the previous paragraph, it is hoped that the values of the simulation of this research will be similar or close to the real values obtained from different companies. For that reason the simulation of this research is based on safety data (five years period) given by three different mines each with similar characteristics. These mines are open pit and each has approximately five hundred workers. Based on that information the parameters of the safety model presented in this document were adjusted to have values of the same magnitude as those obtained from real data. The following figure shows the number of incidents of Mine 1, Mine 2, and the simulation for a five year period.

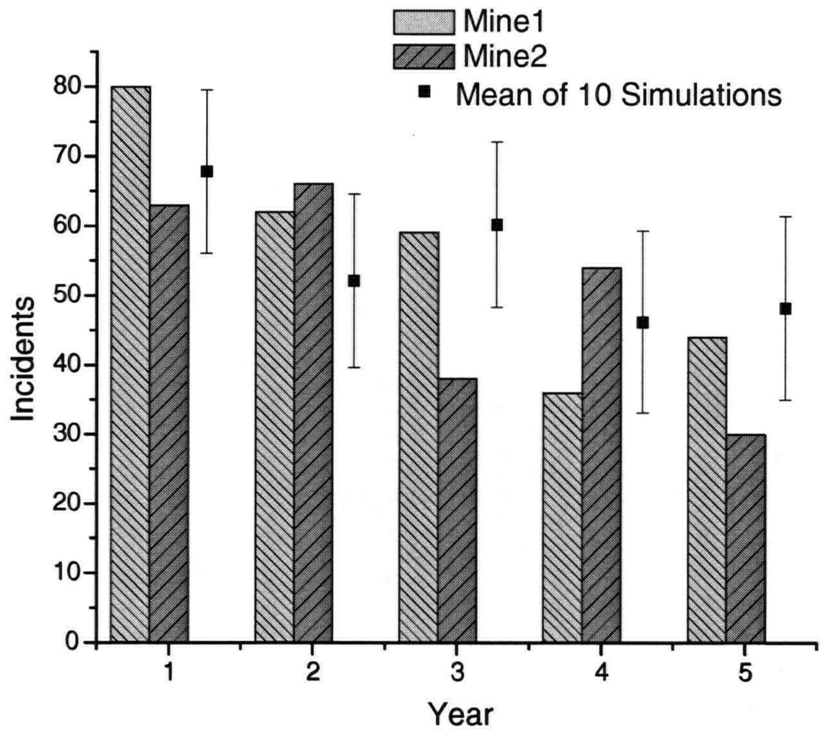


Figure 23 - Number of incidents of mines and simulation

Figure 23 shows the number of incidents in five years period of two different mines and the simulation of this research. The total number of incidents in five years period is 281 for Mine 1, 251 for Mine 2, and 274 for the simulation after ten runs. It is important to consider that because the number of errors and incidents in the safety model are generated randomly, every time the model is run the total number of incidents and errors will be different. However, the simulation numbers remain close to the observed values from the mines.

Table 2 shows the results of ten runs of the model in order to obtain an average of the number of incidents per year. Due to the random generation of values in the model, the number of incidents per year varies from year to year.

Year	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	Average
1	76	84	64	79	53	60	80	73	58	53	**68**
2	46	53	58	47	82	59	46	38	52	41	**52**
3	53	54	69	81	49	58	48	62	47	75	**60**
4	36	49	53	42	37	75	26	52	48	46	**46**
5	42	36	29	45	69	63	37	59	57	43	**48**
TOTAL	**253**	**276**	**273**	**294**	**290**	**315**	**237**	**284**	**262**	**258**	**274**

Table 2 - Number of incidents in five year period

4.3 Worker Errors

For the development of this model, two different scenarios were tested, where these scenarios can be considered as the best and worst situations to begin in a mining operation. The first scenario considers the situation that the mining company has to run a mining operation with workers that have low or have no experience at all in the mining industry. In the second scenario, a mining company starts its operation with workers that come from other mining operations and that can be considered experienced workers.

4.3.1 Scenario 1: Beginning with low experience

This first scenario is characterized by the low experience that most of the workers have when a mining operation begins. This low experience is due to different reasons:

Mining operation in an agricultural town:

When a mining operation begins its operations in remote areas, it is very difficult to bring miners with the enough expertise to work in the operation; for this reason, a mining company hires most of the 'front-line workers' (drivers, machinery operators, etc) from a local area. Most of these workers have never worked in a mining operation. Therefore, the average experience per worker when the operation begins is very low.

The mining company has to put a lot of effort in training these new workers not only in technical skills but also the company has to provide a good safety program for the workers.

To make it clear, the following figure shows how the experience of all the workers at the mining operation increases during time. This also shows how the maximum experience is reached when a training program is and is not given to workers.

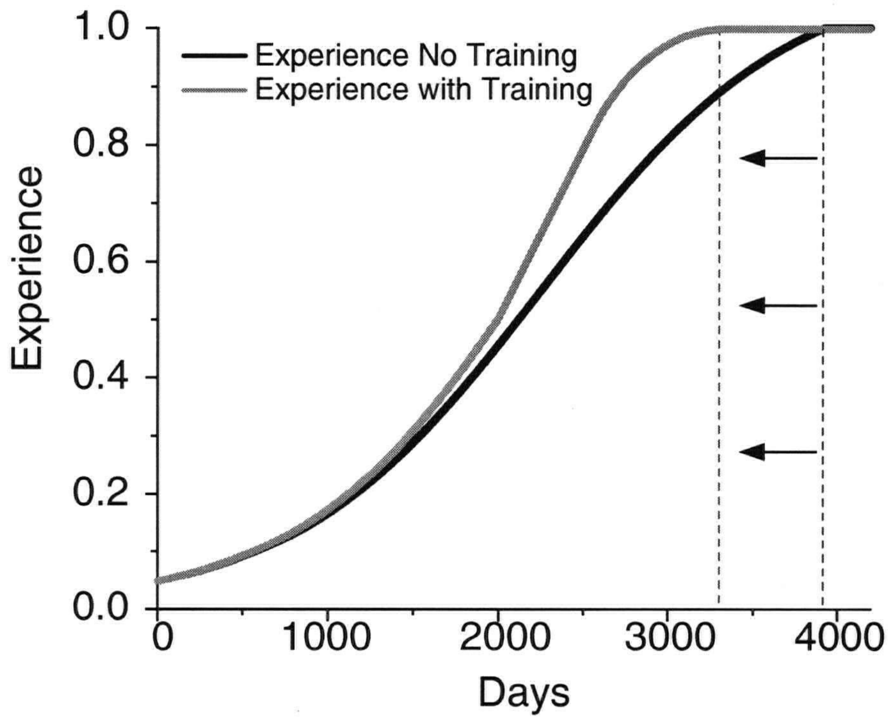


Figure 24 - Experience with and without training with low experience

From Figure 24, it can clearly be appreciated that workers reach the maximum experience faster when a training program is implemented. Without training, the mining operation needs almost 4000 working hours in order for its workers to have maximum experience.

On the other hand, with a training program the number of hours necessary to reach maximum experience has been reduced to 3300 hours. In other words the time to reach the maximum experience with a training program has been reduced by more than 18%.

Due to the low experience level at the beginning of the project, the number of incidents is very high. The number of incidents will be reduced if a training program is implemented as shown in Figure 25.

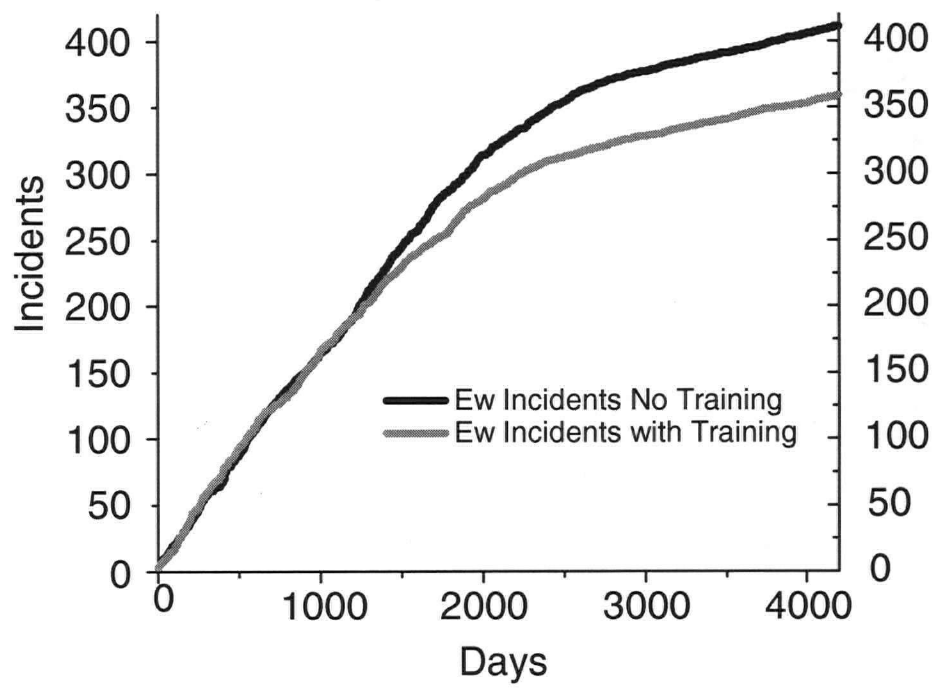


Figure 25 - Number of worker incidents with and without training beginning with low experience

The incidents without a training program can be more than 400 based in the mine life of 4200 days (approx. 11 years). However, with the implementation of the training program, those incidents are reduced to 350, a reduction of 13% of the incidents without training.

Figure 26 shows how the incident rate changes when inexperienced workers acquire more experience. The incident rate (the slope of the incident occurrence curve) decreases when workers have more knowledge, practice and safety commitment in the job they are performing.

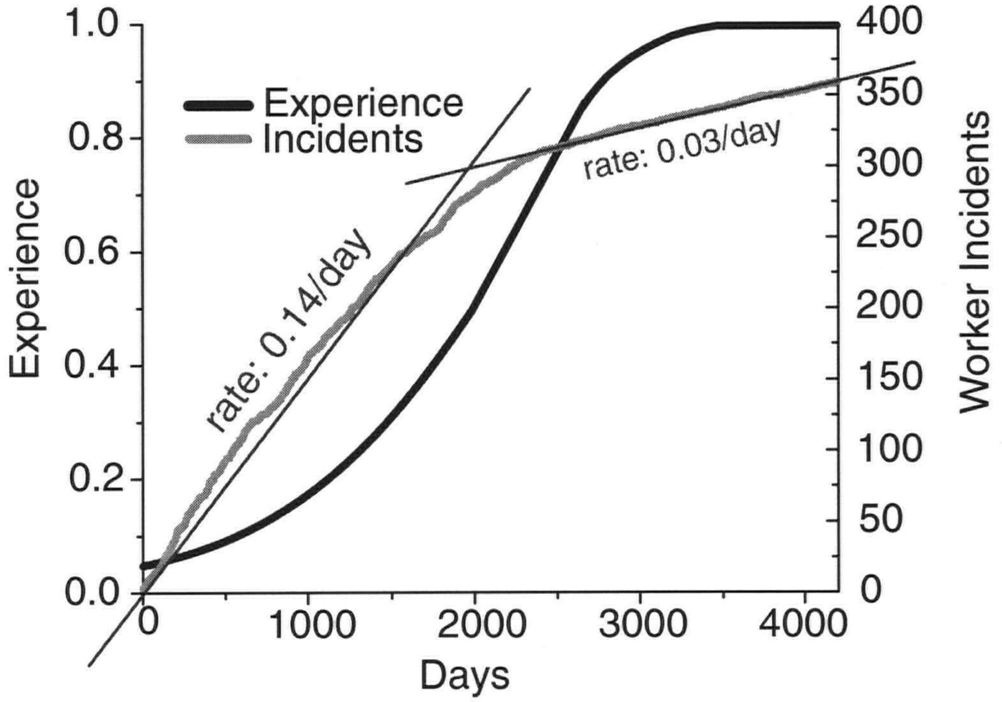


Figure 26 - Incident occurrences and experience beginning with low experience

For the first 2000 days, the incidents occur at a very fast rate of 0.14/day. However, after 2000 days and when workers have more experience, the incident rate has been reduced to 0.03/day.

4.3.2 Scenario 2: Beginning with high experience

In this second scenario it is described the best situation where a mining company begins its operation with most of the workers already experts in their jobs. Also in this scenario is considered that workers have a high safety commitment when they perform their jobs. Finally, due to the experience of the workers, most of them increase their knowledge and technical skills very fast when a training program is implemented. For that reason, reaching the maximum experience in this situation will be faster than beginning with workers with low experience.

The graph below shows two curves, one where workers perform their job with little or no training provided from the mining company, and in the second curve it is appreciated that even though the workers are considered experts, the mining company gives them a complete training program during the life time of the project. As it happened in the first scenario, the maximum experience is reached faster when a training program is provided than when it is not.

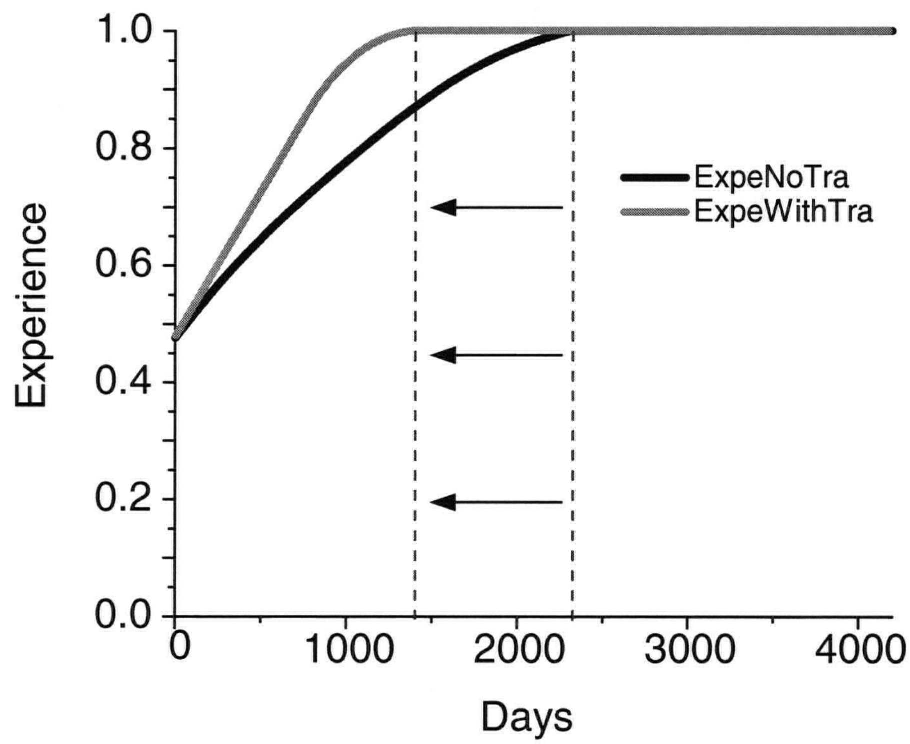


Figure 27 - Experience and training with high experience

From the graph above, the maximum experience is reached after two thousand seven hundred working hours if there is not a training program provided; however, if a training program is implemented, less than one thousand four hundred working hours will be necessary. In other words, the maximum experience is gotten in almost 50% of the time when a training program is implemented than when it is not.

Due to the high experience that workers have when a mining project begins, it is expected to have fewer errors and consequently less incidents during the life of the whole project. In the following graph, the number of incidents without training is more than 120 and the number of incidents with training is less than 75.

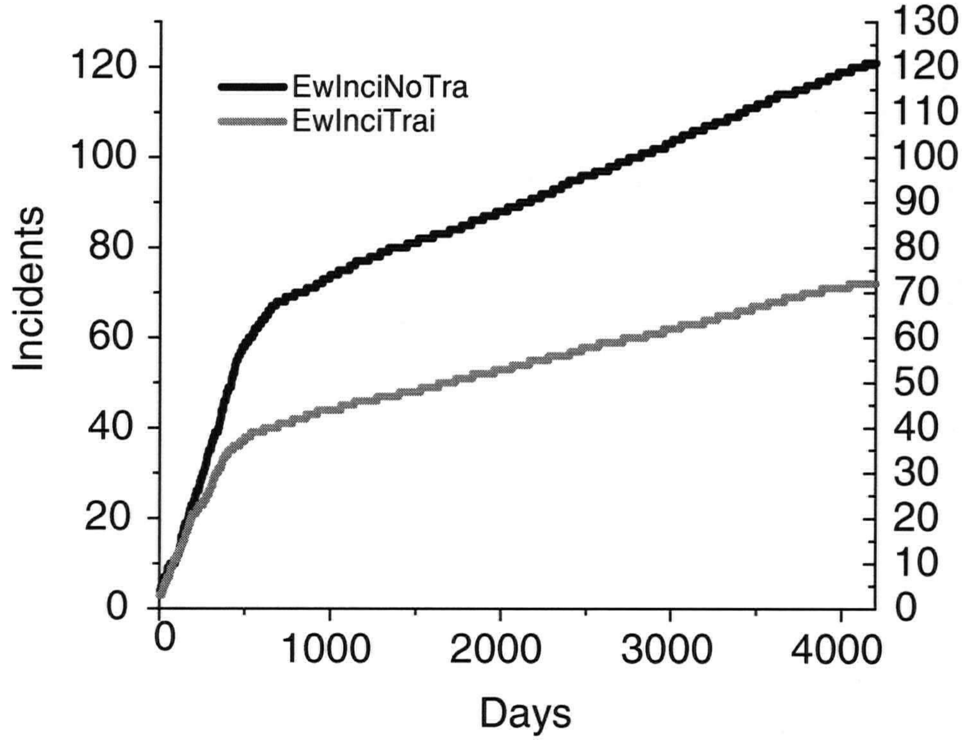


Figure 28 - Number of incidents beginning with high experience

Comparing Figures 26 and 29, the clear difference in the number of incidents when workers begin with low and high experience is shown. The number of incidents is almost three times less when people have the required knowledge, training and experience in their jobs than when they start with little or no experience.

Finally, Figure 29 is very clear showing how the incident rate changes when workers get more experience. In this case, it is seen that the incident rate begin very fast with a slope of 0.0730, this is because even though workers have experience, it will take some time until all of them understand their jobs in the new mining operation. On the other hand, the incidents rate decrease as the miner experience increase.

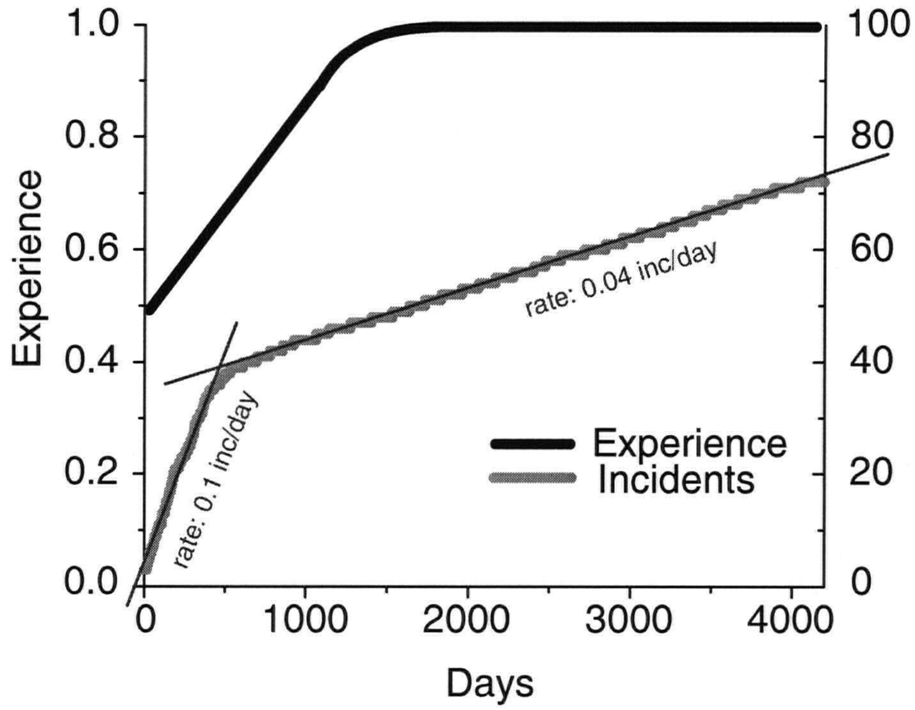


Figure 29 - Incident occurrences and experience beginning with high experience

The previous graph clearly shows how fast the incident rates change. This is explained because most of the workers in the mining operation are experienced and they are willing to perform their job as safe as possible. For that reason, the change in the incident rate can be appreciated in less than 500 working hours.

4.4 Results of Combination of Latent and Worker Errors

Previously it was mentioned that there are design errors or organizational errors which are not very easy to detect, fix, and eliminate; unless a combination with a worker error occurs. When a combination occurs, the probability of having an incident is very high. Following an investigation of the causes of the incident, it can be concluded that a latent error existed.

There are two kinds of latent errors assumed in this research: Errors of Omission Mine (EOOm) and Errors of Mistaken Belief Mine (EMBm). In order to evaluate the results of these types of errors, there are some considerations:

- *Total Latent Errors:*

  The total number of errors for EOOm and EMBm is the sum of each type of errors during the period of life of the mining operation. Each error occurs randomly and for that reason it is very difficult to predict when a new error will occur.

- *Incidents from Latent Errors:*

  In these types of errors, an incident occurs only when a combination with a worker error happens. Not all latent errors lead to incidents, for that reason the number of incidents of these types of errors is less than the total number of latent errors. As the occurrence of an error, the occurrence of an incident due to the combination of errors also happens randomly.

- *Fix of Latent Errors:*

  Most of the time, a latent error is found only when an incident occurs, however not only one latent error can be found and fixed after an incident happens, some time it is possible to find two or three latent errors which can be repaired in order to avoid a future incident. It is also assumed that after an incident, more than one latent error is fixed. For this research it is assumed that one, two or three latent errors can be fixed after an incident. The number of latent errors fixed occurs randomly.

Figures 31 and 32 show the results of total errors, incidents, and fixed errors for each type of latent errors (EOOm and EMBm).

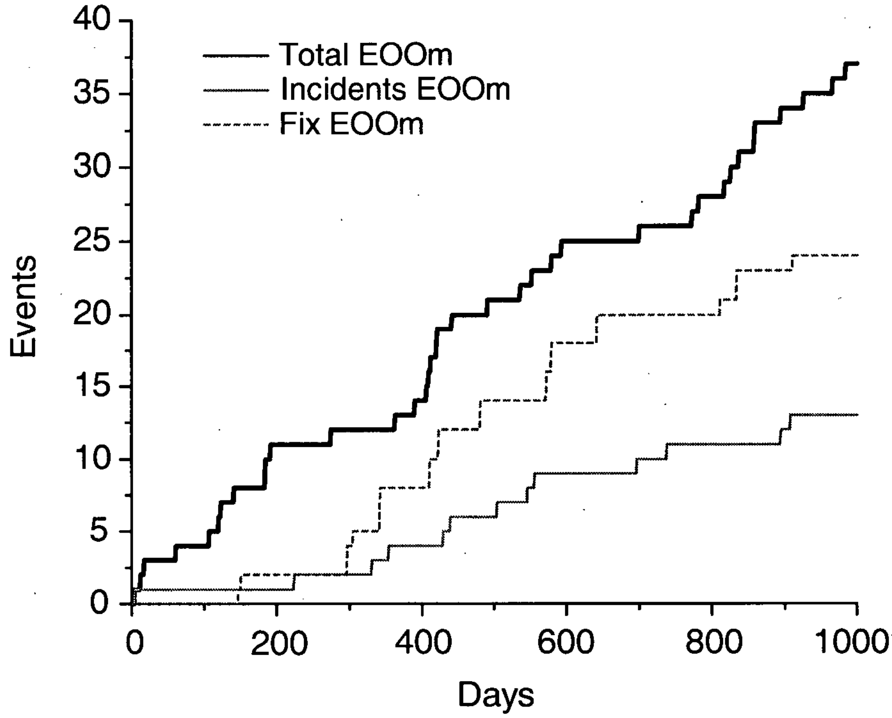


Figure 30 - Errors, incidents and Fix of EOOm

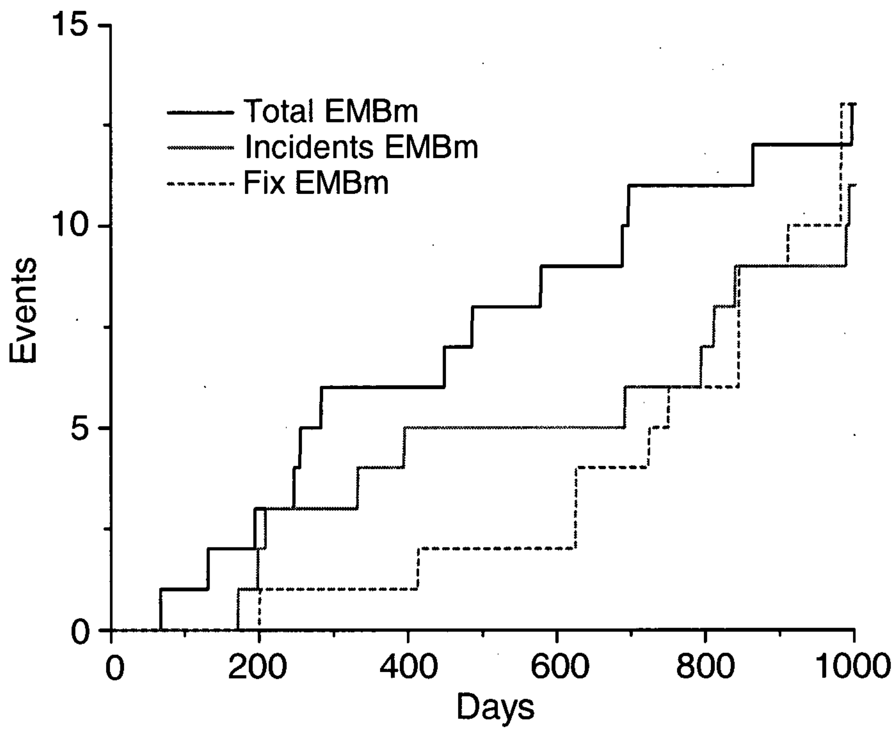


Figure 31 - Errors, incidents and Fix of EMBm

In Figures 31 and 32 three events of errors and incidents are shown to occur in 4200 days. The results for 1000 days are shown in order to have a better view of the graph; however, the complete graphs for 4200 days are shown in Appendix B.

- The first event of the two graphs is the total number of EOOm and EMBm errors that occur. In both cases an error occurs as soon as the mining operation starts. The total number of errors for EOOm is 136, and the total number of errors for EMBm is 57 during the 4200 day period. As discussed before, the probability of having an EOOm is higher than EMBm due to external causes such as production pressure. The EMBm is much less because it is assumed that in a mining operation, there are professionals who are aware of most of the working conditions of the mining operations, and who are very unlikely to commit an error of mistaken belief.

- The second event of the two previous graphs refers to the number of incidents that occur due to each type of latent error. Like human errors, the number of incidents follows a random distribution with probability of dependency given in the previous chapter. From the model, the total number of incidents occurred due to EOOm is 43, and the number of incidents occurred due to EMBm is 39. In this case the number of incidents is similar, this is because both type of errors have the same probability of becoming an incident. However, because the number of EOOm is higher than EMBm, the number of incidents is also higher but not in the same proportion.
  Note that there are periods of time where the number of latent errors keeps increasing, but not necessarily the number of incidents. In other words, the number of incidents for a period of time can be zero, even if more latent errors occur in the mining operation.

- The third event that is the fix of errors for EOOm and EMBm is also presented in Figures 31 and 32. The fixing of errors also follows a random distribution that has been arbitrary designated to fix one, two, or three latent errors at the same time. The time required to repair or eliminate those errors occur randomly.

Note that the latent error is not fixed as soon as it is detected (incident occurs), it can take some time. Depending on the type of latent error, the time to fix it can be very variable. Also, if one latent error is found, it is possible find and fixes other ones in the same period of time . For that reason, in the curve of the third event it can be appreciated that the increase of fixed errors is variable. The results of this model gives 102 and 47 fix errors for EOOm and EMBm, respectively.

Finally, from the results presented above, the remaining latent errors that can not be found and fixed are 34 for EOOm and 16 for EMBm. All the results for the different events of latent errors are presented in Appendix B.

4.5 *NET Errors (EOOm & EMBm)*

An interesting part of this research is observed when NET latent errors are plotted. The net latent errors are those referred to the difference between total latent errors and total fixed errors.

NET errors = Total errors – Fixed errors

The difference mentioned above is the combination of two different frequencies of worker errors and latent errors. It was mentioned before that in order to fix a latent error an incident might occur. Also, it was established that a latent error by itself will not lead to an incident; only the combination of worker and latent error will lead to an incident.

Two different frequencies of worker and latent errors were established in this model. The following graph shows that the rates for worker and latent errors are different. The solid curve represents the number of worker errors where the rate changes from 0.32 errors per day in the first 2500 days to 0.06 errors per day in the next 1700 days. On the other hand, the rate for latent errors is 0.057 errors per day during the 4200 days period.

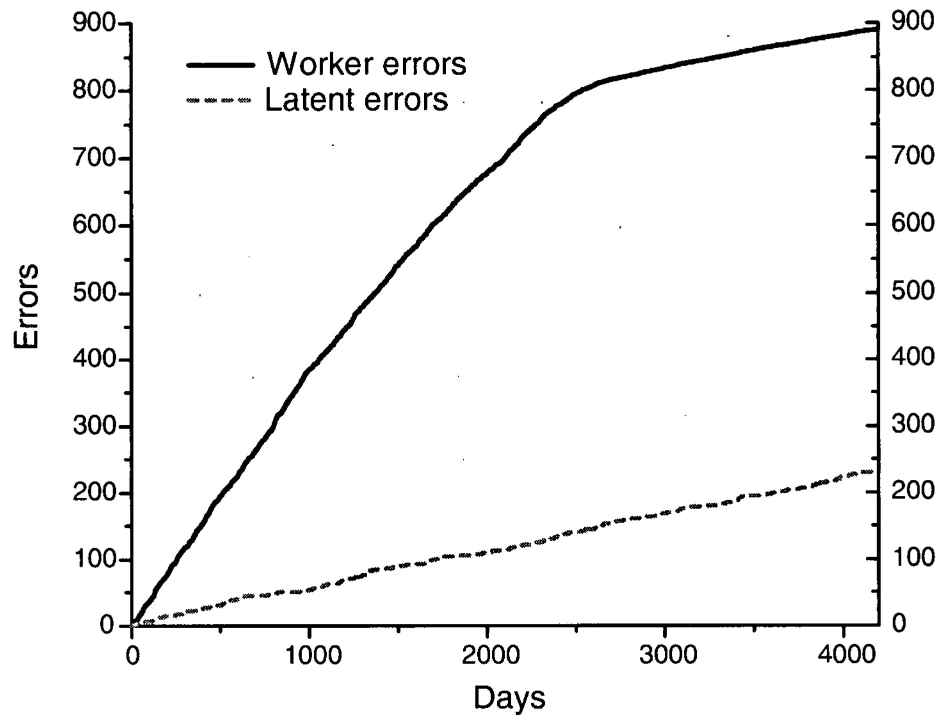


Figure 32 - Total number of Worker and Latent errors

Figure 33 shows the difference between two different frequencies of total errors and fixed errors. Although the net errors increase with time, there is evidence of oscillatory behavior in these curves. The reason for this is due to the presence of two different frequencies in the system – latent errors have a low frequency of occurrence whereas worker errors have a higher frequency. As a result a form of "beats" should occur when the two types of errors interact leading to incidents and repair or fixes. This phenomenon is a manifestation of the model with a reasonable physical explanation. However, it is not known if this behavior occurs in practice. There are many possibilities for influencing this behavior e.g. increasing the frequency of errors, such as a reduction in training effort or hiring people with low mining experience.

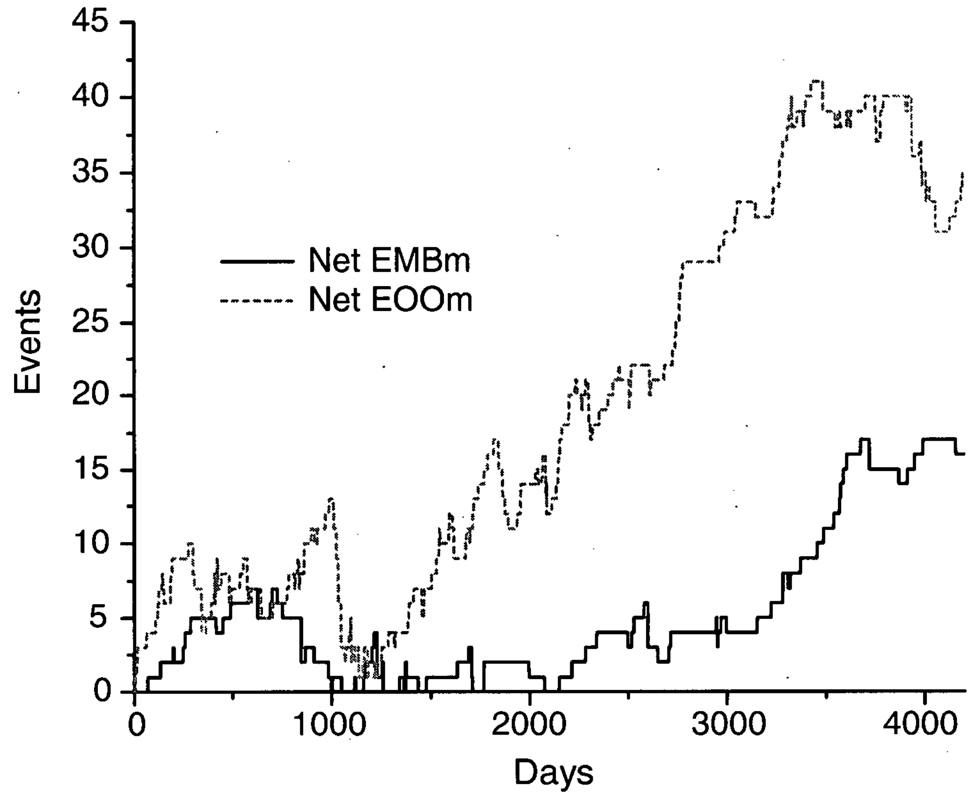


Figure 33 - Net latent errors (EOOm & EMBm)

4.6 Discussion

4.6.1 Worker errors

From the different graphs presented above, it can be observed that the number of incidents in the four thousand two hundred days is never flat. Some of the reasons for this are:

- *Short period of time:*

  According to Brown, et al. (2000) it is necessary to have at least one hundred thousand working hours to determine the probability of committing errors in any industry. For that reason, it was assumed in this research that the mining operation will last for a maximum term of twelve years; and during this short time it was not possible to see a flat incident rate line. It was only possible to see how the slope of an incident rate curve can change when the worker experience increases.

➢ *Excess of confidence:*

There are different authors such as Holmes, et al. (1997) and Mattila, et al. (1985) who establish that an excess of confidence contributes to human errors. When a worker obtains all the training, knowledge and practice in his/her job; he/she gets a lot of confidence in what he/she is doing. However, this confidence may lead to the worker performing the job without following simple safety rules such as wearing safety gloves when a tool is used. Due to the practice and knowledge in the job, any worker can assume that nothing will happen to him/her when is doing a job.

➢ *New Technology:*

Technology changes faster than twenty or thirty years ago. However, there are many workers who are not prepared for these changes. As mentioned at the beginning of this thesis, there are many workers who have been working for many years with particular equipment or in some particular manner, and who find it very difficult to change when a new procedure or technology is introduced in any mining operation. These workers are especially those who have been working in the industry for more than twenty years and they are unwilling to change. Even though after twenty years of work, these workers can be considered experts, when a change occurs they can be inexpert in the job, which increases the probability of committing an error.

Based on this, it is very difficult or at least very challenging to make the incident occurrence curve flat in any mining operation. The only thing that companies and workers can do is trying to minimize the number of incidents and hence the consequences of these incidents.

4.6.2 Combination of errors

Most of the latent errors occur when a new mining operation is starting. Due to the pressure for begin production, some latent errors appear and they are not detected in the short time, unless an accident occurs. From data of the mines used for this research, it can be concluded that most of the latent errors are in the mining operation itself and not in the plant. Some of the combinations of latent and worker errors in open pit operations are:

- *Lack of visibility on road*

  The transit of haul trucks in open pit operations is fluent and unstoppable. Due to the size of these machines the roads have to be repaired frequently. Some times due to the conditions of the road and the weather, some visible obstacles are created. These obstacles block the visibility of drivers especially in intersections. Due to the lack of prevention and obstacle fixing, it can be said that a new latent error appeared. Furthermore, if a driver does not pay attention to the road conditions and does not take precautions, he/she can have an incident that may or may not end in terrible consequences.

- *Confined Spaces*

  Another typical latent error from the obtained data is the confined spaces. Most of the time, pumps are installed in confined areas when a mining operation begins. After some years these pumps required maintenance. A mechanic gets into the confined space to repair a pump. Some times this worker overestimates his/her expertise and performs his/her without taking basic precautions like wearing safety gloves. Due to the confined space to maneuver tools and the lack of safety precautions, the worker can damage his/her hand. This is another example of how a confined space can be a latent error. Even though there have been many injuries due to confined spaces, mining operations still having important machineries installed in places difficult to access.

More examples of combination of errors are presented in Appendix A.

5 CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

The following conclusions are based on the basis of the dynamic model presented in this thesis.

- Even though there have been many studies about mining safety, none has tried to make quantitative models; for that reason, the first conclusion is that it is possible to develop a quantitative model of safety in mining operations.

- Several assumptions are made in the current model:
  - Values of probabilities of human errors and incidents
  - Human errors are unavoidable, but error rate can be reduced with training and experience, including experience due to the occurrence of an incident.
  - A level of experience can be reached faster if a training program is implemented
  - Latent errors alone do not lead to an incident

- The model developed agrees with available observations in terms of number and rate of incidents. However, it is very difficult to completely verify the model without further data. If the model were to be used at a particular mining operation, it would have to be adjusted and calibrated to achieve agreement with available safety data at that operation.

- The model exhibits some interesting oscillatory behavior when interactions between latent errors and worker errors are considered. This is due to the different frequencies of these two types of errors. It is not known if this behavior occurs in practice.

5.2 Recommendations

From the study presented, the following recommendations have been made.

- In future work assumptions must be relaxed to make the results more realistic. For example, it is assumed that the occurrence monotonically with the number of working days and training, and the experience, in turn, leads to fewer errors and incidents. In reality, the increase in experience may not be smooth and the actual relationship between experience, training and error and incident reduction is not known. It may be possible to establish more realistic relationships at a particular mine using periodic surveys that estimate the number of errors of commission, omission, and mistake belief committed by employees, whether or not they lead to incidents. This might be done without prejudice by anonymous surveys or by interviews done by consultants. Combined with incident records and employee records of years of experience and hours of training, the actual relationship between experience, working hours, training, errors and incidents could be measured.

- A labor model that includes hiring, attrition, and different experience levels within the labor force should be incorporated in order to make the model more representative of possible changes in the labor force at a mine.

- The study, quantification and modeling of safety in mining operations have not been developed for many researchers and companies. It is necessary to make more deeply studies in this topic in order to give mining companies and specially workers the required information to work more safely every time.

- The oscillations occurring in NET errors are manifestations of the model due to the presence of two different error frequencies in the model. However further study is required in order to determine if these oscillations actually occur in a mining operation.

BIBLIOGRAPHY

Adler, P. and K. Clark (1991). "Behind the Learning Curve: A Sketch of the Learning Process." Management Science **37**(3): 267-281.

Bandener, N. (2005). "User Interfaces of Safety-Critical Systems: The Management Oversight and Risk Tree." Universität Paderborn.

Banks, J. (1998). Handbook of Simulation, John Wiley & Sons, Inc. 3-30.

Baron, M. M. and E. M. Paté-Cornell (1999). "Designing Risk-Management Strategies for Critical Engineering Systems." IEEE Transactions on engineering management **46**(1): 87-100.

BHP-Billiton (2005). "A Sustainable Perspective." BHP Billiton Sustainability Report.(available at: http://sustainability.bhpbilliton.com/2005).

Brown, K. A., P. G. Willis, et al. (2000). "Predicting safe employee behavior in the steel industry: Development and test of a sociotechnical model." Journal of Operations Management **18**(4): 445-465.

Clifton, R. W. (1998). "Keeping injuries at bay: Why it's up to management." Occupational Hazards **60**(9): 57-59.

Cooke, D. L. (2003). "A system dynamics analysis of the Westray mine disaster." System Dynamics Review **Volume 19, Issue 2 ,**: 139 - 166.

Department_of_Mineral_Resources (2000). A Study of the Risky Positioning Behavior of Operators of Remote Control Mining Equipment (Report no. 5004). Sydney, New South Wales, Australia: Department of Mineral Resources, In C.J. Pitzer (ed).

Devore, J. L. (2004). Probability and Statistics for engineering and the sciences. Canada, THOMSON brooks/cole.

Doyle, J. K. and D. N. Ford (1998). "Mental models concepts for system dynamics research." System Dynamics Review **14**(1): 3-29.

Duffey, R. and J. Saull (2002). Know the Risk. Boston, USA, First Edition, Butterworth and Heinemann.

Duffey, R. and J. Saull (2004). "The Probability and Management of Human Error." 12th International Conference on Nuclear Engineering(April 25-29 Virginia, USA).

Einarsson, S. (1999). "Human error in high hazard systems: Do we treat the problem in an appropriate way?" Journal of Risk Research **2**(2): 115-128.

FAA (2000). "Federal Aviation Administration System Safety Handbook." Federal Aviation Administration(December 30, 2000).

Forrester, J. W. (1961). Industrial Dynamics. Waltham, MA, Pegasus Communications.

Gertman, D. I. (1992). "INTENT: A Method for Estimating Human Error Probabilities for Decision-based Errors." Reliability Engineering and System Safety **35**: 127-137.

Gertman, D. I. and H. S. Blackman (1994). Human Reliability and Safety Analysis Data Handbook. New York, John Wiley & Sons, Inc.

Gillen, M., S. Kools, et al. (2004). "Construction workers' perceptions ofmanagement safety practices: A qualitative investigation." Work **23**(3): 245-256.

Gillen, M., C. McCalla, et al. (2004). "Construction managers' perceptions of construction safety practices in small and large firms: A qualitative investigation." Work **23**(3): 233-243.

Green, M. (2003). "Human Error in Medicine." ExpertLaw(Available at: http://www.expertlaw.com/library/malpractice/medical_error.html#1).

Helmreich, R. L. and A. C. Merritt (2000). "Safety and Error Management: The role of Crew Resource Management." University of Texas(Aviation Resource Management pp. 107-119).

Hollnagel, E. (1993). "Human Reliability Analysis Context and Control." London: Academic Press.

Holmes, N., T. J. Triggs, et al. (1997). "Occupational injury risk in blue collar, small business industry: Implications for prevention." Safety Science **25**: 67-78.

Hyland, P. and L. Vrazalic (2005). "Applying a Taxonomy of Error in Usability Testing." University of Wollongong(Available at: http://www.dsl.uow.edu.au/publications/techreports/hyland03applying.pdf).

Kirkwood, C. W. (1998). "System Dynamics Methods: A Quick Introduction." College of Business - Arizona State University.

Kohn, L., J. Corrigan, et al. (1999). To Err Is Human: Building a Safer Health System. Washington, DC, NAtional Academy Press.

Laurence, D. (2005). "Safety rules and regulations on mine sites – The problem and a solution." Journal of Safety Research **36**(1): 39-50.

Laurence, D. C. (2002). "Learning Safe Work Behavior - A New Tool for the Mining Industry." Proceedings NSW Minerals Council OHS Conference **Terrigal, 1-3 August,**.

Luxhøj, J. T. and K. Kauffeld (2003). Evaluating the Effect of Technology Insertion into the National Airspace System. Department of Industrial and Systems Engineering. New Brunswick New Jersey, The University of New Jersey.

Mattila, M. and J. Lepisto (1985). "Accident Prevention - A survey of the Current Performance." Report from the Workshop Effectivering av Olycksfallsbekampning.

Reason, J. (1990). Human Error. U.K:, Cambridge University Press 1990.

Reason, J. (2000). "Human Error: Models and Management." British Medical Journal **320**: 768-770.

Roberts KH, B. R. (2001). "Must accidents happen? Lessons from high-reliability organizations." Academy of Management Executive **15**(3): 70-79.

Rundmo, T. and A. R. Hale (2003). "Managers' attitudes towards safety and accident prevention." Safety Science **41**(7): 557-574.

Safety (May 2002). "Avoiding Disaster." World Mining Equipment(available at: http://www.intecvideo.com/AvoidingDisaster.htm).

Safety_On-line (2001). Available at http://www.safetyonline.com.au/industry_wrap/default3.asp.

Senders, J. W. and N. P. Moray (1991). HUMAN ERROR: Cause, Prediction, and Reduction. Hullsdale, New Jersey, Lawrence Erlbaum Associates, Publishers.

Society_of_Automotive_Engineers_(SAE) (2000). "Aerospace Recommended Practice ARP5580: Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications."

Starr, C. and C. Whipple (1982). "Coping with nuclear power risks: the electric utility incentives." Buchanan JR, editor. Nuclear safety **1**: 1-7.

Sterman, J. D. (2000). Business Dynamics - System Thinking and Modelling for a Complex World. Boston, Irwin McGraw-Hill.

Sweeney, D. E. (2003). The Ethos of Errors: Analyzing Investigations of Industrial Events. Civil and Environmental Engineering. Edmonton, University of Alberta: 202.

System_Dynamics_Society (2005). available at: http://www.systemdynamics.org/ **accessed: November 2005**.

Texas_Workers'_Compensation_Comission (2005). "Fault Tree Analysis." Workers health & Safety Division. Safety Education & Training Programs(Available at: http://www.tdi.state.tx.us/wc/information/videoresources/documents/stpfaulttree.pdf accessed: January 2006).

The_Mining_Associaton_of_British_Columbia (2005). "Mining Safety Record is No Accidents." Available at http://www.mining.bc.ca/media_whats_new/documents/MiningSafetyRecordNewsRelease_000.pdf.

University_of_Washington (1998). "Achieving a safe and Healthful Workplace: Perspectives from Management, Labor and Government in Washington State."" Policy Analysis & Program Evaluation Initiative Department of Environmental Health.

Weber, W., H. Tondok, et al. (2004). "Enhancing software safety by fault trees: experiences from an application to flight critical software." Reliability Engineering & System Safety **89**(1): 57-70.

Weibull.com (2005). "FMEA and FMECA An Overview of Basic Concepts and Directory of Other Resources." http://www.weibull.com/basics/fmea.htm **Accessed December 2005**.

Whittingham, R. B. (2004). The Blame Machine: why human errors cause accidents. Great Britain, Elsevier Butterworth-Heinemann.

Zohar, D. and G. Luria (2003). "The use of supervisory practices as leverage to improve safety behavior: A cross-level intervention model." Journal of Safety Research **34**(5): 567-577.

APPENDIX A

HUMAN ERRORS

All the incidents that occur in a mine site due to human error vary from mine to mine. There are different and uncountable human errors that may or may not lead to an incident. Nowadays, big mining companies are putting a lot of effort in the prevention of injuries in the mining operations. Most of these big companies are documenting each of the incidents that occur in the mine sites, even if an incident did not have big consequences.

Due to this documentation, many workers and managers are aware of the possible hazards that may appear in any operation. Also, with this documentation, workers can prevent an incident, avoiding mistakes that a co-worker made in the past.

Even though, mining companies are putting a lot of effort in mining safety, human errors and incidents still happen; thus, more documentation appear each year. The table below describes some of the incidents that occurred in mining operations; also it will be possible to see what the causes of each incident are and which the human errors that led to that incident were.

Many mining companies have data sheets more complex than the one we present below; some of those data sheets contain information like:

1. Incident	2. Description
3. Causes	4. Action
5. Contact	6. Status
7. Root cause	8. Root cause action plan

Note that the incidents in the table below were documented for a mining company in the last five years; also the human errors in the table below were added after the approval of experienced safety managers in two different mining operations.

Table 3 Incidents and Type of Errors

	INCIDENT	DESCRIPTION	CAUSES	ERROR
1	**Damaged haul truck**	Haul truck was hit by a frost chunk from the bucket of a shovel.	- Failure to follow established procedures - lowering truck before tripping - The haul truck positioned farther away from the shovel prevented the operator from lowering the bucket - Due to grade restrictions the shovel was not set up in an ideal situation.	**EOOw + EOOm**
2	**Damaged pick up**	An operator was driving a pickup truck returning from the pit when he came in contact with a crew bus.	- Roads were in poor condition due to warm weather causing excess mud and water accumulation and ice formation during the morning hours. - Driving fast down a slope and not aware of ice condition under mud. - Driver is unfamiliar with the use of ABS brakes	**EOOm + EMBw**
3	**Leach plant operator sustained burns to his knees.**	While kneeling down to clean the moly dryer, a Leach Plant Operator pulled some of the hot moly out onto his knees causing burns to them.	- The operator neglected to wear the personal protective equipment to perform the work in question.	**EOCw**
4	**Forklift out of control**	An electric forklift being operated went out of control and struck a support leg on one of the racks. There were no injuries and damage was limited to one section of the rack.	- Electrical system malfunction resulting in loss of steering and dynamic braking. - Lack of inspection before using the forklift. - Plant operation manager was aware of the electrical and mechanical problems of the forklift.	**EOCw + EOOm**

	INCIDENT	DESCRIPTION	CAUSES	ERROR
5	**Damaged bus**	Drill machine hit a bus.	- Mechanical failure - right propel quite, causing the drill to lurch sideways, hitting the bus. - Human error. The drill operator was busy trying to get the drill to work and did not think he had parked the bus close enough to the drill to actually hit.	**EMBw**
6	**Improper switching procedure**	Contacted energized line while putting on grounds.	- This accident was caused because only two out of three of the necessary switches were opened before starting work. - Both workers were inexperienced on this switch system and thought that they were opening the correct switches.	**EMBw** **+** **EOOm** Lack of training
7	**Operator sustained a pinched finger**	Worker was loosing hold down bolts when the combination wrench which he was using pinched his finger in between the wrench and the frame.	- Confined space. - Worker was not using safety gloves.	**EMBm** **+** **EOCw**
8	**Dozer shovel loss of control**	Dozer shovel lost traction while pilling mobile substation up a grade of approximately 10%. The substation and dozer slid down the hill approximately 15 meters until the substation jackknifed and turned onto its side. There was no apparent damage to the dozer and the operator was not injured. Approximately 1 liter of transformer oil was released.	- Snowy, slippery road conditions caused the dozer to lose traction. - Operator was in a hurry to get the substation for the blast. As a result, he misjudged the ramp conditions and chose to pull the substation rather than calling for grading and sanding ramp. - The top of the ramp was very steep and rough were the shovel's bench intersected with interior ramp to the pit botton. - The cable buggy is an 824 wheel dozer, if an 834 was used it may not have started spinning and lost traction.	**EOOw** **+** **EOOm**

	INCIDENT	DESCRIPTION	CAUSES	ERROR
9	**Injured mill operator**	While removing a shovel tooth from a Crusher, the worker slipped off a plank and fell 6 feet onto rock injuring his shoulder.	- The scaffold plank that was used to access the feeder was not anchored properly. - The scaffold plank that was used did not have cleats on the bottom to prevent it from slipping.	**EOOw**
10	**Explosives Incident**	A slurry truck being operated on a blast pattern drove over four boosters and detonators. These were not attached to the blast pattern. There was no detonation, no injuries and no other equipment damage associated with this incident.	- The pumper operator did not see the four boosters/detonators as they were obscured by the drill cuttings - Multiple attention demands of traveling on the blast pattern, trying to navigate between the blast holes and look to see where the primed blast holes were.	**EOOw**
11	**Welder pinched arm between man basket & shovel**	While maneuvering a man basket into place to install a handrail at front of the catwalk on a shovel, the worker pinched his arm between the man basket and the shovel	- The worker inadvertently swung the man basket to the left, pinching his arm in the process. - A combination of poor function, and setup, as well as worker having his arm outside the man basket and not using handholds caused this incident.	**EMBw**
12	**Worker stuck on elbow by shell lifter**	While removing ball mill lifters from the shell of Ball Mill, a shell lifter struck worker's left elbow.	- No clear communication as to when the outside people were done knocking in the liners. - No waiting until liners were all completely knocked in. - Removing the bottom rows before the top rows, working under loose liners.	**EOCw**
13	**Equipment operator injured back while lifting 8x8 timber**	While lifting an 8x8 timber, the worker injured his back.	- Human error. Equipment Operator lifted 8x8 timber with his body causing pain to his back. Worker didn't follow procedure to lift heavy equipment.	**EOCw**

APPENDIX B

Simulations

For the purpose of this research, human errors, experience, and number of incidents have been simulated many times. The following graph presents how the incident rate reduces when workers get more experience in the jobs they are performing. In this case, it is assumed that the mining operation begins with some experienced people that in proportion to the total workers, the average experience can be qualified as medium.

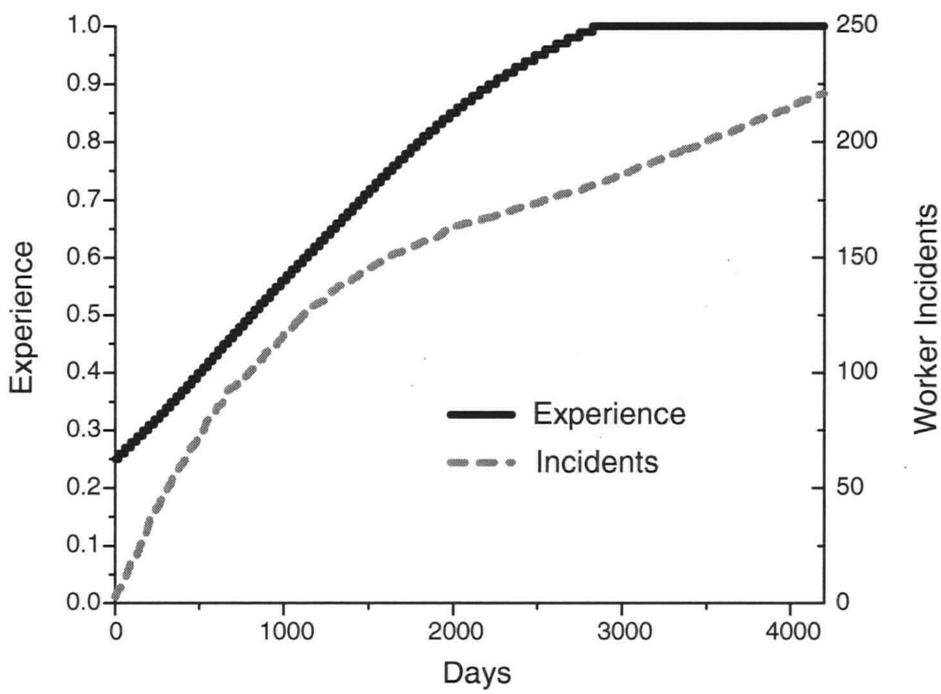


Figure 34 - Experience and Incidents with training with medium experience

From the previous graph it can be seen that when workers begin with medium experience, they will reach the maximum experience approximately in 2800 days. At the same time the incident rate reduces after one thousand working days.

In the following graphs, the total number of incidents that occur due to the combination of errors between latent and worker errors are presented. As it was explained before, the total number of errors and incidents coming from EOOm are more than those coming from EMBm.

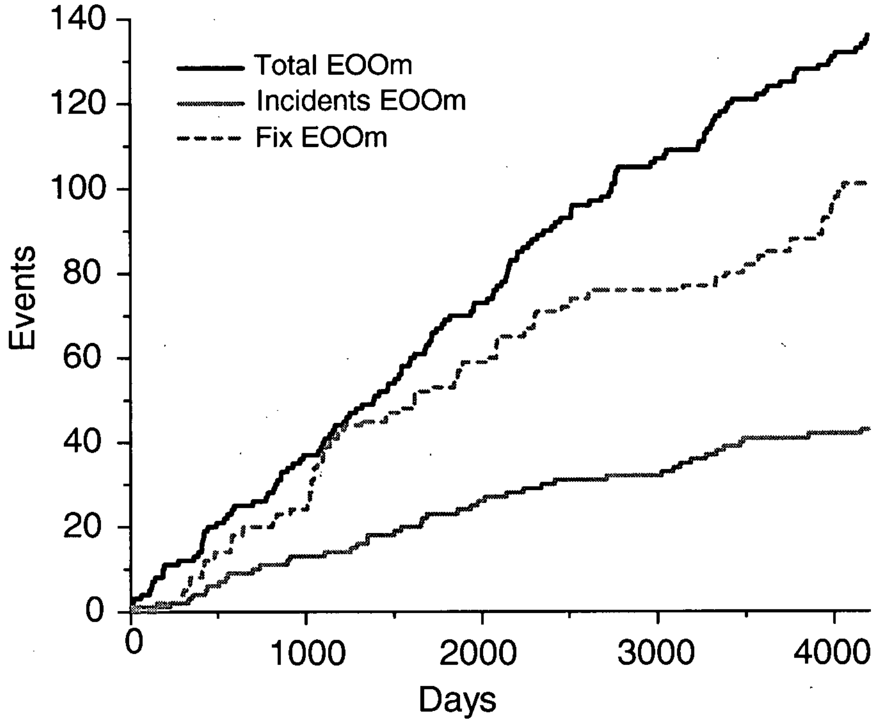


Figure 35 - Total events for EOOm

	Days(X)	TotalEOOm(Y)	IncidentsEOOm(Y)	FixEOOm(Y)
4178	4177	134	43	101
4179	4178	134	43	101
4180	4179	134	43	101
4181	4180	134	43	101
4182	4181	134	43	101
4183	4182	134	43	101
4184	4183	134	43	101
4185	4184	134	43	101
4186	4185	135	43	101
4187	4186	135	43	101
4188	4187	135	43	101
4189	4188	135	43	101
4190	4189	135	43	101
4191	4190	135	43	101
4192	4191	135	43	101
4193	4192	135	43	101
4194	4193	135	43	101
4195	4194	136	43	101
4196	4195	136	43	102
4197	4196	136	43	102
4198	4197	136	43	102
4199	4198	136	43	102
4200	4199	136	43	102
4201				

Table 4 Total events for EOOm

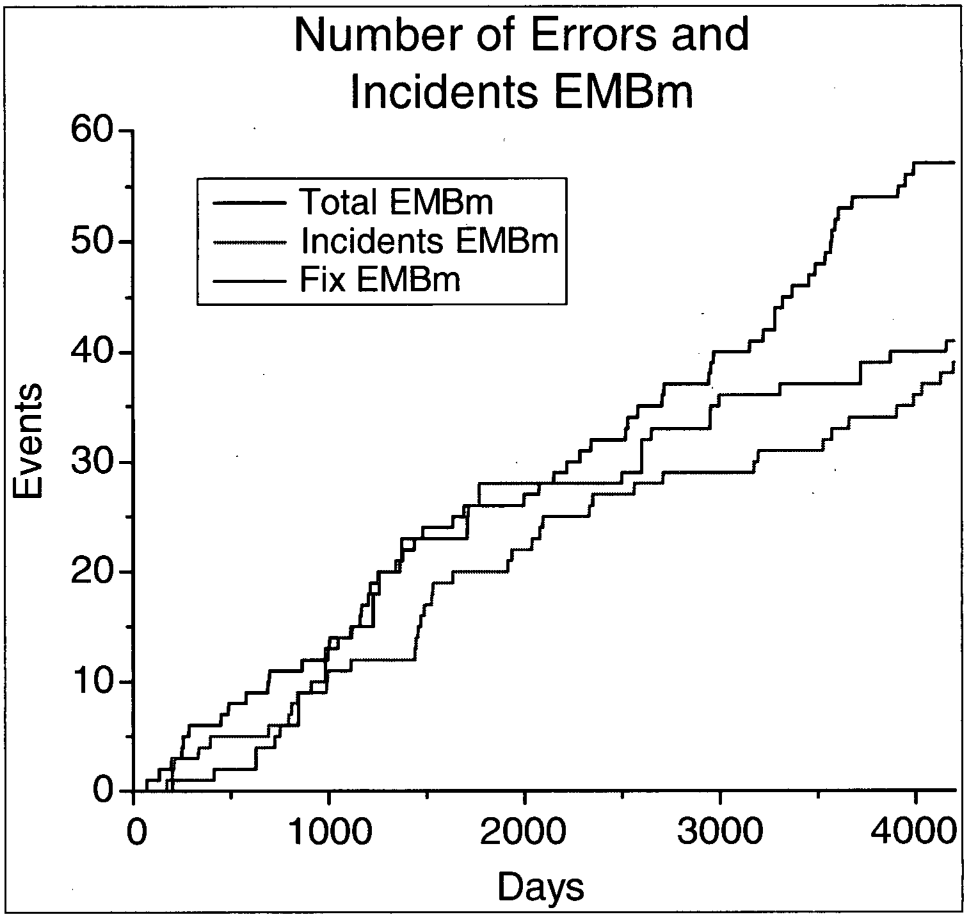


Figure 36 - Total events for EMBm

	Days[X]	TotalEMBm[Y]	IncidentsEMBm[Y]	FixEMBm[Y]
4180	4179	57	38	41
4181	4180	57	38	41
4182	4181	57	38	41
4183	4182	57	38	41
4184	4183	57	38	41
4185	4184	57	38	41
4186	4185	57	38	41
4187	4186	57	38	41
4188	4187	57	38	41
4189	4188	57	38	41
4190	4189	57	38	41
4191	4190	57	38	41
4192	4191	57	38	41
4193	4192	57	38	41
4194	4193	57	38	41
4195	4194	57	38	41
4196	4195	57	39	41
4197	4196	57	39	41
4198	4197	57	39	41
4199	4198	57	39	41
4200	4199	57	39	41
4201				

Table 5 Total events for EOOm

APPENDIX C

Safety Model (variables)

In this appendix the complete safety model developed for this research is presented. The software used was iThink ® (High Performance Systems, Inc.). The model has been divided in five parts which are:

- Worker errors
- Worker incidents
- Experience
- Latent errors
- Combination of errors

Worker errors are basically the random generation of each type of error (EOC, EOO, EMB). Each error has different probabilities, and the sum of all these errors gives the total worker errors, also called active errors.

Worker incidents are the probability of becoming a worker error into an incident. For this research it is assumed that each error has the same probability of becoming an incident. It doesn't mater the type of error committed, the consequences will be the same.

Experience is the graphical function presented in this research in order to establish the average knowledge or skills for workers when the mining operation begins.

Latent errors are those generated randomly for managers and people responsible for the main decisions of any project into the mining operation. In this fact, only two kinds of latent errors were evaluated in this research; errors of omission mine and errors of mistaken belief mine. Each of these errors has different probability of occurrence.

Combinations of errors are those generated when a latent error is combined with an active error. In this research it is assumed that no latent error alone will lead to an incident, however the combination with an active error may lead to an incident with or without terrible consequences.

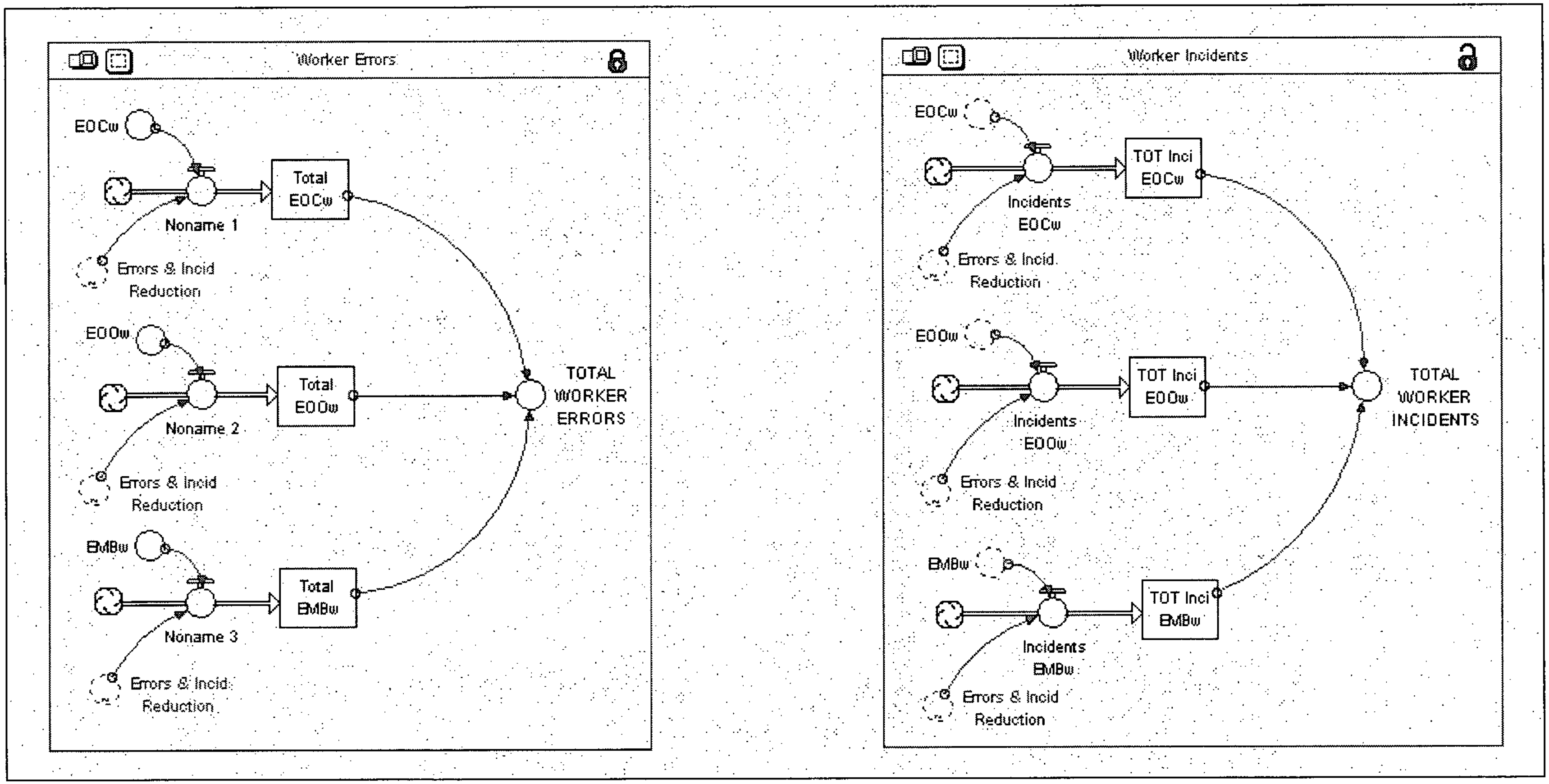


Figure 37 - Errors and incidents from workers

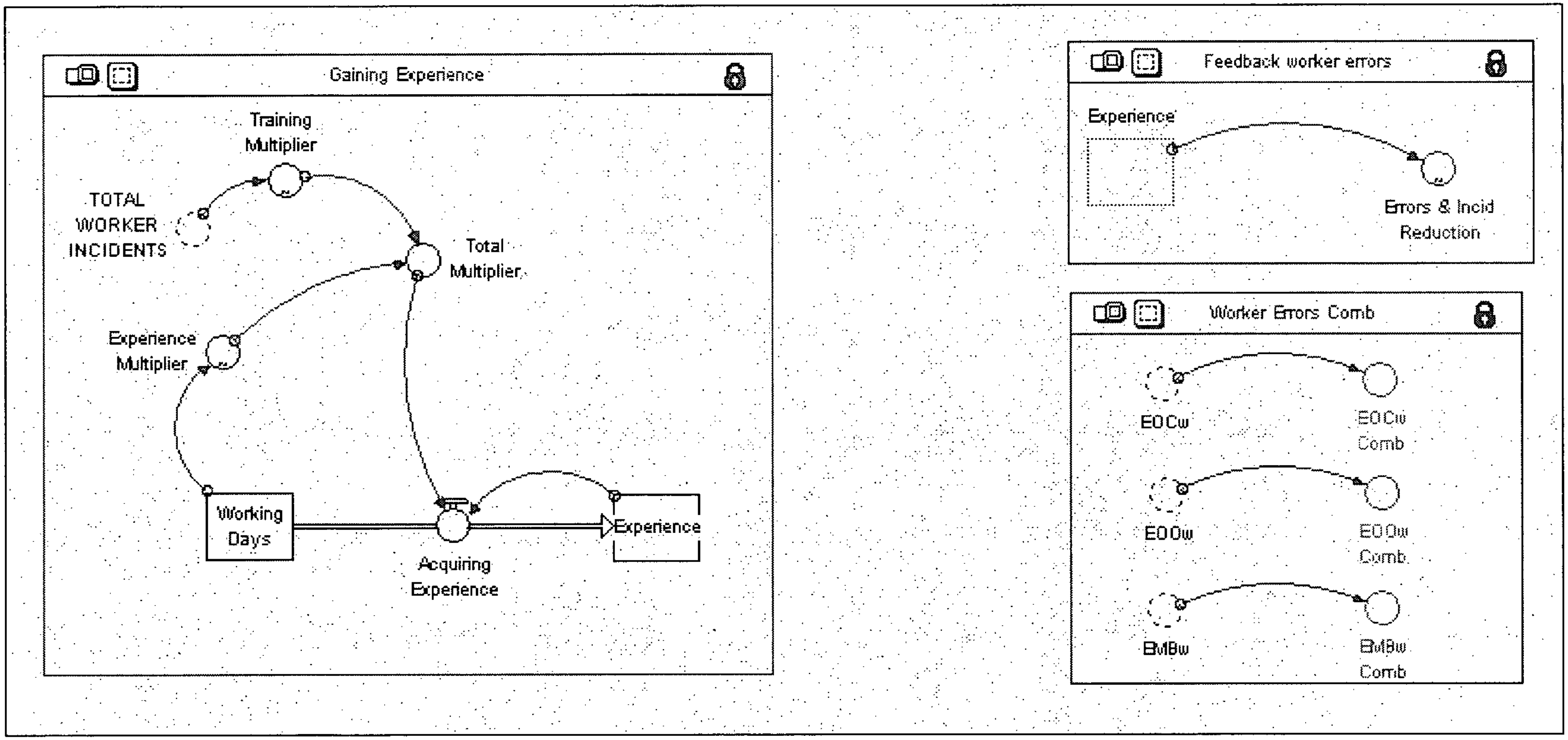


Figure 38 - Experience and feedback

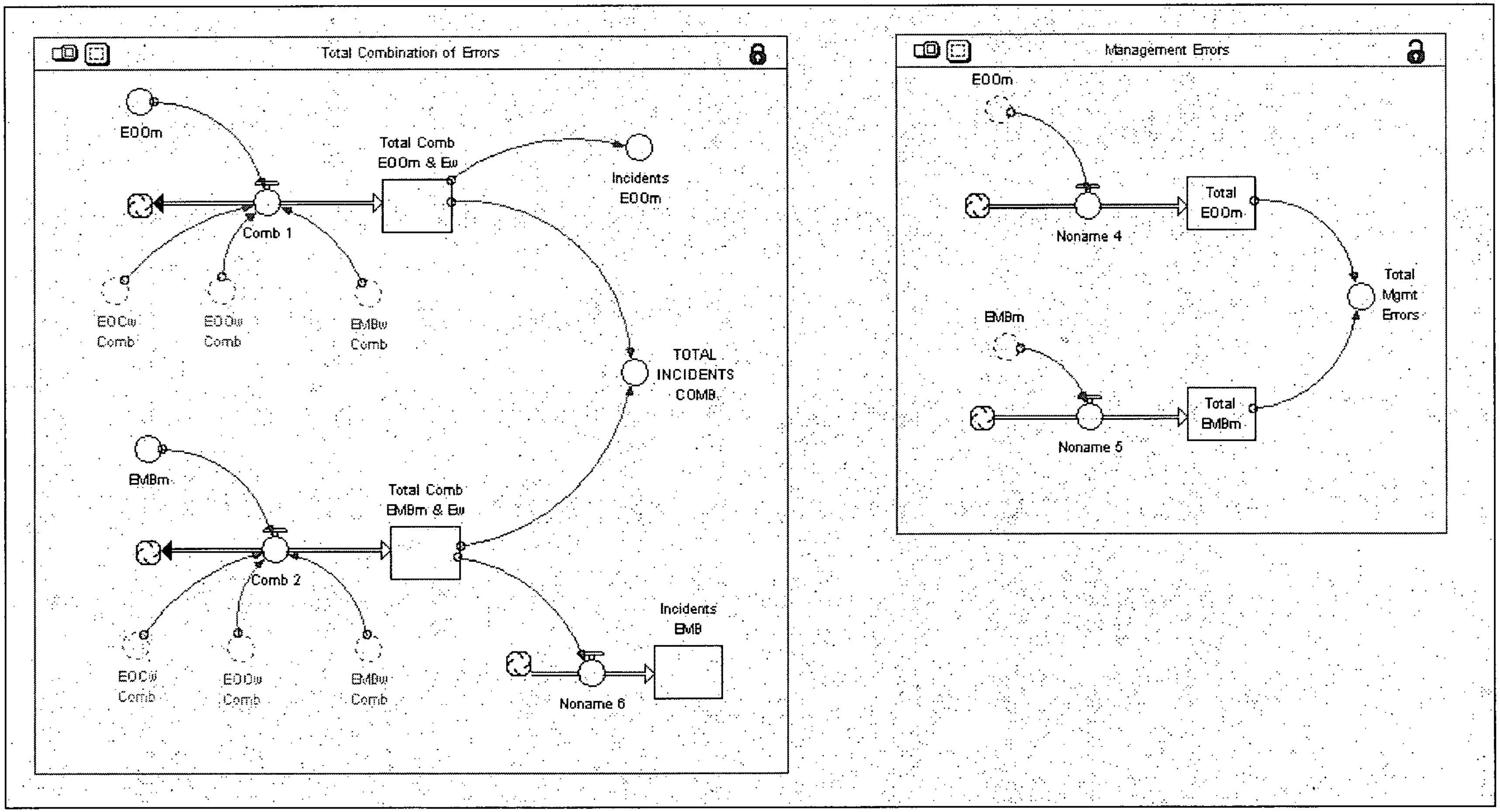


Figure 39 - Latent errors and combination of errors