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Linkage of Annual Oil Sands Mine Plan to Composite Tailings Plan

by

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Abstract

One of the major issues in the current oil sands waste management techniques is a lack of direct linkage between the long-term mine plans and the quantity of the tailings produced downstream. This research is focused on developing a linkage between oil sands long-term mine plans and the final composite tailings (CT) produced to assist the oil sands production process to be in compliance with the regulations set by Directive 074. A series of mass-balance relations between the ore tonnage and the final CT tonnage were developed. This was followed by the development of a code to employ the mass-balance relations in reporting the CT production schedule using the long-term mine plan. To capture the uncertainties associated with the CT production process, a stochastic simulation model was developed. Finally, sensitivity analysis was carried out to capture the sensitivity of the CT tonnages produced to the fluctuations of the input variables.

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List of Abbreviations

Parameters

CT	Composite/consolidated tailings
MFT	Mature fine tailings
TFT	Thin fine tailings
PLU	Pleistocene units
CWF	Clear water formation
UKM	Upper McMurray formation
MKM	Middle McMurray formation
LKM	Lower McMurray formation

Nomenclature

Parameters

F_{CT}	CT fines tonnage
Sd_{CT}	CT sands tonnage
W_{CT}	CT water tonnage
$S\%_{CT}$	CT solids%
Sd_{Feed}	Sand content of the feed
F_{Feed}	Fines content of the feed
W_{Feed}	Water content of the feed
B_{Feed}	Bitumen content of the feed

M_{Feed}^{F}	Mass of fines in the feed
M_{Feed}^{Sd}	Mass of sands in the feed
M_{Feed}^{W}	Mass of water in the feed
M_{Feed}^{B}	Mass of bitumen in the feed
S_{Feed}	Solid content of the feed
$S\%_{MFT}$	MFT solid content (%)
$\%on-spec$	CT on-spec% to be sent to the diffuser
F_{DT}	Total fines tonnage sent to DT
Sd_{DT}	Total sand tonnage sent to DT
W_{DT}	Total water tonnage sent to DT

Reject properties

$Rj\%$	Reject percent
$Rj\%_{Sd}$	Sand reject percent
$Rj\%_{F}$	Fines reject percent
$Rj\%_{W}$	Water reject percent

Cell properties

V_{Cell}	Cell volume
ρ_{Cell}	Cell dry density
Eff_{Cell}	Cell efficiency
PhC_{Cell}	Cell physical capture
F_{Cell}	Fines to cell

Sd_{Cell}	Sands to cell
W_{Cell}	Water to cell
$F\%_S$	Fines percent in solids

Cyclone underflow

UF_{CT}^{Sd}	Underflow sand tonnage sent for the CT production process
UF_{CT}^{F}	Underflow fines tonnage sent for the CT production process
UF_{CT}^{W}	Underflow water tonnage sent for the CT production process
$Sd\%_{UF}$	Sand content of the underflow (%)
UF_F	Total tonnage of fines in cyclone underflow
UF_{Sd}	Total tonnage of sand in cyclone underflow
UF_W	Total tonnage of water in cyclone underflow
$UF_{F\%}$	Fines% present in cyclone underflow
$UF_{Sd\%}$	Sand% present in cyclone underflow
$UF_{W\%}$	Water% present in cyclone
$UF\%_{CellDT}$	The percentage of total cyclone underflow sent to the cell DT
$Sd_{Cyclone}$	Total sand tonnage sent to cyclones
$F_{Cyclones}$	Total fines tonnage sent to cyclones
$W_{Cyclone}$	Total water tonnage sent to cyclones

Froth

B_{Froth}	Total tonnage of bitumen in froth

W_{Froth}	Total tonnage of water in froth
Sd_{Froth}	Total tonnage of sand in froth
F_{Froth}	Total tonnage of fines in froth

SET properties

$B\%_{SET}$	SET bitumen
$Sd\%_{SET}$	SET sand
$F\%_{SET}$	SET fines
$W\%_{SET}$	SET water
R	Recovery (%)

MFT for CT

$S\%_{MFT}$	MFT solid content (%)
MFT_{CT}^{F}	Added MFT fines for CT production
MFT_{CT}^{Sd}	Added MFT sand for CT production
MFT_{CT}^{W}	Added MFT water for CT production

Chapter 1

Introduction

1.1. Background

The mine and tailings long-term plans define the complex strategy of the displacement of ore, waste, overburden and tailings over the mine life. The objective of the long-term mine plans is to minimize the environmental footprint and maximize the cash flow. Limitation of space because of lease conditions, scale of operations and construction of external and in-pit dyke impoundments add to the complexity of planning in oil sands mining. Contrary to metal and non-metal mine planning; oil sands long-term mine plans are driven by the quantity and quality of mature fine tailings (MFT) and composite/consolidated tailings (CT) produced downstream.

Production scheduling is an important aspect of mine planning and design. Maximizing the net present value (NPV) and considering the sequence of material that has to be mined over time, under the defined constraints, is used to create a schedule for long-term production (Dimitrikopoulos et al., 2004).

Not meeting the production target in the early years of a project is one of the main problems in long-term mine planning, and one of the main contributors to this underperformance is geological and grade uncertainties, which will also lead to the production shortfalls in the later years of the operation (Goody et al., 2004).

The hot water process that is being used to extract bitumen from oil sands in northern Alberta, will result in producing a tailing stream which contains residual bitumen, clays, sand and a small amount of soluble organic compounds (Kasperski, 1992). In oil sands mining, every barrel of oil produces approximately three cubic meters of tailings, which contains between 35 and 65% of solids content, with fines content between 8 and 25% and approximately 1% of residual bitumen (Beier et al., 2008). Due to the specific characterization of tailings, it will segregate with the sands going down the water and fines going up. Since it is harmful for the environment and wild life to dispose tailings into the river system, MFT is stored on site. Therefore this method of tailings disposal will result in several tailings ponds with a fine tails zone that will take many decades to fully consolidate (Boratynec, 2003).

In order to increase the tailings dewatering rate and reduce the formation of a fine tailings zone, composite tailings (CT) is used to produce non-segregating tailings, which is a mixture of coarse sand, gypsum, and MFT. The CT process reduces the storage and tailings management costs, and will decrease the volume of mature fine tailings (MFT) on leases. In addition, the CT process will help to reclaim the disturbed areas for terrestrial land use faster (Caughill, 1992).

To produce CT, using the pipelines, coarse tailings are pumped from the extraction plant to the CT plant, where they are cycloned to produce a densified coarse tailings stream. The resulting densified stream is combined with the MFT and gypsum in order to produce CT. The produced CT is then transported hydraulically to the specified tailings disposal facility. After deposition of CT in the pond, the dewatering of the mixture starts rapidly which will leave a soft deposit behind (Syncrude, 2009).

The implementation of the CT process has a number of benefits such as reducing the existing volumes of the MFT and increasing the percentage of dry landscape. This is a positive response to environmental and regulatory concerns regarding the long-term management of fluid fine tailings and also results in reducing the tailings management and storage costs (Matthews et al., 2002).

1.2. Statement of the Problem

Management of tailings results in environmental challenges and financial burdens for operators. One of the mine waste management techniques is to create a non-segregating mixture or CT that will increase the rate of the dewatering process resulting in a higher consolidation rate of fine tailings (Chalaturnyk et al., 2002).

The oil sands long-term mine plans are driven by the quantity and quality of the MFT and composite/consolidated tailings produced downstream. Unfortunately, common approaches to mine planning rely on deterministic ore-body models as the basis for the mine tailings long-term plans. The operation uncertainties caused by different operational factors, are not considered which may result in over-estimating or under-estimating the total tailings produced at the end of the process.

In oil sands mine planning, developing an optimal risk-based methodology for the oil sands mine and in-pit CT disposal planning is very important. The long-term mine plan should minimize and eventually reduce long-term storage of fluid tailings in the reclamation landscape, and to create a trafficable landscape at the earliest opportunity to facilitate progressive reclamation.

Currently, in oil sands mine planning, there is a lack of integrated linkage between the long-term mine plans and the final non-segregating tailings produced at the end of the process, which can cause serious problems, as there are storage area limitations based on the defined regulations for the oil sands industry.

In this research the goal is to provide a linkage between the long-term mine schedule and tailings planning. The resultant schedule takes into account the mass balance calculations, the final quantity of tailings produced, and the volume of impoundments and the dykes required. The linkage between the long-term mine schedule and tailings plan assists mine planners in making a decision on the dyke construction schedule and also on raising the dyke height in each period in accordance with the tailings produced based on the tailings calculation plan.

The purpose of this study is to develop and modify the tailings containment system and provide an integrated linkage between the long-term mine plans and the final CT produced downstream. The governmental regulations set for the oil sands tailings specify the maximum tonnage of fines and sand produced each year from the tailings. In order to be in compliance with these regulations, there should be specific considerations on the tailings production in terms of the tonnages of the tailings produced during each period. This shows the importance of the integration of mine planning and waste management in oil sands production. This research is conducted to improve the oil sands waste management system by developing relations between the ore feed and the oil sands mine plan with the final CT produced based on the corresponding plans. And also the goal of this study is to modify the production schedules based on the tailings disposal area limitations set by regulations.

Fig. 1 represents a schematic diagram of the problem definition. This figure illustrates the relation between the block model and the production schedule with the final CT fines tonnage, CT sand tonnage and CT water tonnage produced downstream. Fig. 1 shows the CT production process for one block. First, the block by block production schedule is provided and the block information such as fines grade, bitumen grade, sand content and water content is sent to the oil sands production process. The overall reject percent, sand reject percent, target SFR in pipe and on spec CT percent sent to Tremie, are four different terms in the stochastic model. In other words, different distributions are assigned to these four terms in order to capture the uncertainties in the CT production process. The final output of this model is the tonnage of CT produced for each block based on the long-term production schedule, considering the risks associated with this process. The tailings plan provided by this model can be used in order to improve the tailings management plan and modify the long-term mining schedules to be in compliance with Directive 074 regulations (ERCB, 2009). Based on Directive 074, oil sands companies are required to predict the total tailings production by type for the life of the mine; this model is provided to fulfill this requirement.

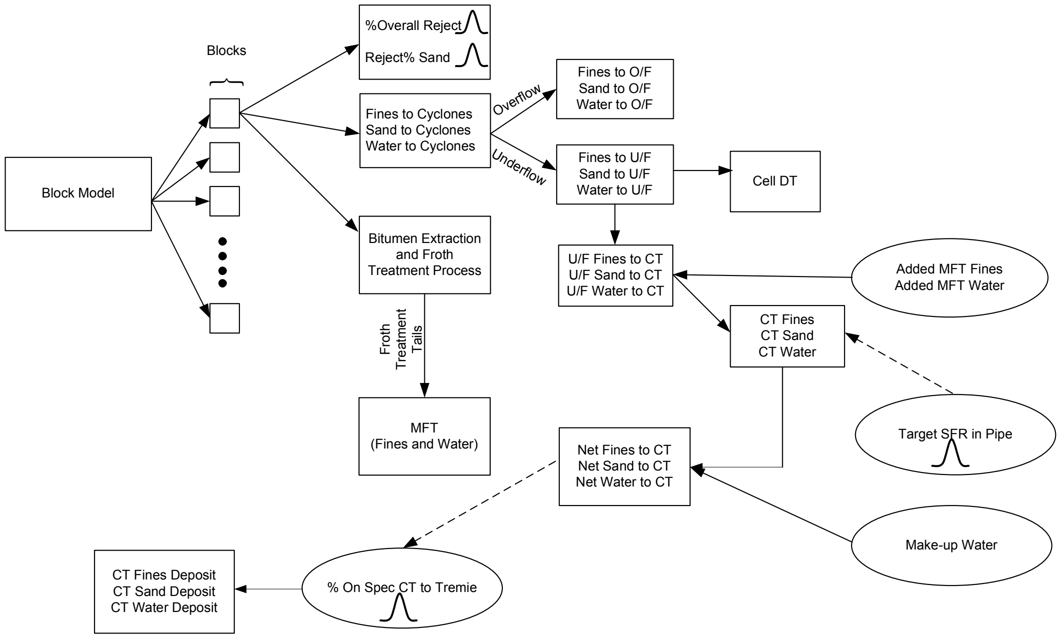

Fig. 1 – Schematic representation of the problem definition

The following research question drives this dissertation:

Is it possible to generate a linkage between the long-term mine schedules and the CT produced at the end of the oil sands production process, considering the uncertainties associated with the CT production, which would lead to improvement and modification of the oil sands tailings management system and being in compliance with the regulations set by Directive 074?

1.3. Summary of Literature Review

The hot water-based process in oil sands extraction leads to the production of the tailings stream which consists of sand, clay, residual bitumen, and a relatively small portion of organic compounds. The total tailings has about 55 wt% solids; the solid consists of 82 wt% sands, 17 wt% fines (smaller than 44μm) and 1wt% residual bitumen (Chalaturnyk et al., 2002). Processing each cubic meter of the synthetic crude oil (SCL) produces about 2 m^3 of fine tailings (Azam et al., 2005).

Since the fines and clay mineral, which are parts of the suspension formed in the tailings, are resistant to consolidation, major treatments should be done in order to make the oil sands tailings both economically and environmentally acceptable (Kasperski, 1992).

Different tailings management techniques include volume reduction of the processed fines by use of selective mining, modifying the oil sands extraction process to avoid having large volumes of dispersed fines, and last but not least development of non-segregating tailings. Developing non-segregating tailings is the most preferable technique for the oil sands industry based on economical considerations (Azam et al., 2005).

All of the oil sands management techniques will end up producing a non segregating tailings stream with highly reduced water content. There are several factors which affect the number of steps required to dewater oil sands tailings such as: cost-efficiency, winter operation, dewatering efficiency, technical feasibility, robustness, and practicality of the operation (BGC, 2010).

The goal of the consolidated tailings process is to increase the dewatering rate and hence, the consolidation rate of the oil sands tailings stream, in order to create a trafficable landscape at the earliest time possible. Research shows that a mixture of cyclone underflow and MFT will become non-segregating with the addition of lime (CaO) or phosphogypsum ($CaSO_4.2H_2O$) (Matthews et al., 2002; Boratynec, 2003).

The consolidated tailings or composite tailings (CT) process is mainly involved with creating a mixture of sand, clay, and silt which is non-segregating (Mikula et al., 1998; Soane et al., 2010). The main advantages and benefits of the CT process include higher consolidation rate than what was expected for on-spec CT, production of nonsegregating tailings, low cost and being economically affordable, MFT consumption and hence volume reduction in the fluid tailings. In addition, CT process can be operationally implemented at large scale (BGC, 2010).

The cyclone underflow has a solid content of approximately 70 wt%, and the MFT contains about 30 wt% solids. Gypsum acts as a chemical amendment for this mixture to increase the strength of tailings and changing it to a trafficable landscape. The resulting CT has a solid content of about 60 wt%, sand to fines ratio (SFR) of about 4:1, and clay to water ratio of greater than 0.1. Therefore, CT performance is affected by the clay content or the fluid tailings properties (Mikula et al., 2008).

The major limitations of the current oil sands tailings management reviewed in Chapter 2 are:

- Lack of a direct relation between the long-term mine plans and the final CT produced at the end of the process and hence inability to modify mine plans based on the limitations for the dedicated disposal areas.
- Not considering the risks and uncertainties associated with the CT process and only relying on deterministic models.

1.4. Objectives of the Study

One of the objectives of this research is to provide the mass relationships and mathematical formulations to be able to link the long-term mine plan to the final CT produced at the end of the oil sands production process in order to satisfy Directive 074 requirements on the tailings management plan and storage area limitations. The first objective consists of two elements: (i) establishment of mathematical formulations – providing mass-balance equations between the ore feed and the final CT, (ii) verification of the mathematical formulations using real mining data.

Another objective of this research is to consider different uncertainties and risks associated with the CT production process. The idea of simulating the CT production process, considering the risks associated with the operation, was to avoid over-estimating and especially under-estimating the CT tonnage in order to satisfy the storage area limitations based on the defined regulations.

To be able to reach the goals, this research includes considerations of different operational factors affecting the oil sands production process, and developing computer code to implement the mathematical formulations in relating the mine plan to the tonnage of CT produced at the end of the process. In addition, a stochastic simulation model is developed in order to capture the uncertainties associated with the uncertain inputs to the CT production process.

The objectives of the study are to

1. Understand and establish deterministic mass-balance relationships and mathematical formulations required to link the long-term mine plans to the final CT produced downstream in order to fulfill the requirements of heading number 4 in appendix E of the directive 074 to predict the total tailings production by type for the life of mine.
2. Develop the mathematical formulations as proto-type software capable of linking real-mine production schedules to the quantity and quality of CT produced downstream.
3. Modify the long-term mine plans based on the limitations in tailings containment area.
4. Extend the deterministic models and code to a stochastic framework using Monte Carlo simulation.
5. Capture and quantify the uncertainties associated with linking mine plans with CT production process using the stochastic framework.
6. Verify the mathematical formulations and the developed code using real mining data.

1.5. Scope and Limitations of the Study

This research is concerned with providing a linkage between the long-term oil sands mine plans and the CT produced downstream. The desired CT solid percent is assumed to be 55% fixed. The percentage of sand sent to the underflow stream is set to be 93%. It should be noted that these numbers are selected based on Suncor's data.

The following assumptions are made in developing the mathematical model for the CT production process:

1. The MFT is available for the CT process during the mine life and the solid percent for MFT is fixed at 30.
2. The percentage of sand being sent to underflow stream from the cyclone is 93.
3. The desired CT solid percent is 55.
4. The desired underflow stream has a sand content of 65%, fines content of 5% and water content of 30%.

It should be considered that this study has some limitations due to the assumptions that have been made in developing the stochastic simulation model. In other words, in order to assign proper distributions to capture the variability of the uncertain inputs, historical data from operations should be gathered and the distributions should be fitted on the real data. It should be noted that these distributions may be different based on several operational factors.

1.6. Research Methodology

The main motivation for conducting this research is to improve the oil sands waste management techniques by providing a linkage between the mine plan and the tailings. There are two main steps in order to achieve the research objectives: constructing a mass-balance relation between the ore feed and the final CT produced and establishing a CT calculation model and also a simulation model to consider the different uncertainties associated with this process.

In the first part of this research, a deterministic mass-balance relation should be established using the mathematical formulations required to link the long-term mine plans to the final CT produced. To achieve this research objective, following tasks are completed:

1. Establish mass-volume relationships in the oil sands ore feed.
2. Conduct a comprehensive study on all of the different factors affecting the CT production process in order to obtain the mass-balance equations and mathematical formulations.
3. Establish the final mass-balance relations and the mathematical formulations.
4. Establish a deterministic model to be able to implement the mathematical formulations on the block-by-block long-term production schedule.
5. Develop computer code linking the mine production schedule and the CT produced by mathematical formulations established in step 4. In this study, the code is developed in the VBA environment (CT calculation deterministic model).
6. Implement the CT deterministic model on the long-term production schedule in order to verify the model.

In the second part of this research, the main concern is to capture the uncertainties associated with the CT production process by constructing a simulation model. To achieve this research objective, following research tasks are completed:

1. Conduct a comprehensive study on the CT production process to determine different input variables in the CT production process.
2. After selecting the input variables, probability distributions should be assigned to each input so that the distributions could capture the uncertainties associated with each variable input.
3. Establish a stochastic CT calculation model using the deterministic model and the distributions assigned for the uncertain variables.
4. Determine the number of simulation runs to achieve the desired confidence interval and running the simulation model. In other words, number of replication should ensure meeting the desired confidence interval. In each replication of the simulation, samples will be taken from the probability distributions to be employed as an input for the CT calculation model. For the long-term mine plan, for each period, a sample will be taken from the assigned probability distributions; therefore, during each simulation run, the number of samples taken from the probability distribution assigned to each uncertain parameter will be equal to the number of periods.
5. Analyze the simulation results and studying the effects on the system based on the probable risks and uncertainties, comparing the results from the deterministic model with the results from the stochastic simulation model.
6. Establish the sensitivity analysis on the simulation results to capture the sensitivity of the model to the changes imposed to the system due to the variations and uncertainties in the input parameters.

1.7. Contributions and Industrial Significance of the Study

Tailings management is a major concern in Alberta's oil sands industry. Environmental challenges caused by the oil sands tailings production led to setting regulations for oil sands tailings operations. According to the Directive 074 (ERCB, 2009), the oil sands production operators are required to satisfy the conditions and regulations set by this directive. The main goal of these regulations is to ensure that the fluid tailings produced at the end of the oil sands production process, will become a reclaimable and trafficable landscape in order to overcome the environmental challenges caused by oil sands industry. In addition, according to this directive, the tailings production should meet the limitations on the deposition area specified by the directive.

Therefore, the quantity of the CT which is acceptable should be a constraint for the oil sands production. Linking the long-term mine plan to the tonnage of CT produced at the end of each period, will help to modify the mine plans to be in compliance with the regulations. Furthermore, capturing the tonnage of CT to be produced at the end of each period, leads to the development of the CT disposal strategy.

This research has developed mathematical formulations and simulation models, which assist in prediction of the expected value of the quality of CT produced at the end of the oil sands production process. The results of this research also quantifies the uncertainties associated with the CT attributes such as reject percent, sand reject percent, target SFR in pipe and on-spec CT%. The contribution of this research is considerable in the oil sands industry in order to modify and re-evaluate the mine plans, and also, the methodology presented in this research can be employed to satisfy the regulations set by Directive 074.

The main limitation of current oil sands mine plans is in over-estimating and under-estimating the quantity of the final CT produced. Furthermore, the lack of an accurate relation between the oil sands long-term mine plans and the final product can lead to serious problems in case of having deposition area limitations.

An important industrial contribution of this research is a methodology/tool that enables mine planners to modify and re-evaluate the oil sands mine plans based on the deposition area constraint, and the amount of CT which is expected to be produced based on the mine plans. Also, a methodology/tool is developed based on Monte Carlo simulation, that enables mine and tailings planners to assess and quantify uncertainties associated with the quantity and quality of CT produced.

1.8. Organization of Thesis

Chapter 1 of this thesis is concerned with an introduction to the study, the problem statement and definition of the problem followed by objectives of the study, scope and limitations of the study, the proposed methodology and the contributions of the research.

Chapter 2 contains a literature review of the oil sands tailings properties, the CT production process and the Monte Carlo simulation method. The first part of this chapter provides a general description on the Alberta's oil sands mining operations.

Chapter 3 contains the theoretical framework and provides the mass-balance relationships between the feed and the final produced CT. The initial part of this chapter provides and discusses the general oil sands production process and the important factors affecting the CT production process.

This chapter is concerned with providing the mathematical model and formulations in order to achieve the research objectives.

Chapter 4 is concerned with the implementation of the mathematical model on a large scale oil sands data. The initial part of this chapter is the development of a computer code in order to link the mathematical formulations to the long-term mine plan. The VBA code is provided in Appendix A. A case study of the oil sands mine plan is carried out to verify the computer code and the mathematical formulations developed in this study. Subsequently, the stochastic simulation model for the CT production process is developed in this chapter. The main goal of developing this simulation model is mainly capturing the uncertainties associated with the CT production process. The sensitivity analysis of the stochastic simulation is done in this chapter to determine the sensitivity of the model to different parameters. The chapter concludes with a detailed summary of the simulation results.

Finally, the contributions of this research and suggestions for future work are covered in Chapter 5.

Chapter 2

Literature Review

This chapter is concerned with a literature review on oil sands production process. This literature review provides information on general oil sands tailings properties, oil sands tailings management and composite tailings process.

2.1. Oil Sands Tailings Properties

The hot water-based process in oil sands extraction leads to the production of the tailings stream which consists of sand, clay, residual bitumen, and a relatively small portion of organic compounds. The total tailings has about 55 wt% solids; the solid consists of 82 wt% sands, 17 wt% fines (smaller than 44µm) and 1wt% residual bitumen (Chalaturnyk et al., 2002). Processing each cubic meter of the synthetic crude oil (SCL), produces about 2 m^3 of fine tailings. The total fine tailings produced annually is approximately 70 Mm^3 (Azam et al., 2005).

Since the fines and clay mineral, which are parts of the suspension formed in the tailings, are resistant to consolidation, major treatments should be done in order to make the oil sands tailings both economically and environmentally acceptable (Kasperski, 1992). In the Clark hot water process, there are four main sources for the resulting tailings stream including the waste rock being rejected by the screens, the primary separation cell (PSC) bottom layer, the tailings of the PSC's middling stream, and the froth treatment tailings. The resulting tailings stream is in an aqueous suspension form, and depending upon settling, oxidation, and bacterial action it can have a variable composition (Kasperski, 1992).

One important advantage of oil sands tailings stream is that it has relatively high water content and therefore it is in a fluid form, thus transportation and pumping of the tailings stream to the pond can be done easily. On the other hand, the tendency of the tailings stream to be segregated after deposition into the pond is a considerable disadvantage for the oil sands tailings stream which requires a lot of considerations (Caughill, 1992).

The tendency of the coarse fraction in the tailings stream to settle will lead to forming a suspension of fines and segregation of solids (Azam et al., 2005). In other words, after deposition of the tailings stream into the ponds, tailings tend to segregate as a result of its gap-graded characteristics and high void ratio. Therefore, after deposition, the coarse-grained material, which is mainly sand, tend to settle and be separated from the fine tails which flow toward the pond centre. The clear water formed on top of the tailings pond will be recycled and will be sent to the extraction plant. The segregation rate will decrease with time, until it reaches a solid content of 30 to 40% after about two years, and it will be known as mature fine tailings or MFT (Boratynec, 2003). The produced MFT has a void ratio greater than 5 and its hydraulic conductivity is in excess of 10^{-6} m/sec (Azam et al., 2005; BGC, 2010).

The segregation behavior of the oil sands tailings stream is affected by the solid content, particle size distribution, and the fine particles mineralogy (Azam et al., 2005).

Tailings segregation occurs in three steps upon deposition into the tailings ponds; the first step of the sedimentation is the Stokes law sedimentation which the solids settle according to their size and relative density, after that the thin fine tailings undergo hindered sedimentation followed by consolidation. The hindered sedimentation is caused by the interaction between solid particles which have an adequate connection with each other. And finally, the consolidation is caused by an effective inter-particulate stress which developed between the fine tailings particles (Kasperski, 1992). As it was mentioned before, after approximately two years of tailings deposition into the ponds, MFT will be formed. The full consolidation of MFT might never happen as a result of its low hydraulic conductivity (Boratynec, 2003).

As the result of poor consolidation and settlement behavior of MFT, it is a major concern for the oil sands industry in terms of environmental liabilities. Therefore, tailings management is very crucial in order to reduce the MFT volumes (Donahue et al., 2008).

The untreated segregating tailings will have some consequences such as increase in the volume of process water and fresh water required for the oil sands production process, increase in the volume and number of the tailings ponds, and increase in the pond reclamation time (Chu et al., 2008).

2.2. Oil Sands Tailings Management

Special geotechnical considerations are required for long-term management of fine tailings produced as a result of oil sands extraction process (Azam et al., 2005). Containment of large volumes of fluid tailings and long-term storage of MFT over the last 40 years is a result of oil sands tailings management techniques (BGC, 2010). There are two major concerns about the segregating oil sands tailings; environmental challenges and space area limitations defined in the lease agreements. The environmental challenges caused by oil sands tailings include the toxicity of the pore water. In order to overcome this environmental issue, which is mainly land reclamation and water recirculation, dewatering techniques should be developed to reduce the volume of water present in the tailings and preparing the water for recycling and sending it back to the extraction plant. Based on the directive 074, the oil sands companies are required to reduce the volume of fluid tailings and convert them to trafficable landscapes. Therefore, the companies' tailings management systems should obey the directive 074 regulations. The second problem that faces the oil sands tailings is the fact that the tailings ponds should be removed at the end of the leases based on the zero discharge policy set by the regulations, preventing release of accumulated process-affected water. In other words, tailings cannot be permanently stored in the depositional area and it should become a trafficable landscape using an appropriate tailings management technique (Boratynec, 2003).

The Directive's main concern is to overcome the environmental issues caused by the oil sands industries. According to this Directive, the amount of captured fines in the dedicated disposal areas (DDAs) is required to be 50% by weight of fines (<44 μm). It should be considered that this amount of fines that is required to be captured is in addition to the fines captured in hydraulically placed dykes and beaches. To ensure providing a trafficable landscape, Directive 074 set the following regulations for the oil sands industry:

- The undrained shear strength for the deposited material should be at least 5 KPa
- The deposited material which does not meet the minimum shear strength criteria has to be removed or remediated
- After five years of deposition, deposited material should be ready for reclamation, and it should have sufficient strength and stability to become a trafficable surface.
- Tailings management techniques and processes in compliance with the Directive requirements should be provided annually (Longo et al., 2010).

Different tailings management techniques include volume reduction of the processed fines by use of selective mining, modifying the oil sands extraction process to avoid having large volumes of dispersed fines, and last but not least development of non-segregating tailings. Developing non-segregating tailings is the most preferable technique for the oil sands industry based on economical considerations (Azam et al., 2005).

The main goal of this type of oil sands management techniques is to produce a non segregating tailings stream and to increase the settling and dewatering rate of the tailings after deposition. The most important benefits of the non segregating tailings include: considerable reduction in the volume of tailings ponds required for retention of tailings, reduction in costs, reducing the environmental challenges, increasing the volume of recyclable water sent back to the extraction plant hence reduction in the volume of fresh water required, and reduction in the pond reclamation time (Chu et al., 2008).

There are three main concerns in developing non-segregating tailings. The first issue is that increasing fines content of tailings will result in lower consolidation and dewatering rate. The second concern in this technique is that the water released as a result of tailings consolidation should be environmentally acceptable; therefore the release water chemistry is highly important. The third issue is concerned with the fact that as a result of tailings consolidation, the solid content will increase which makes the pumping and transportation of the produced tailings stream difficult and increases the energy needed for tailings transportation. The maximum pumpable tailings stream with a fines content of 10% to 20% should have a solid content of not more than 68%, this should be considered in developing the nonsegregating tailings (Azam et al., 2005).

Since the production of each barrel of the synthetic crude oil (SCO), which requires about 2 m^3 of water, leads to the production of approximately 1.8 tonnes of tailings, oil sands management plays an important role in overcoming the environmental issues caused by the oil sands production process (Cabrera et al., 2009).

Oil sands management is concerned with developing techniques to reduce the volume of MFT and to dewater the fluid tailings. Since the volume of tailings is really huge, the reclamation and tailings management techniques are required to be economically acceptable and efficient.

There are three different strategies for reclaiming oil sands tailings: creating a dry landscape, creating a wet landscape, and creating wetlands.

One of the most important tailings management techniques is to produce a trafficable dry landscape by employing a dewatering process to reduce the water content of the tailings by a significant amount. The dry landscape techniques include composite tailings production, evaporation, cyclic freeze-thaw consolidation, drainage, and evapotranspiration.

The technique of creating a wet landscape is involved with placing the MFT in a fluid form over a water layer, and it is highly dependent on the flow properties of the MFT. The wetland reclamation strategy is mainly integration between the dry landscape and wet landscape reclamation techniques (Tang, 1997).

All the oil sands management techniques will end up producing a non segregating tailings stream with highly reduced water content. There are several factors which affect the number of steps required to dewater oil sands tailings such as: cost-efficiency, winter operation, dewatering efficiency, technical feasibility, robustness, and practicability of the operation (BGC, 2010).

In oil sands tailings the term (f/(f+w)) is commonly used as a dewatering determinant factor. f represents the mass fines content and w presents the water content (Guo et al., 2010). This ratio is the ratio of fines content to the sum of fines content and water content in CT, and it represents the amount of fine particles and water between the pore spaces and sand particles (Tang, 1997).

Based on the limitation on the tailings long-term storage, tailings disposal is a main concern for oil sands industry. Dedicated disposal areas (DDA), overburden dumps, tailings ponds, thin lift dewatering areas, and other waste disposal facilities all complete for limited out-of-pit and in-pit space. Therefore, efforts should be made to overcome the environmental challenges regarding these wastes reclamation (BGC, 2010).

2.3. The Composite Tailings Process

One of the important technologies that have been used in tailings stabilization over the recent past years is the coagulation of fines in order to modify the whole tailings stream. Dry tailings filtration, freeze-thaw, flocculation, centrifugation, and mechanical enhancements are some other dewatering methods used for stabilization of oil sands tailings.

In 1980s research showed that the addition of lime to Syncrude coarse extraction tailings will produce a non-segregating tailings stream, however, it was not commercially implemented on Syncrude tailings stream until 1990. In 1990 Syncrude added lime to the coarse extraction tailings in order to stabilize tailings. The produced tailings stream did not appear to be stable enough, it was soft, and had relatively low beach angles. Advanced studies showed that although lime addition to the oil sands tailings stream helps in producing a dry and trafficable landscape, containment of tailings is necessary for deposition and dewatering. During the 1990s, Syncrude had a successful pilot trial for the CT production, and based on that they started the commercial implementation of CT production on the tailings stream (Matthews et al., 2002).

The consolidated tailings or composite tailings (CT) process is mainly involved with creating a mixture of sand, clay, and silt which is non-segregating (Mikula et al., 1998; Soane et al., 2010).

In order to produce the composite tailings, the total tailings will be sent to the hydrocyclone to simply separate the fine tailings from the coarse tailings. Cyclone overflow which contains the fines tailings stream is sent to the tailings pond to produce MFT after consolidation, and the cyclone overflow containing the course tailings stream is mixed with the MFT produced in the tailings pond at a sands to fines ratio (SFR) between 3:1 and 4:1. Finally, gypsum is added to the mixture to produce CT. The resulting CT is then pumped to the deposition area to settle (Soane et al., 2010).

When gypsum is added to pure water, it will be dissociated to Ca^{2+} and SO_4^{2-}. The calcium ion which results in the precipitation of calcium carbonate is a determinant factor in creating a nonsegregating tailings stream via changing the surface properties of the clay particles. furthermore, calcium ions affect the particle size distribution as they interact with the clay particles (Boratynec, 2003). Comparing to the segregating mixture which has the tendency to settle, the nonsegregating mixture tends to have a uniform distribution of solids. The most important difference between a segregating and nonsegregating mixture is the amount of the ability of sands to capture the fines present in the mixture. A tailings mixture is characterized as a segregating mixture if the fines percent captured by the sand matrix is less than 50%. On contrary, the amount of fines captured by the sand matrix in the nonsegregating mixture is about 90% (Tang, 1997).

The resulting CT will consolidate during two stages; upon deposition of CT into the containment ponds, the initial consolidation of CT will occur which leads to the clear water formation on the surface of the mixture, this is called the initial consolidation of the CT which can take between several days to a few weeks. The second consolidation stage occurs when the sand particles interact with each other to form a sand matrix; this stage is called self-weight consolidation of CT which is a long-term process. Fines content of the CT mixture and the type of the chemical amendments to the CT process will affect the initial consolidation stage. The consolidation (both initial and long-term consolidation) rate is affected by the hydraulic conductivity of the fine tailings or MFT. MFT with a high bitumen content has a lower hydraulic conductivity and as a result the consolidation rate will become lower (Tang, 1997).

It should be considered that since the CT disposal is done in layers, the release water from the initial CT layer should be collected and removed before another layer is deposited. This process is very important in order to make sure no water is being trapped in the previous layers of CT. CT has a high water content hence it can be hydraulically transported through the pipes; in order to prevent segregation in the CT mixture, it should be deposited in a low energy environment. For instance segregation can be provoked by air entrainment. (Tang, 1997).

The composite tailings process can be summarized as flocculation of the clay matrix in the tailings stream with gypsum in order to make the clay matrix able to support the coarse quartz tailings present in the oil sands tailings stream. The internal stress caused by the coarse quartz leads to consolidation of the nonsegregating mixture (Mikula et al., 1998).

The tailings fines and solid content are two main factors in creating a nonsegregating CT mixture. After adding the chemical coagulant such as gypsum, the clay matrix will become strong enough to be able to hold the sand particles. The sand particles result in compression of the clay matrix which increases the hydraulic conductivity of the fine tailings and creates a nonsegregating mixture (Tang, 1997).

The goal of the consolidated tailings process is to increase the dewatering rate and hence the consolidation rate of the oil sands tailings stream in order to create a trafficable landscape in the earliest time possible. Research shows that a mixture of cyclone underflow and MFT will become non-segregating with the addition of lime (CaO) or phosphogypsum ($CaSO_4.2H_2O$) (Matthews et al., 2002; Boratynec, 2003).

The main advantages and benefits of the CT process include higher consolidation rate than what was expected for on-spec CT, production of nonsegregating tailings, low cost and being economically affordable, MFT consumption and hence volume reduction in the fluid tailings. In addition, CT process is can be operationally implemented at large scale (BGC, 2010).

The cyclone underflow has a solid content of approximately 70 wt%, and the MFT contains about 30 wt% solids. Gypsum acts as a chemical amendment for this mixture to increase the strength of tailings and changing it to a trafficable landscape. The resulting CT has a solid content of about 60 wt%, sand to fines ratio (SFR) of about 4:1, and clay to water ratio of greater than 0.1. Therefore, CT performance is affected by the clay content or the fluid tailings properties (Mikula et al., 2008).

After dewatering and consolidation of the tailings stream, the water should be collected to be recycled and sent to the extraction plant (Matthews et al., 2002). Furthermore, the CT deposit release water can be used to mix with the cyclone overflow stream to improve the fines settling behavior in the tailings pond. After fines settlement in the tailings pond, the MFT will be formed and it can be sent to the CT process. In addition, the released water from the CT deposit will reduce the volume of fresh water required for the oil sands extraction process. The resulting MFT volume reduction will reduce the need for long-term containment of the fluid tailings (Mikula et al., 1998).

There are several factors affecting the segregation properties of the oil sands tailings such as fines content, particle size distribution (PSD), water chemistry, total fraction of solids, mineralogy of fines fraction, and fines (fines+water). Each of these factors can shift the segregation boundary either individually or in combination with other factors.

Increasing fines content using settled fine tailings, coagulation of tailings by using coagulants, and increasing solids content by hydrocyclone densification, are three methods used in order to modify oil sands tailings segregation properties.

One of the main parts of composite tailings production is to add a coagulant to the CT mixture. The role of coagulant is to change the clay properties in the produced CT mixture. Different methods such as pH and cation adjustment can be implemented in coagulation of CT mixture. As it was mentioned before, oil sands tailings tendency to segregate is a result of its gap-graded characteristics which will be modified by the addition of a coagulant (Matthews et al., 2002). The coagulant affects the segregation boundary for the tailings mixture by shifting it upwards to a lower solid content (Azam et al., 2005).

Different coagulants have been used in developing the composite tailings process such as lime (Cao, $Ca(OH)_2$), gypsum ($CaSo_4.2H_2O$), acid-lime (H_2SO_4-CaO), and organic polymers. Through different CT production processes using different coagulants, result showed that gypsum is affordable and effective comparing to other coagulants. Research showed that gypsum is effective at dosages between 900 and 1200 grams per cubic meter (Matthews et al., 2002).

Another main component of the CT process is densification of the coarse tailings stream in order to increase the solids content. Densification of the coarse tailings stream increases the total solids content without changing the fines content; therefore, the tendency of tailings stream to segregation will be reduced (Matthews et al., 2002). Research shows that in producing the CT mixture three important factors should be considered including rapid dewatering rate, dissipation of pore pressure in a reasonable rate, and last but not least creating a nonsegregating mixture (Mikula et al., 1998).

The CT fines content has a direct relation with the dosage efficiency, and MFT content, whilst it has an inverse relation with the dewatering and consolidation rate. In addition, increasing the fines content of the composite tailings leads to lower hydraulic conductivity and lower permeability of the oil sands tailings stream.

Since the CT production process will consume the cyclone underflow and the existing MFT, cyclone overflow, which contains the thin fine tailings (TFT), is sent to the tailings pond to form additional MFT for the CT process in the settling ponds (Matthews et al., 2002).

The two important factors in the composite tailings production process are solid content and the sand to fines ratio of the mixture; these two factors affect the consumption rate of MFT which is the main concerns in oil sands tailings management (Mikula et al., 1998).

The density of the produced CT depends on the sands source; the addition of beach sand to MFT results in producing high density CT while the addition of cyclone underflow stream to MFT leads to production of lower density CT (Beier et al., 2008).

Deposition methods and operation efficiencies can affect the CT quality in order to produce a trafficable landscape. As the main components of CT include MFT/fines, sand and gypsum, the quality of the produced CT is affected by the characteristics of these components. In order to produce a non-segregating mixture with a desired trafficability, the quality of these components should be in compliance with the defined set standards. If the quality of one or more of CT's main components deviates from the set standards, the produced mixture will not be non-segregating, and it is recognized as off-spec CT or soft-CT, which will segregate after deposition into the ponds. In contrast, the mixture which is in compliance with the specified set standards is called the on-spec CT (Guo et al., 2010).

2.3.1. Syncrude CT Full-Scale Prototype

In 1996, Syncrude successfully did a pilot trial of the CT process using gypsum. During this pilot trial, 6,000 m^3 of CT was deposited in a three month period (Mikula et al., 1998).

In order to develop the CT process, Syncrude ran a full-scale prototype demonstration in 1997-1998. In this process, CT was pumped through the pipe line and was deposited into the pit. Daily monitoring and controlling of the deposition area showed that the content of the pond depends on the depositional method. After deposition of the produced CT into the prototype pond, its surface was capped hydraulically using a sand layer. Studies of the prototype pond characteristics showed that near the discharge pipe the deposit has a lower fines content compared to the deposit with a greater distance from the discharging area; therefore the sand to fines ratio (SFR) of the produced CT was not constant for the whole deposit. In other words, the produced CT near the discharge point was coarser with a higher SFR, whilst the produced CT with a greater distance from the discharge point was fines with a lower SFR.

There are different theories explaining the zonation behavior present in the CT deposit. The first theory is concerned with the variability present in the feed, which may result in variable SFR values through the CT containment pond; the coarse stream is deposited near the discharge pond whilst the fines stream is deposited with a greater distance from the discharging area. The second theory is based on the segregation boundary; according to this theory, if the CT mixture is close to the segregation boundary, the fines present in the CT mixture might tend to move to a greater distance from the discharging point through the CT river (Pollock et al., 2000). Clay behavior is one of the determinant factors in the segregation characteristics of the CT mixture, and clay properties change with changing the water chemistry (Mikula et al., 1998).

In order to reduce the zonation effect in the CT deposit, Syncrude used a tremie pipe for discharging CT into the deposition area. As a result of using multiple discharge locations and a tremie pipe, less zonation occurred, and therefore, it was concluded that CT mixture segregation near the discharge point affects the zonation. The zonation occurred in the Syncrude's CT prototype showed that the finer grained area requires further efforts in terms of having a reclaimable dry landscape. In other words, in case of having the zonation occurred through the CT deposit, the long-term stabilization of the CT with a higher SFR would be more challenging compared to reclamation of the coarse grained CT mixture near the discharge point (Pollock et al., 2000). Since 2000, the CT production process has been commercially operating at the Mildred Lake Site (BGC, 2010).

2.3.2. Suncor CT Full-Scale Prototype

In 1996 Suncor ran a commercial trial for the CT process in which 7 Mm^3 of CT was deposited in a retention pond. This trial was completed successfully in 1997. Mine plans, gypsum costs, and release water chemistry were three main factors impacting Suncor's CT production process. In Suncor's CT process, the flue gas desulphurization slurry (FGDS) was used as a source for gypsum. The addition of FGDS for CT production leads to high level of calcium and sulphate in the released water from the CT deposit. The research conducted on the Suncor's trial CT process demonstrated that rapid settling of the fine tails will occur when the calcium present in the CT release water mixes with the clays in the fine tailings. As a result of rapid settling of the clays, the solid content of the CT release water will decrease significantly; therefore there will be a reduction in the toxicity of the release water (Mikula et al., 1998).

2.4. Monte Carlo Simulation

Monte Carlo method is a mathematical technique that can be used in order to solve a problem, which is involved with interactions between objects and interactions between objects and the environment. This method is concerned with the direct simulation of the desired system dynamics, and it allows people to account for risk in quantitative analysis and decision making. This simulation method can be used in many different purposes such as project management, engineering, research and development, genetics, traffic flow, social science, population growth (Bielajew, 2001). The Monte Carlo method uses random variables in order to solve different numerical and computational mathematics problems. Within a certain probability, it is guaranteed that the error of Monte Carlo approximation is smaller than a given value. It should be considered that the solution resulting from this method is an approximate of the solution, but using probability error, this solution can be controlled in terms of accuracy. Monte Carlo method is able to find the direct determination of an unknown functional solution. The main advantage of this method is that the solution provided by this method is in a given number of operations which is equal to the required number of operations to be able to calculate the solution of the problem at only one point of the domain (Atanassov et al., 2008). In order to solve a problem, analytical and numerical algorithms and methods can be developed; the Monte Carlo method can be employed to verify the precision of these analytical and numerical algorithms (Bookhsh et al., 1990).

Monte Carlo simulation and Monte Carlo numerical algorithms are two different directions for implementing and developing the Monte Carlo algorithms. Monte Carlo numerical algorithms can be employed to provide solutions for deterministic problems and to model the random variables. In contrast, the Monte Carlo simulation can be employed to simulate the probabilities of different events in the system. In other words, Monte Carlo simulation algorithms can simulate the random variables in order to solve probabilistic problems (Atanassov et al., 2008).

2.5. Summary and Remarks

The relevant literature has been reviewed in Chapter 2 of this dissertation. The environmental challenges such as toxicity of the pore water released from the segregating tailings and the space area limitations led to the development of directive 074 regulations. Based on directive 074, oil sands companies are required to reduce the volume of fluid tailings and convert them to trafficable landscapes. Therefore, the companies' tailings management systems should obey Directive 074 regulations. The main goal of oil sands management techniques is to be in compliance with directive 074 regulations.

In summary, the main focus of most current oil sand management techniques is to produce non-segregating tailings, which is economically and environmentally acceptable. One of the most important oil sands management techniques is composite tailings production. The consolidated tailings or composite tailings (CT) process is mainly involved with creating a mixture of sand, clay, and silt which is non-segregating (Mikula et al., 1998; Soane et al., 2010).

The major shortcomings of current oil sands management techniques can be summarized as: (i) lack of a direct relation between the long-term and short-term mine plans to the final CT produced (ii) limitations in considering the uncertainties associated with the oil sands production process which can result in not meeting the production targets and having storage area limitations. These shortcomings can lead to not being in compliance with the directive 074 regulations. Consequently there is a need to develop a map between the block by block information provided by the mine plans and the expected tailings to be produced at the end of the mine life considering that there are some uncertainties associated with this process which should be taken into account. The outcome of this research is expected to contribute towards the development of oil sands tailings management strategies, which will result in overcoming some of the environmental challenges associated with the oil sands production process.

Chapter 3

Theoretical Models and Algorithms

This chapter focuses on developing a linkage between the ore and the total CT tonnage produced downstream. The general theoretical framework and mathematical formulations are developed to construct the mass-balance relation between the ore tonnage and the CT tonnage.

3.1. Mass-Volume Relationships

Oil sands tailings are composed of four different phases with different characteristics. The four different phases are mineral grains, bitumen, gas and water. Since the viscosity of the bitumen is higher than the viscosity of the water, it has a really low mobility and can be assumed as a solid phase. The unique characteristics of oil sands tailings, lead to defining some mass-volume relationships which are complicated due to the effects of the clay contained with the tailings stream. When the mineral phase split into two phases, the oil sands tailings will become a five-phase material.

Defining of the mass-volume relationships for oil sands tailing helps to increase the understanding of the material behavior. The most common mass-volume relationships for the oil sands tailing include: sands fine ratio (SFR), fines water ratio (FWR), fines void ratio and sands void ratio (Boratynec, 2003). Fig. 2 shows a schematic diagram of oil sands tailings different phases.

Where:

$M : total\ mass\ of\ ore\ feed$

$M_g : mass\ of\ gas$

$M_w : mass\ of\ water$

$M_b : mass\ of\ bitumen$

$M_f : mass\ of\ fines$

$M_{sd} : mass\ of\ sand$

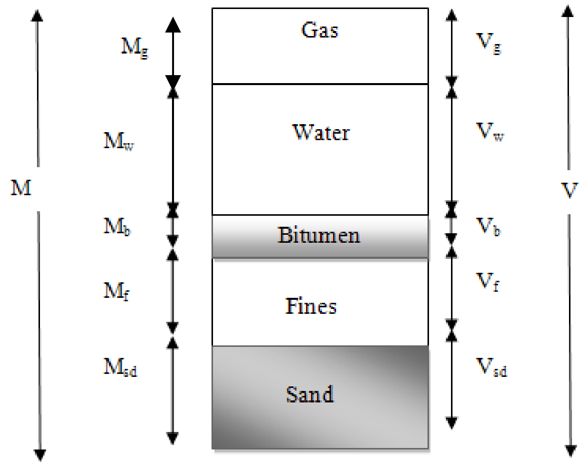

Fig. 2. – Schematic diagram of oil sands tailings different phases

3.1.1. Definitions of Mass-Volume Relationships

Eqs. (1) to (6) represent the mass-volume relationships for the oil sands ore. It should be noted that the total mass of gas in negligible and it is not considered in the following equations.

$$Fines\ content\ feed\ (F_{feed}) = \frac{M_{Feed}^{F}}{M} \tag{1}$$

$$Sand\ content\ feed\ (SD_{feed}) = \frac{M_{Feed}^{Sd}}{M} \tag{2}$$

$$Water\ content\ of\ feed\ (W_{feed}) = \frac{M_{Feed}^{W}}{M} \tag{3}$$

$$Solid\ content\ of\ feed (S_{Feed}) = 1 - B_{Feed} - W_{Feed} \tag{4}$$

$$Sands\ to\ fines\ ratio\ (SFR) = \frac{M_{Feed}^{Sd}}{M_{Feed}^{F} + M_{Feed}^{B}} \tag{5}$$

$$Sd_{Froth} = \frac{B_{Froth}}{B\%_{SET}} * Sd\%_{SET} \tag{6}$$

3.2. Composite Tailings (CT)

To produce non-segregating tailings, research shows that a mixture of tailings cyclone underflow and MFT, with the addition of lime (CaO) or phosphogypsum (CaSo4.2H2O) produces composite tailings which is a non-segregating tailings stream (Boratynec, 2003). One important advantage of composite tailings production is that the transportation and pumping of the produced CT is easy. Using MFT to produce CT, the required sand comes directly from the extraction process.

Fig. 3 shows a schematic diagram of the CT production process. The ore feed from the oil sands mine is sent to the separation cell (flotation cells) to separate bitumen from the fines using aeration (air flotation) technique. The tailings from the froth treatment will be sent to the ponds. Mature fine tailings will be formed in almost a two year period in the pond. In the hydro-cyclone, coarse solids will be simply separated from fine solids; cyclone over flow contains fine solids whilst the cyclone under flow carries the coarse solids. A portion of cyclone under flow will be sent to cell DT and the remaining portion will be used in the composite tailings production. In order to complete the CT production process, fines and water will be added from the MFT deposit with a solid content of approximately 30%. Finally, Gypsum will be added to MFT to produce the non-segregating tailings.

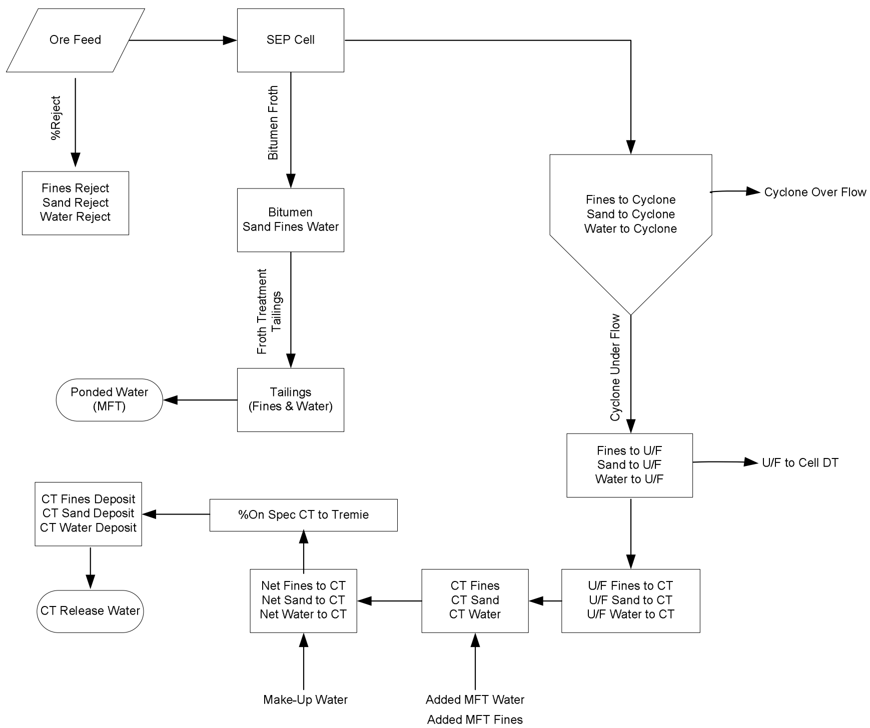

Fig. 3. – Mass balance flow diagram for CT production

3.3. Mass-Balance Relation between CT and the Ore Feed

The goal of this research is to develop the mine plan according to the limitation of CT required at the end of the process. In order to find the mass-balance relation between CT and the mine plan, the mass balance relation between the ore and the final CT produced should be developed first. Eq. (7) shows that the total mass of CT can be calculated by finding the total mass of sand, fines, and water needed to produce CT. Eq. (8) controls the total mass of fines in the CT deposit for a specific ore tonnage. To calculate the CT sand and CT water deposit, Eqs. (9) and (10) can be employed.

$$Total\,mass\,of\;CT = F_{CT} + Sd_{CT} + W_{CT} \tag{7}$$

$$F_{CT} = \%\,on-spec \times \left(MFT_{CT}^{F} + UF_{CT}^{F}\right) \tag{8}$$

$$Sd_{CT} = \%on-spec \times UF_{CT}^{Sd} \tag{9}$$

$$W_{CT} = \%\,on-spec \times \left(make-up\;water + MFT_{CT}^{W} + UF_{CT}^{W}\right) \tag{10}$$

3.3.1. CT Fines Deposit

According to Eq. (8), the total mass of fines in CT can be found by adding the total mass of added MFT fines and the mass of underflow fines to CT. According to Eq. (11), the total tonnage of added MFT fines sent to CT production can be found using the tonnages of under flow sand and fines sent to the CT production, and the target SFR in pipe. To find the tonnage of under flow sand sent for producing CT, Eq. (12) can be employed. The total sand content of the cyclone underflow is affected by the target sand percent to underflow, and the total tonnage of sand sent to the hydro cyclone; this relation is represented in Eq. (13).

Eqs. (14) and (15) shows that the difference between feed sand content and the tonnage of sand sent to hydro cyclone is the summation of sand sent to rejects and the tonnage of sand sent to the froth. The total sand content of the cyclone under flow can be calculated by employing Eq. (16). Based on Eq. (16), the total tonnage of sand in cyclone under flow is affected by the target sand percent in cyclone underflow, sand content of the feed, sand reject percent, bitumen in forth, the bitumen percent and the sand percent specified in the SET properties. The total fines tonnage of underflow sent to CT production, the total fines content of the cyclone underflow, and the total percentage of under flow sent to cell DT can be found using Eqs. (17), (18), and (19) respectively.

Eq. (20) shows that cell properties such as cell efficiency and physical capture of the cell, and the sand content of the cell, are three main factors affecting the total sand content of the cell DT. According to Eq. (20), the sand content of the cell has a direct relation with the cell dry density and the volume of the cell, and has an inverse relation with the fines content of the cell.

Finally, Eqs. (22) to (24) can be employed to find the total percentage of cyclone under flow sent to cell DT . It should be noted that Eqs. (1) to (22) are derived from Suncor’s flow sheet.

The total tonnage of under flow sand sent to the CT production process can be found using Eqs. (25) and (26).

In order to find the total tonnage of under flow fines required for CT production, Eq. (27) and should be employed. Eq. (28) represents the total tonnage of added MFT fines sent for CT production.

Based on Eq. (29), the summation of added MFT fines and the under flow fines tonnage sent to CT production has a direct relation with the tonnage of under flow sand sent to CT production, and an inverse relation with the target SFR in pipe.

Using Eqs. (8), (27) and(28), the total CT fines tonnage can be calculated, which is represented in Eq. (30).

$$MFT_{CT}^{F} = \frac{UF_{CT}^{Sd}}{SFR} - UF_{CT}^{F} \tag{11}$$

$$UF_{CT}^{Sd} = SandToUF \times \left(1 - UF\%_{CellDT}\right) \tag{12}$$

$$UF_{Sd} = Sd\%_{UF} \times Sd_{Cyclone} \tag{13}$$

$$Sd_{Cyclone} = Sd_{Feed} - Sd_{RJ} - Sd_{Froth} \tag{14}$$

$$Sd_{Cyclone} = Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right) \tag{15}$$

$$UF_{Sd} = Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right) \tag{16}$$

$$UF_{CT}^{F} = UF_{F} \times \left(1 - UF\%_{CellDT}\right) \tag{17}$$

$$UF_{F} = \frac{UF_{Sd}}{UF_{Sd\%}} \times UF_{F\%} \tag{18}$$

$$UF\%_{CellDT} = \frac{Sd_{DT}}{UF_{Sd}} \tag{19}$$

$$Sd_{DT} = \frac{Sd_{Cell}}{PhC_{Cell} \times Eff_{Cell}} \tag{20}$$

$$Sd_{Cell} = \left(V_{Cell} \times \rho_{Cell}\right) - F_{Cell} \tag{21}$$

$$F_{Cell} = V_{Cell} \times \rho_{Cell} \times F\%_{S} \tag{22}$$

$$Sd_{DT} = \frac{\left(V_{Cell} \times \rho_{Cell}\right) \times \left(1 - F\%_S\right)}{PhC_{Cell} \times Eff_{Cell}} \tag{23}$$

$$UF\%_{CellDT} = \frac{\dfrac{\left(V_{Cell} \times \rho_{Cell}\right) \times \left(1 - F\%_S\right)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M)_{Sd} - \left(\dfrac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right)} \tag{24}$$

$$\begin{aligned} UF_{CT}^{Sd} &= \\ & Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right) \\ & \times \left(1 - \frac{\dfrac{\left(V_{Cell} \times \rho_{Cell}\right) \times \left(1 - F\%_S\right)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\dfrac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right)}\right) \end{aligned} \tag{25}$$

$$\begin{aligned} UF_{CT}^{Sd} &= \\ & Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right) \\ & \times \left(1 - \frac{\dfrac{\left(V_{Cell} \times \rho_{Cell}\right) \times \left(1 - F\%_S\right)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\dfrac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right)}\right) \end{aligned} \tag{26}$$

$$\begin{aligned} UF_{CT}^{F} &= \frac{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\dfrac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right)}{Sd_{UF}} \\ & \times UF_{F\%} \times \left(1 - \frac{\dfrac{\left(V_{Cell} \times \rho_{Cell}\right) \times \left(1 - F\%_S\right)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\dfrac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}\right)\right)}\right) \end{aligned} \tag{27}$$

$$MFT_{CT}^{F} = \frac{1}{SFR\ in\ pipe} \times Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)$$

$$\times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_S)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right)$$

$$- \frac{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)}{Sd_{UF}}$$

$$\times UF_{F\%} \times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_S)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \tag{28}$$

$$MFT_{CT}^{F} + UF_{CT}^{F} = \tag{29}$$

$$\frac{UF_{CT}^{Sd}}{SFR} = \frac{1}{SFR} \times Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - (\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET}) \right)$$

$$\times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_S)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right)$$

$$F_{CT} = \%on - spec \times \frac{1}{SFR} \times Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)$$

$$\times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_S)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \tag{30}$$

3.3.2. CT Sand Deposit

The total tonnage of sand in the produced CT can be found using the total CT fines deposit and the target SFR in pipe; therefore, Eqs. (30) and (31), result in Eq. (32) which represents the CT sand deposit.

$$Sd_{CT} = F_{CT} \times SFR \tag{31}$$

$$Sd_{CT} = \%on-spec \times Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)$$
$$\times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_{S})}{physical\ capture \times cell\ efficiency}}{Sd\%_{UF} \times \left(Sd_{Feed} - RJ\%_{Sd} - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \quad (32)$$

3.3.3. CT Water Deposit

Based on Eq. (10), added MFT water, make-up water, and mass of under flow water sent to the CT production process, are three different water sources for production of CT. mass of the added MFT water can be calculated using Eqs. (33) and (34).

In order to find the total mass of under flow water sent to the CT production process, Eqs. (35) to (38) should be employed. Eq. (39) controls the total tonnage of make-up water required for CT production for a specific ore tonnage.

Finally, Eq. (40) represents the total tonnage of water required to produce CT for a specified ore tonnage.

$$MFT_{CT}^{W} = \frac{MFT_{CT}^{F}}{S\%_{MFT}} - MFT_{CT}^{F} = MFT_{CT}^{F} \times \left(\frac{1}{S\%_{MFT}} - 1 \right) \quad (33)$$

$$MFT_{CT}^{W} = \left(\frac{1 - S\%_{MFT}}{S\%_{MFT}} \right) \times \frac{1}{SFR} \times (Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)$$
$$\times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_{S})}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) -$$
$$\frac{Sd\%_{UF} \times \left(Sd_{Feed} - RJ\%_{Sd} - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)}{UF_{Sd\%}}$$
$$\times UF_{F\%} \times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_{S})}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \quad (34)$$

$$UF_{CT}^{W} = W_{UF} \times (1 - UF\%_{\ Cell\,DT}) \quad (35)$$

$$UF_{W} = \frac{UF_{Sd}}{UF_{Sd\%}} \times UF_{W\%} \quad (36)$$

$$UF_W = \frac{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)}{UF_{Sd\%}} \times UF_{W\%} \tag{37}$$

$$UF_{CT}^{W} = \frac{Sd\%_{UF} \times \left(Sd\%_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)}{UF_{Sd\%}} \times UF_{W\%} \times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_S)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \tag{38}$$

$$if \;\; \frac{F_{CT} + Sd_{CT}}{S\%_{CT}} \times (1 - S\%_{CT}) - (UF_{CT}^{W} + MFT_{CT}^{W}) < 0 \rightarrow make-up\, water = 0 \tag{39}$$

$$if \;\; \frac{F_{CT} + Sd_{CT}}{S\%_{CT}} \times (1 - S\%_{CT}) - (UF_{CT}^{W} + MFT_{CT}^{W}) \geq 0 \rightarrow make-up\, water = \frac{F_{CT} + Sd_{CT}}{S\%_{CT}} \times (1 - S\%_{CT}) - W_{CT}$$

$$W_{CT} = \%on - spec \times Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right) \times \left(1 - \frac{\frac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_S)}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B_{Froth}} \times Sd\%_{SET} \right) \right)} \right) \times \left\{ \left(\frac{1 - S\%_{MFT}}{S\%_{MFT}} \times \left(\frac{1}{SFR} - \frac{UF_{F\%}}{UF_{Sd\%}} \right) \right) + \frac{UF_{W\%}}{UF_{Sd\%}} \right\} + make-up \;\; water \tag{40}$$

3.3.4. Total Mass of CT

Based on Eqs. (7) and (39), the total mass of CT depends on whether the make-up water is required for CT production or not. Eq. (41) represents the total mass of CT produced when make-up water is not added to the process. Finally, Eq. (42) controls the total mass of produced CT in case of adding make-up water to the CT production process.

$$If \quad \frac{F_{CT} + Sd_{CT}}{S\%_{CT}} \times (1 - S\%_{CT}) - (UF_{CT}^{W} + MFT_{CT}^{W}) < 0 \rightarrow make - up\ water = 0$$

$$\Rightarrow Total\ \ mass\ of\ \ CT = \%On - spec \times Sd\%_{_{UF}} \times \left(Sd_{Feed} - RJ\%_{Sd} - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right) \times \left(1 - \frac{\dfrac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_{S})}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \times \left(\frac{1 + SFR}{SFR} + \left\{ \left(\frac{1 - S\%_{MFT}}{S\%_{MFT}} \times \left(\frac{1}{SFR} - \frac{UF_{F\%}}{UF_{Sd\%}} \right) \right) + \frac{UF_{W\%}}{UF_{Sd\%}} \right\} \right) \tag{41}$$

$$If \quad \frac{F_{CT} + Sd_{CT}}{S\%_{CT}} \times (1 - S\%_{CT}) - (UF_{CT}^{W} + MFT_{CT}^{W}) \geq 0 \rightarrow make - up\ water = \frac{F_{CT} + Sd_{CT}}{S\%_{CT}} \times (1 - S\%_{CT}) - (UF_{CT}^{W} + MFT_{CT}^{W})$$

$$\Rightarrow Total\ mass\ of\ CT = \%on - spec \times \left(\frac{1 + SFR}{SFR} \right) \times \left(\frac{1}{S\%_{CT}} \right) \times Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right) \times \left(1 - \frac{\dfrac{(V_{Cell} \times \rho_{Cell}) \times (1 - F\%_{S})}{PhC_{Cell} \times Eff_{Cell}}}{Sd\%_{UF} \times \left(Sd_{Feed} - (RJ\% \times RJ\%_{Sd} \times M) - \left(\frac{B_{Froth}}{B\%_{SET}} \times Sd\%_{SET} \right) \right)} \right) \tag{42}$$

The total tonnage of CT produced for a specified ore tonnage given by Eqs. (41) and (42) can be employed in relating the long-term mine plan to the final tailings produced at the end of the oil sands production operations. These mathematical formulations are employed in a CT calculation model in which the long-term mine plan exported from the optimization software will become the input for the model. The long-term mine plan contains information on block such as tonnage, bitumen grade, sand content, block fraction and period of extraction, and is imported to the CT calculation model, and the information such as economic block value (EBV), ore tonnage and the tonnage of CT produced for each block, based on the fraction of the block to be extracted in each period, will be the outputs of the model.

3.4. Risk-Based CT Calculation Model

Considering different risks and uncertainties is very critical in production scheduling. The main goal of this part of this research is to consider the uncertainties associated with the long-term mine scheduling in relating the mine plan to the final CT. Uncertainties associated with the CT production process result in not meeting the production targets at the end of the process, which can cause serious problems especially in case of having storage area limitations.

In the CT production process, some inputs such as reject percent, sand reject percent, target SFR in pipe and the on-spec% CT can be variable based on several operational factors. Different probability distributions should be defined to capture the uncertainties associated with this process. The target SFR in pipe is related to the CT solids percent, and based on the experiments, in order to have a trafficable landscape, the produced CT should have a SFR of approximately 4.0. The CT produced with a SFR of less than 4.0 is soft and requires capping with rapid-draining materials to become a reclaimable and trafficable landscape (Suncor, 2009).

The on-spec% CT depends on the sand content of the feed, water and MFT, and based on deductions from several literatures, it can fluctuate between 85% and 100%. Based on assumptions, the lognormal probability distribution is assigned to the on-spec% CT to calculate the final CT produced.

The overall reject percent and the sand reject percent depend on several operational factors; therefore, these inputs are uncertain during the CT production process. Normal distributions are assigned to reject percent and sand reject percent. Table 1 shows the distributions assigned to four uncertain inputs.

Table 1- Probability distributions assigned to four uncertain input variables for CT calculation

Input	Distribution assigned to the input
Reject percent	Normal
Sand reject percent	Normal
Target SFR in pipe	Uniform
On-spec CT	Lognormal

It should be considered that, since the normal distributions assigned to reject percent and sand reject percent might include negative values, truncation limits should be defined for these two distributions. In other words, in order to avoid from sampling negative values for the reject percent and sand reject percent, the negative values of the probability distributions should be truncated.

After assigning distributions to capture the uncertainties in the CT process, the simulation should be run with a sufficient number of runs based on the desired confidence interval.

During each simulation run, in each period, values for reject percent, sand reject percent, target SFR in pipe and on-spec CT will be sampled from the distributions assigned to each variable input. Therefore, number of samples selected from each probability distribution in each simulation run is equal to the total years of the mine life.

The simulation should be run with four distributions assigned to four uncertain inputs for the CT process. In addition to running the simulation considering the risks and uncertainties associated with all of the variable inputs, it is crucial to perform the sensitivity analysis for the simulation outputs. The purpose of the sensitivity analysis is to find out the variable inputs which the total tonnage produced in each period is most sensitive and least sensitive to. In order to perform the sensitivity analysis, simulation should be run with different combinations of uncertain inputs.

3.5. Summary and Remarks

In summary, the mathematical formulations and mass-balance equations required to integrate the long-term mine plan to the final CT produced at the end of the production process have been derived in this chapter. A comprehensive study on the mass-volume relationships between the ore feed and the CT tonnage has been carried out in this chapter in order to achieve the objectives of this research.

Chapter 4

Case Study and Discussion of Results

The mathematical formulations and mass-balance equations developed in Chapter 3 are transformed to a CT calculation model. The CT calculation model is implemented in VBA and the code is provided in Appendix A. This chapter is concerned with the verification of the CT calculation model using large-scale oil sands data. In addition, a stochastic simulation model is developed in this chapter to capture the uncertainties associated with the CT production process. Finally, sensitivity analysis is done on the simulation results to capture the sensitivity of the produced CT tonnage to different variable inputs.

4.1. Oil Sands Large-Scale Data

In order to verify the CT calculation model, it should be implemented on either synthetic or real data. In this case, large-scale data with 864 drillholes, total tonnage of 4830 MT and total ore tonnage of 2743 MT was used to verify the deterministic CT calculation model. The size of the deposit is 4km x 8km with a height of 75m. Fig. 4 shows a cross section of different rock-types in the oil sands formation. 3D view of the drillhole data is presented in Fig. 5.

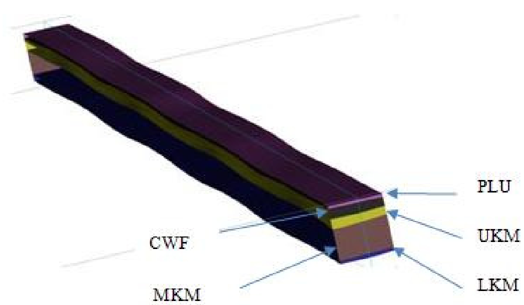

Fig. 4 – Different rock-types of the oil sands formation on a single cross section

It should be noted that CWF stands for Clear Water Formation, PLU stands for Pleistocene Units, UKM stands for Upper McMurray Formation, MKM stands for Middle McMurray Formation and LKM stands for Lower McMurray Formation.

A block model with a total of 228,760 blocks with a dimension of 50 m by 50 m by 15 m for each block was created. In this case study, block model contains 14 benches. 6 out of 14 benches contain ore; 3 benches of overburden at the top and 5 benches of waste (Devonian) at the bottom of the block model.

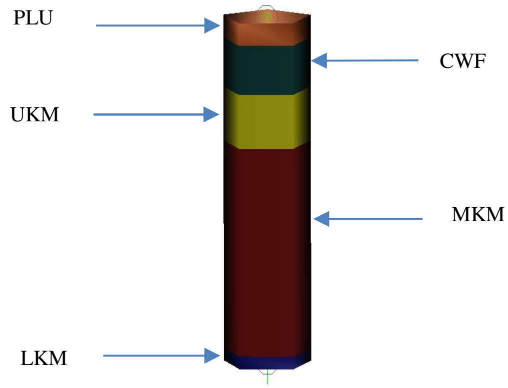

Fig. 5 – Drillhole data 3D view

4.1.1. Directional Mining and Pushback Definition Strategy

The main motivation for conducting directional mining in this research is to provide the space for in-pit disposal of CT. In directional mining, the mining process should be done in a specific direction to facilitate tailings in-pit disposal. The desired mining direction selected for this model is from north to south, but it should be considered that different mining directions can be implemented based on the operational constraints.

To facilitate tailings in-pit disposal, providing space for dyke construction and also to reduce the lead time between mining and start of reclamation, the deposit area is divided into four pushbacks. The number of pushbacks was selected based on the standard sizes of the in-pit tailings facility cells. Therefore, the deposit is divided into four cells. Number of leads in each pushback should be defined in a way that all of the blocks in one pushback are extracted before starting the next pushback. Fig. 6 represents different pushbacks generated in the Whittle software.

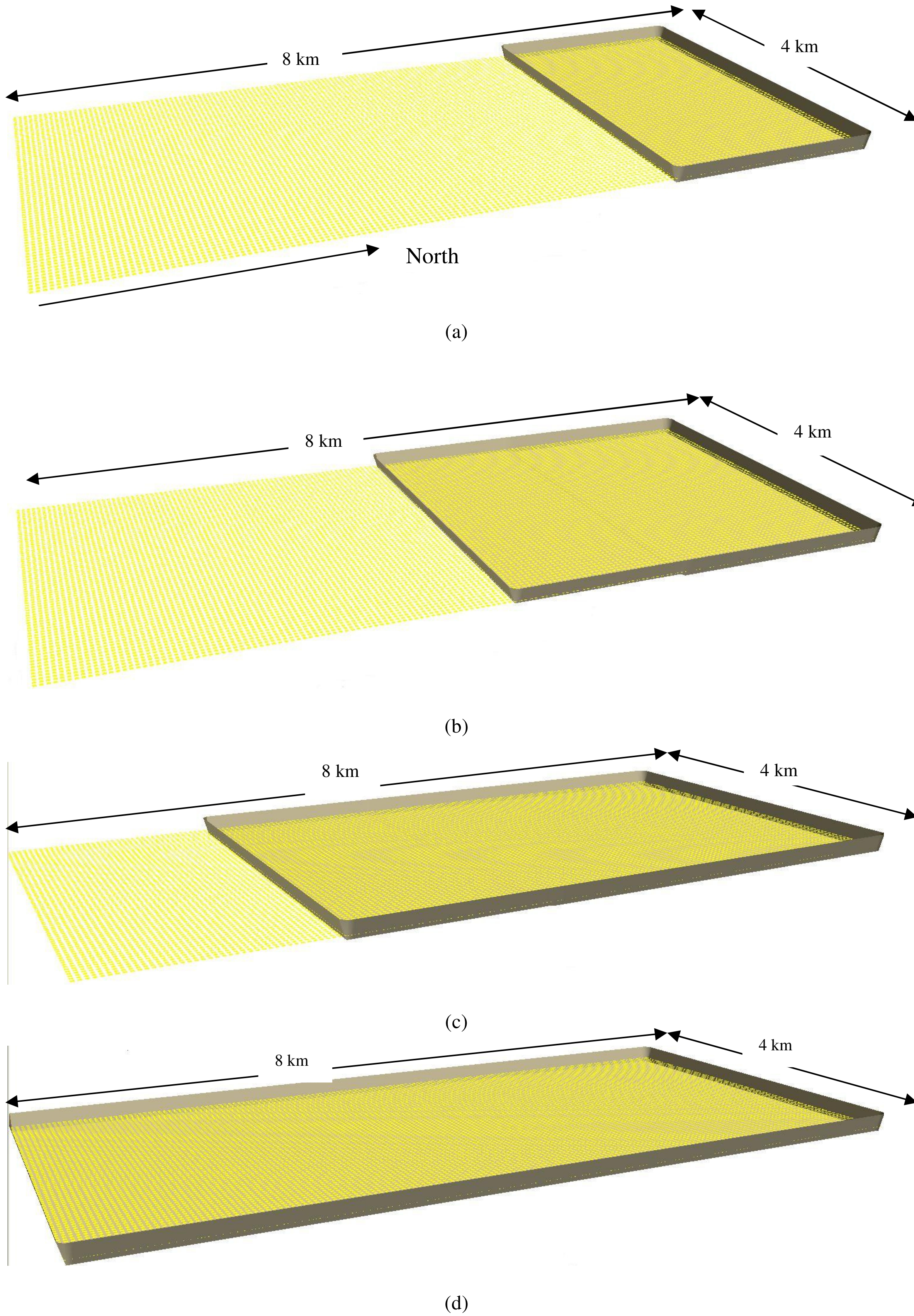

Fig. 6 – 3D view of different pushbacks during the mine life: (a) pushback 1, (b) pushback 2, (c) pushback 3, (d) pushback 4

4.1.2. Schedule Graph

The original block model with a block dimension of 50m x 50m x 15m is imported to the optimization software environment; in the Whittle software (Gemcom Software International, 2011) the original block model is re-blocked to have a block with a dimension of 50m x 50m x 90m. In other words, in this model 6 blocks in the Z direction are grouped together to form a re-blocked model. The main goal of re-blocking the original block model is to make sure that the mining process is proceeding in a way to facilitate in-pit disposal. Table 2 represents the economic and mining parameters for the model.

Table 2 – Economic and mining parameters

Reference Mining Cost ($/Tonne)	4.60
Mining Recovery Fraction	0.95
Processing Cost ($/%m)	5.03
Selling Cost ($/%m)	2.81
Recovery	0.90
Mining Limit (Mt)	262
Mill Limit (Mt)	200

Four pushbacks are defined to divide the deposit into four equal areas. The total ore tonnage and waste tonnage extracted in each pushback is presented in Table 3.

Table 3 – Ore tonnage and waste tonnage in each pushback

Tonnage	Pushback 1	Pushback 2	Pushback 3	Pushback 4
Total ore tonnage (Mt)	780.2	586.4	833.8	703.1
Total waste tonnage (Mt)	545.3	437.2	572.8	508.9

Table 4 represents statistics for the final schedule. Based on this table, the life of mine is 18 years and the NPV is 19.12 M$. The schedule graph for this model is shown in Fig. 7. As it can be seen in this figure, the resulting schedule is pretty smooth and the ore and waste tonnages to be extracted in each period is almost uniform during the mine life. The mining sequence file from this model should be exported to the deterministic CT calculation model. The mining sequence file contains header line and parcel lines for each block. The information such as XI, YI, ZI, number of parcels, mining cost adjustment factor (MCAF), processing cost adjustment factor (PCAF), block tonnage, period, block fraction and pushback number, are provided for each block in the header line. Information such as XI, YI, ZI, rock type, parcel tonnes, fines%, bitumen%, parcel destination and parcel fraction are provided in the parcel line for each block.

Table 4 – Final schedule statistics

Total Ore Tonnage (Mt)	2750
Total Tonnage (Mt)	4700
NPV (M$)	19.12
Life of Mine (Years)	18

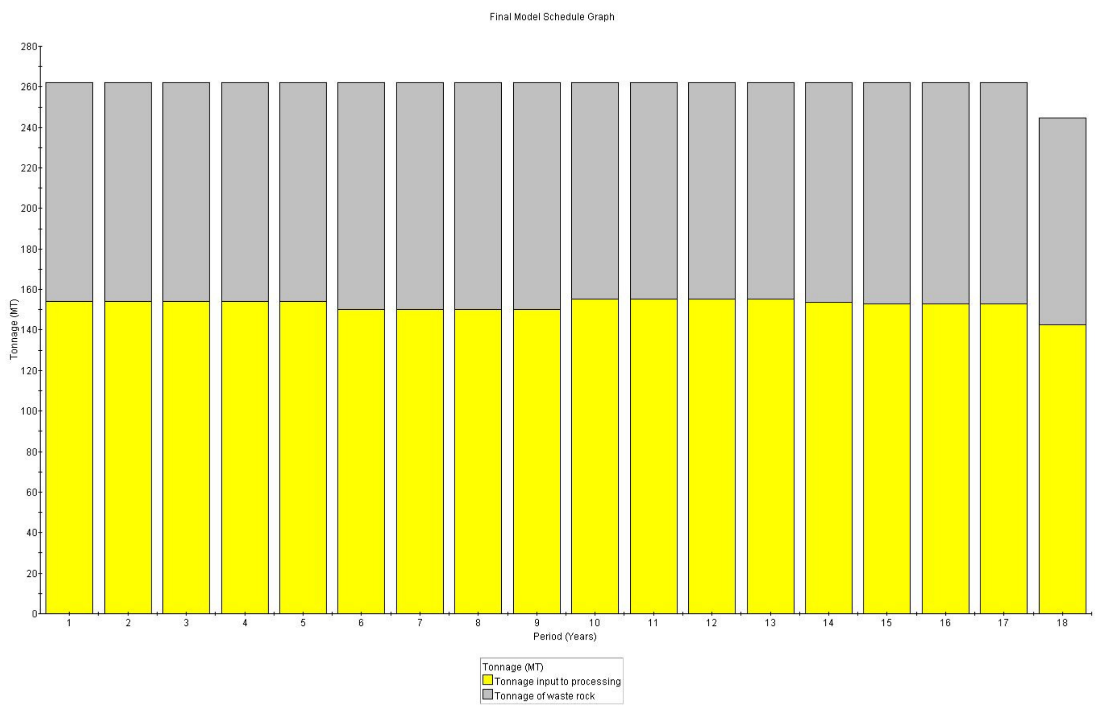

Fig. 7 – Final schedule graph

The final pit designed for this model is illustrated in Fig. 8.

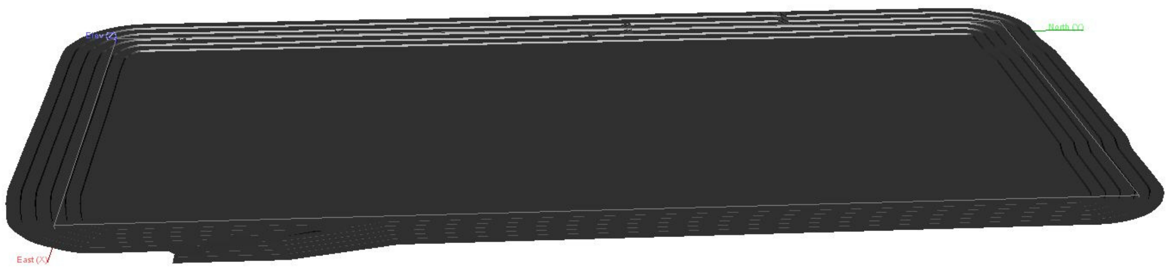

Fig. 8 – Final pit designed

4.2. Deterministic CT Calculation Model

In building the CT calculation model, Suncor's flow sheet is employed to find the mass-balance relation between ore feed and CT tonnage and the equations were derived based on this flow sheet. Some assumptions are made to model the inputs for the CT production process. It should be considered that these assumptions are based on the Suncor's operational factors. A VBA code is developed to implement the CT calculations on the mining sequence file. This code is provided in Appendix A. This code takes the block by block information provided in parcel and header lines and transfers it to the CT calculation equations and provides the information such as ore tonnage, economic block value (EBV), block bitumen, block fines, ore value, solid content and last but not least the CT tonnage produced for each block. The mass-balance equations provided in Chapter 3 are employed to develop this model.

In the deterministic CT calculation model it is assumed that there is no uncertainty with the CT production process and the operational factors would not change during the mine life. Fig. 9 represents the bar chart for the output of the CT calculation model. In this figure, the line shows the CT tonnage produced in each period. From this figure it can be seen that the CT tonnage produced in each period has a direct relation with the ore tonnage processed in the same period. In the first four periods where the ore tonnage is the same, the CT tonnage remains constant. In periods 5, 6, 7 and 8 where there is a slight decrease in the extracted ore tonnage, CT tonnage produced reduces as well. The average CT tonnage is 119.7 MT. The total CT tonnage produced at the end of the mine life is 2033 MT.

Table 5 – Operational factors assumed in the CT calculation model

Cell volume (m^3)	100
Cell dry-density (kg/m^3)	1.559
Cell efficiency (%)	75
Physical capture (%)	70
SFR in pipe	4
MFT %solids (%)	30
%On-spec CT to Tremie (%)	85
CT %solids (%)	55
Reject percent (%)	5
Sand reject percent (%)	50

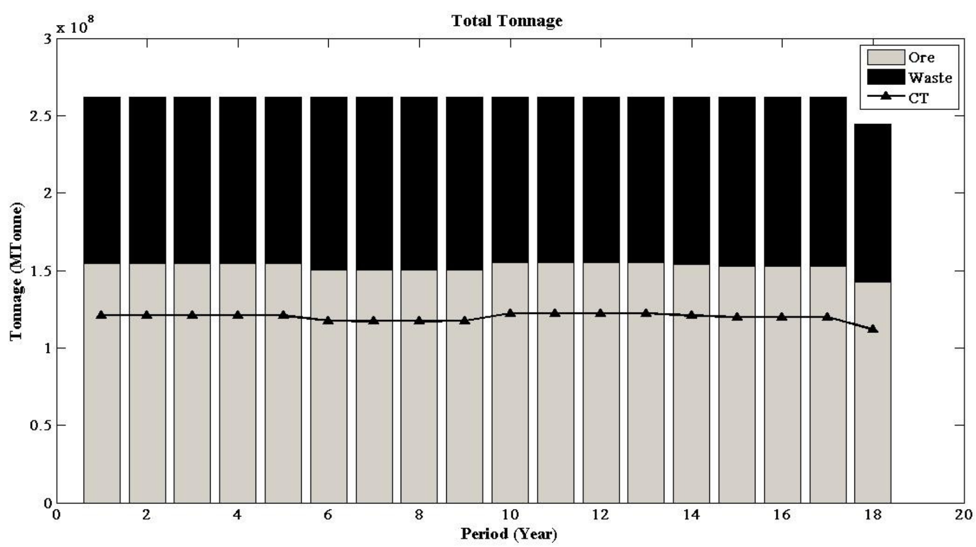

Fig. 9 – Ore tonnage, waste tonnage and CT tonnage produced in each period

As it was mentioned before in the text, sand, fines and water are three main components of CT. The bar chart for the tonnages of these components in each period is presented in Fig. 10. Based on this figure, it can be concluded that sand and water are two main constituents in CT production whilst fines is the smallest constituent.

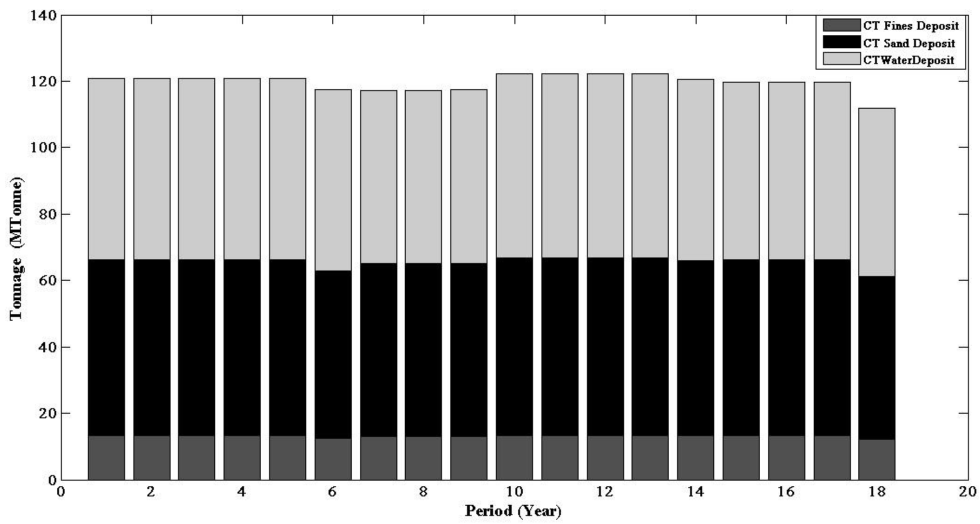

Fig. 10 – Total tonnages of three main components of CT produced in each period

Fig. 11 illustrates the relationship between the tonnages of CT produced and the average fines content of the feed in each period. According to this figure, when fines content of the feed increases, the total mass of CT produced will decrease and therefore there is an inverse relation between CT tonnage and the average fines content of feed. From this graph it is expected to have a direct relation between CT tonnage and average sand content of the feed, since the sand content will increase with reducing the fines content. The inverse relation between sand content and fines content and the inverse relation between the average fines content of the feed and the produced CT tonnage, result in a direct relation between CT tonnage and average sand content of the feed.

The direct relation between CT tonnage produced and average sand content of the feed in each period is illustrated in Fig. 12. Based on this figure, when the average sand content increases from 77.4% to 78%, the total CT tonnage produced in each period increases from about 117 MT to 122 MT.

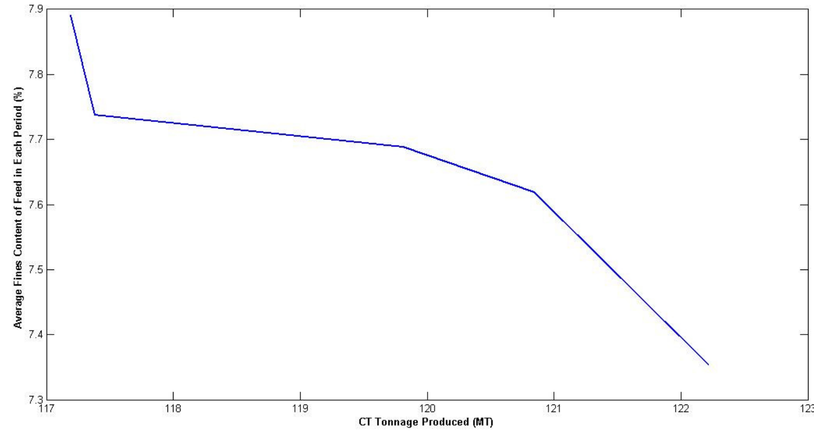

Fig. 11 – CT tonnage produced in each period vs. average fines content of feed in each period

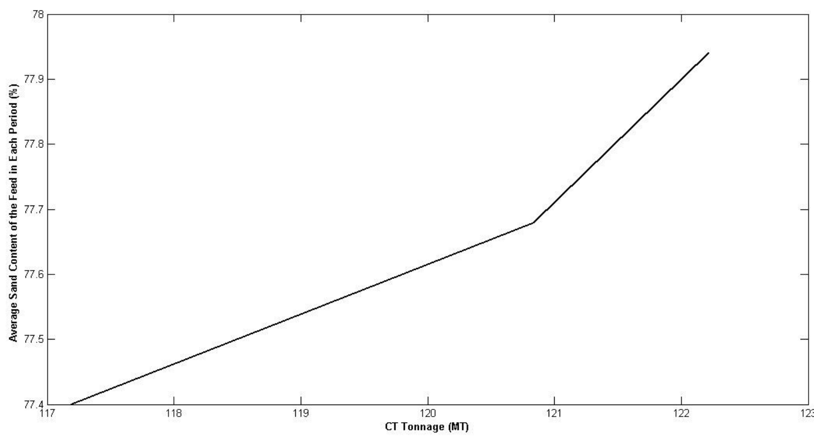

Fig. 12 – CT tonnage produced in each period vs. average sand content of feed in each period

4.3. Stochastic Simulation Model

The deterministic model does not consider the risks and uncertainties associated with the CT production process, and based on this model it is assumed that all operational factors remain constant during the mine-life; hence the CT tonnages predicted and reported based on this model might be inaccurate.

In reality, there are various uncertainties present in the CT production process which can result in deviating from the CT tonnage predicted to be produced based on the deterministic model. Not being able to predict the CT tonnage to be produced at the end of each period and at the end of the mine life result in being incompliant with the directive 074 regulations. In addition, under-estimating the mass of CT can cause serious problems in terms of the storage areas available for CT disposal.

4.3.1. Probability Distributions

Considering probable uncertainties is critical in production scheduling. The objective of this section of research is to capture the risks associated with the long-term mine scheduling in relating the mine plan to the final CT. As it was mentioned before, uncertainties in the CT production process will result in not meeting the production targets at the end of the process, which can cause serious problems especially in case of having storage area limitations.

In the CT production process, the inputs such as reject percent, SFR in pipe and the on-spec CT% to Tremie can be variable based on several operational factors. To be able to capture the variations in the uncertain inputs, proper distributions should be defined. Each distribution should be selected in a way to ascertain that it can model the probable variations of the specified operational factor during the mine life. It should be considered that in building the stochastic model, it is assumed that the four uncertain inputs to the CT calculation model are independent and there is no correlation between these input variables.

In this dissertation it is assumed that there are four input variable during the mine life:

1. **Reject percent**: the overall percentage of the feed tonnage which should be sent to the rejects. Reject percent can vary based on several operational factors.
2. **Sand reject percent**: the percentage of the feed sand content which should be sent to the rejects. Sand reject percent can be variable during the mine life based on several operational factors.
3. **Target SFR in pipe**: the acceptable sand to fines ratio in pipe. SFR in pipe changes with changing the CT solids percent. Based on experiments, in order to have a trafficable landscape, the produced CT should have a SFR of approximately 4.5. The CT produced with a SFR less than 4.5 is soft and requires capping with rapid-draining materials to become a reclaimable and trafficable landscape (Suncor, 2009).
4. **On-spec CT to Tremie**: the percentage of acceptable CT to be sent to the tremie. On-spec CT to tremie depends on sand content of the feed, water and MFT.

In this research it is assumed that reject percent and sand reject percent follow a normal distribution, target SFR in pipe follows a uniform distribution and on-spec CT to Tremie can be modeled using a lognormal distribution. It should be noted that different distributions should be assigned to these input variables based on different oil sands production processes and different operational factors. Table 6 represents four variable inputs to the CT production and the distributions assigned to these variables to capture the risks and model the variations.

Table 6 – Probability distributions assigned to four input variables in the CT production process

Variable Input	Assigned Distribution
Reject percent	Normal
Sand reject percent	Normal
Target SFR in pipe	Uniform
On-spec CT to Tremie	Lognormal

According to Table 5, the reject percent for the deterministic model is 5%. The normal distribution assigned to capture the reject percent variations during the mine life has a mean of 0.05. It should be considered that to avoid sampling negative values for the reject percent from the normal probability distribution, the negative values should be truncated. In this case the normal distribution assigned to the reject percent is truncated to have a minimum reject percent of 4% and maximum reject percent of 6%.

Based on Table 5, the sand reject percent for the deterministic model is 50%. The normal distribution assigned to this input has a mean of 5 with truncated minimum and maximum of 3 and 6 respectively.

The minimum and maximum value for the uniform distribution assigned to the target SFR in pipe are 4 and 4.5 respectively. Also the lognormal distribution assigned to capture the uncertainties associated with the on-spec% CT to Tremie is truncated to have a minimum of 85% and a maximum of 99%.

The statistics such as mean, standard deviation, minimum and maximum truncation for the probability distributions assigned to four input variables are provided in Table 7.

The selected distributions should be employed in the CT calculation code and the code should take samples from the defined distributions instead of using fixed values for the four specified variable inputs. For instance, whenever it is required to use the reject percent in the code in calculating the produced CT tonnage, a sample should be taken from the normal distribution assigned to the reject percent. It is assumed that each of these four inputs remains constant during each period. In other words, in each period during the mine life, one sample is taken from each of these inputs. Therefore, in each run of the simulation, number of samples chosen for each input variable is equal to the mine life (years). Since the mine life in this case study is 18 years, in each simulation run, 18 different values are taken from each distribution assigned to each input variable to capture the uncertainties associated with the corresponding input.

Table 7 – Statistics of the probability distributions assigned to four input variables

Variable input	Distribution	Mean	Standard deviation	Truncation minimum	Truncation maximum
Reject percent (%)	Normal	5.00	0.50	4.00	6.00
Sand reject percent (%)	Normal	50.0	5.00	30.0	60.0
Target SFR in pipe	Uniform	4.25	----	4.00	4.50
On-spec CT to Tremie (%)	Lognormal	90.0	2.41	85.0	99.0

4.3.2. Confidence Interval and Number of Replications

A simulation replication is a single run of simulation which shows the path from the initial condition to the final condition of the simulation (Rossetti, 2010). The objective of this part of this dissertation is to determine the required number of simulation replications. Prior to this, the desired confidence interval should be estimated. Confidence interval estimation is to define a desired interval where it is desired to have the simulation output within that interval. In other words, confidence interval represents the closeness to an unknown population parameter. Where α represents the probability of not falling within the confidence interval in 100 replications, (1-α) represents the level of confidence (Rossetti, 2010).

In this case study, a 95% level of confidence is desired. In other words, it is desired to have the proper number of simulation replications in a way to ascertain with 95% confidence level that the final CT tonnage produced is within the expected interval. First of all, simulation should be run with a specified number of replications. In this case, the simulation is run with 10 replications. The statistics such as average CT tonnage and standard deviation of the CT tonnages produced in each period based on these 10 simulation run should be recorded. The maximum standard deviation in the CT tonnages produced in each period based on 10 replications is about 5 MT and belongs to period 4. In order to find the proper number of replications to ensure that a 95% level of confidence will be reached, Goal Seek program of Excel is employed. With a desired bound of 1MT, the Excel Goal Seek program is employed to minimize the difference between the half-width and the bound. Eq. (43) to (46) were used to calculate the number of replications required to achieve a 95% confidence level. In Eq. (44) t-alpha is derived from t-distribution. Based on Eq. (46), the goal is to minimize the difference between half-width and the desired bound by changing n. The average CT tonnage produced for period 4 during these 10 runs is about 125MT. Based on these settings, to be able to reach a confidence level of 95%, 100 simulation replications are required.

$$
\begin{aligned}
&Confidence\ Level = 0.95 \\
&alpha\,(\alpha) = 1 - 0.95 = 0.05 \\
&n = number\ of\ replications\ required \\
&\sigma\,(for\ 10\ replications) = 5\,Mt \\
&Bound = 1\,Mt
\end{aligned}
\tag{43}
$$

$$t - alpha = TINV(\alpha, n-1) \tag{44}$$

$$half - width = t - alpha \times \frac{\sigma}{\sqrt{n}} \tag{45}$$

$$\min\,((half - width) - Bound \tag{46}$$

4.3.3. Verification of the Stochastic CT Calculation Model

The next step in this research is to verify the stochastic simulation model. To find the CT tonnage produced in each period, considering the risks associated with this process, samples should be taken from each distribution to capture the values for the corresponding input variable. In each simulation run, 1 sample will be taken for each distribution during each period resulting in 18 samples from each distribution for each simulation run. Therefore, number of samples taken from each probability distribution after 100 simulation runs is equal to 1800. To run the simulation, the @Risk program (Palisade, 2010) is employed.

In the stochastic CT calculation model it is assumed that all four specified variable inputs are uncertain during the mine life hence sampling should be done from all four distributions.

The VBA code reads the operational inputs and distribution ranges for each of the four inputs and starts running simulation with running the @Risk program prior to reading the mining sequence file. Afterwards in calculating the CT tonnage for each block it uses the values reported by the @Risk program whenever it is required to use reject percent, sand reject percent, target SFR in pipe or on-spec CT to Tremie in the calculations.

To analyze the outputs of 100 simulation runs, a MATLAB code (MathWorks, 2009) is developed. This code is provided in Appendix B. The code reads the results of each simulation run, and calculates the total CT tonnage produced in each period. The average of 100 values for CT tonnage in each period is calculated within the code.

Fig. 13 represents the average CT tonnage produced based on 100 simulation runs and the ore and waste tonnage processed in each period. The statistics for CT tonnages produced in each period based on 100 simulation runs are provided in Table 8.

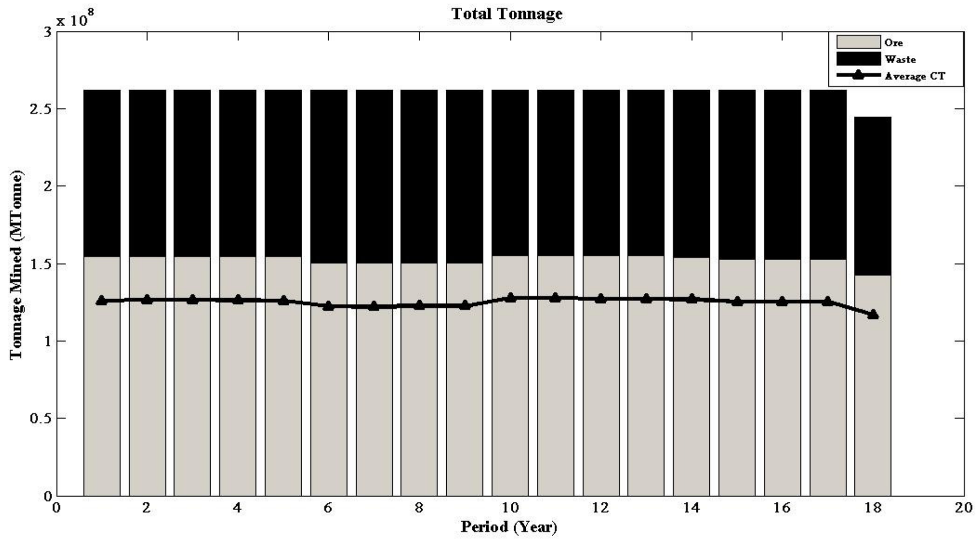

Fig. 13 – Ore tonnage, waste tonnage and average CT tonnage

produced in each period based on 100 simulation runs

The box plots and fluctuations of the CT tonnages produced in each period based on 100 simulation runs are presented in Fig. 14. The average fluctuation in the CT tonnages is 14.35 MT. the maximum fluctuation in the CT tonnages produced is 16.7 MT and the minimum fluctuation is 10 MT. The central mark in each box shows the median of the CT tonnage produced for that period. The lower quartile (25th percentile) and the upper quartile (75th percentile) are shown in Fig. 14. Average fluctuation of 14.35MT in each period is significant and can result in serious storage area problems.

Fig. 15 represents the average, minimum and maximum CT tonnages produced in each period based on the stochastic simulation of four variable inputs.

In Fig. 1the CT tonnages predicted to be produced in each period based on the deterministic model (fixed CT) are compared with the minimum and maximum CT produced in each period based on the stochastic model. In order to verify the stochastic model, the average of total CT produced in each period is provided in this figure. Based on this figure, the results from the deterministic model are very close to the average of total CT produced in each period. The deviation from the deterministic model is noticeable in this figure. The average difference between the fixed CT and the maximum CT produced is 10.85% with the maximum deviation of 11.88% which is about 15MT. The average deviation between the maximum CT tonnage and the fixed CT tonnage (13MT) is a significant deviation from the target.

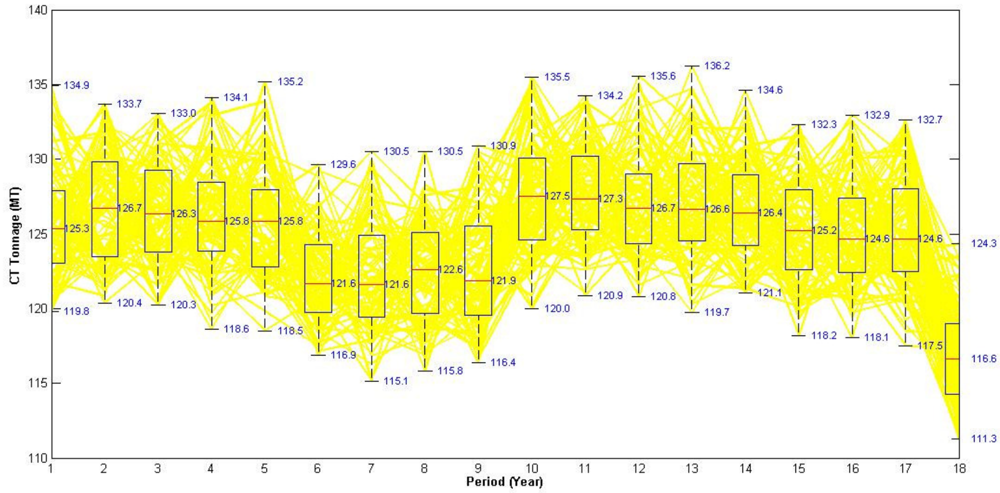

Fig. 14 – Box plots and CT tonnage fluctuations in 100 simulation runs

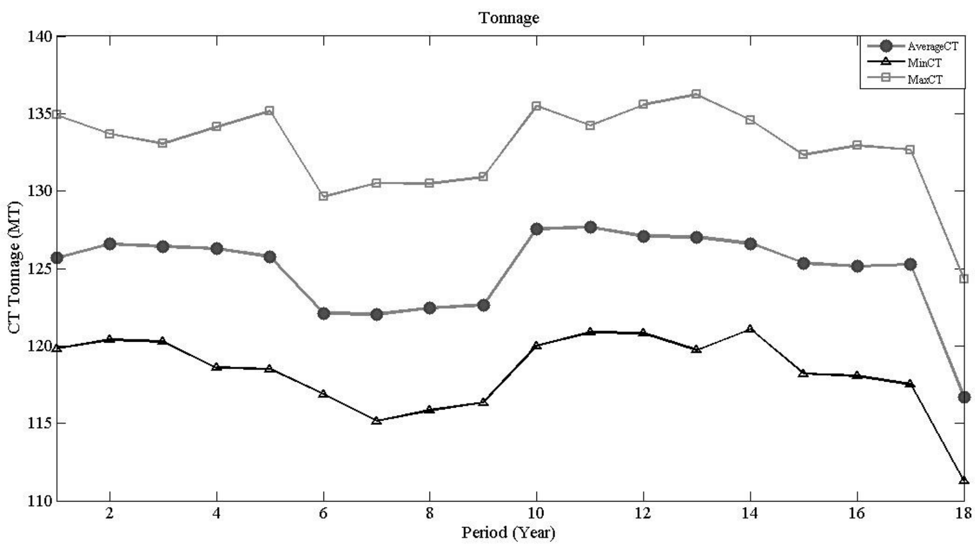

Fig. 15 – Average, minimum and maximum CT tonnages produced

in each period (output of 100 simulation runs)

The difference between the maximum CT tonnage and the target CT tonnage produced in period 8 is illustrated in Fig. 16 which is about 13MT.

Fig. 17 represents the histogram of CT tonnages produced in period 8 based on the results of 100 simulation runs. According to this figure, the CT tonnage produced in this period varies between 116 MT and 130MT.

Table 8 – Statistics of CT tonnages produced in each period based on 100 simulation replications

Period number	Average CT (MT)	Minimum CT (MT)	Maximum CT (MT)	Standard Deviation (MT)
1	125.7	119.8	134.9	3.7
2	126.6	120.4	133.7	3.7
3	126.4	120.3	133.0	3.3
4	126.3	118.6	134.1	3.5
5	125.8	118.5	135.1	3.5
6	122.1	116.9	129.6	3.0
7	122.0	115.1	130.5	3.5
8	122.4	115.8	130.5	3.3
9	122.6	116.3	130.9	3.8
10	127.6	120.0	135.5	3.7
11	127.6	120.9	134.2	3.1
12	127.1	120.8	135.6	3.5
13	127.0	119.7	136.2	3.7
14	126.6	121.1	134.6	3.2
15	125.3	118.2	132.3	3.5
16	125.1	118.0	132.9	3.4
17	125.2	117.5	132.6	3.8
18	116.7	111.3	124.3	3.2

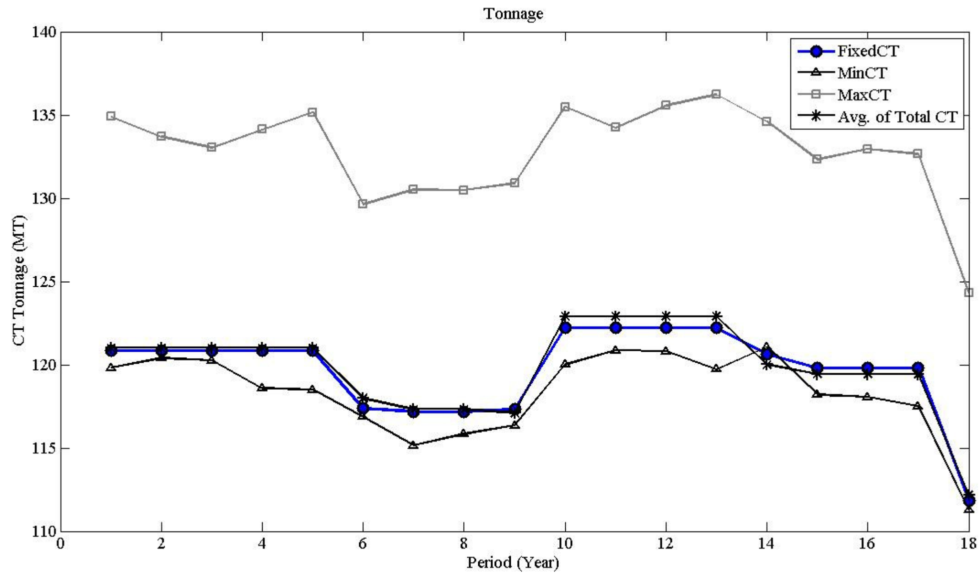

Fig. 16 – Minimum and maximum CT tonnages produced compared with the CT tonnage expected to be produced based on the deterministic model and the average of total CT in each period

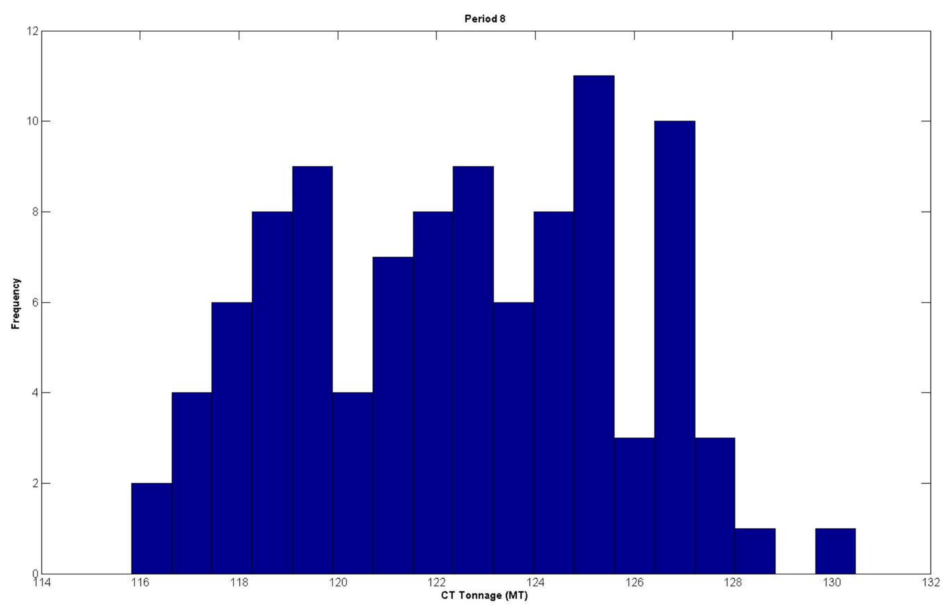

Fig. 17 – Histogram of CT tonnages produced based on 100 runs in period 8

4.4. Sensitivity Analysis

In addition to running the simulation considering the uncertainties associated with all input variables, it is crucial to do the sensitivity analysis. The purpose of this analysis is to find the input variables which the CT tonnage produced in each period is most sensitive and least sensitive to. In other words, the goal of sensitivity analysis is to find the sensitivity of the CT tonnages produced in each period and the total CT tonnage produced at the end of the mine life to the variations of four uncertain inputs in the CT process. In order to do the sensitivity analysis, first each simulation should be run considering the uncertainty in one input variable in each run and assuming that other variable inputs are constant during the mine life.

4.4.1. Reject Percent

In this section of the sensitivity analysis, the goal is to capture the uncertainty associated with the reject percent and its impact on the CT tonnage produced as the result of the CT production process. In order to complete the task, the simulation should be set up assuming that the only uncertain input to the CT process is the reject percent and all the other inputs to the CT production process remain constant during the mine life. As it was mentioned before in the text, a normal distribution with a mean of 0.05 and standard deviation of 0.005 is assigned to the reject percent. The truncation minimum and maximum is set to be 0.04 and 0.06 respectively.

The ore tonnage, waste tonnage and average CT tonnage produced in each period of 100 runs for reject percent simulation are illustrated in Fig. 18.

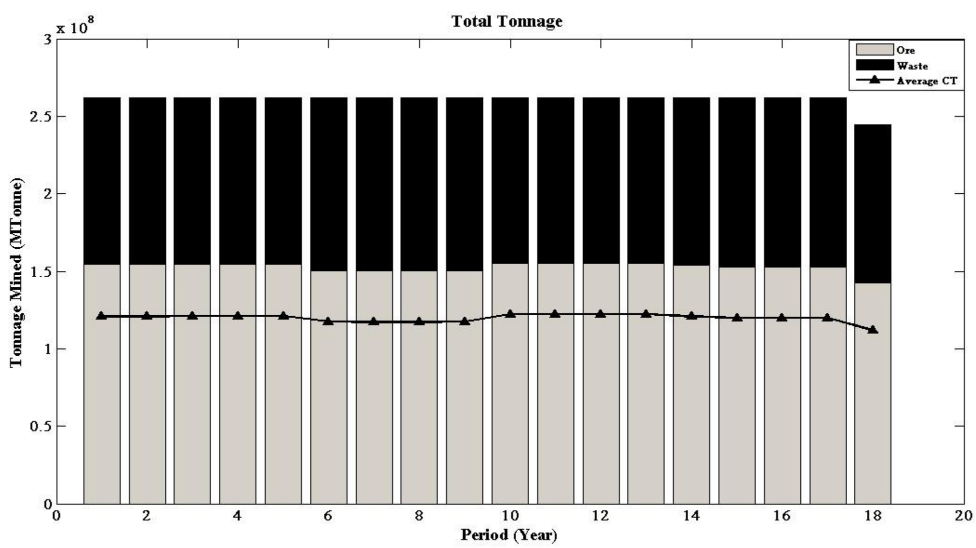

Fig. 18 – Ore, waste and average CT tonnage produced in each period (reject percent simulation)

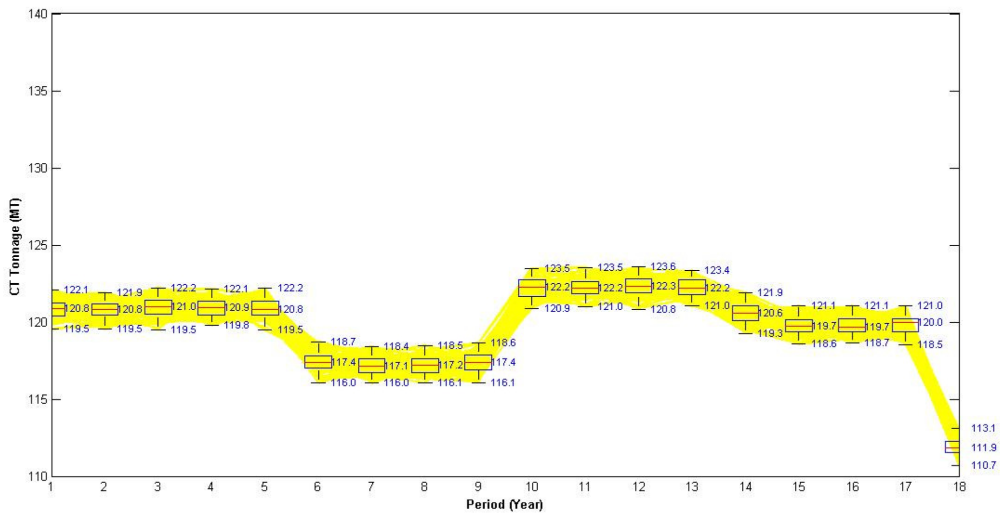

Fig. 19 – The box plots and the fluctuations of CT tonnages produced in each period

(output of 100 runs for reject percent simulation)

The fluctuations of the CT tonnage produced in each period and the box plots for reject percent simulation are presented in Fig. 19. The average fluctuation based on this figure is 2.5 MT which is significantly lower than the average fluctuation reported in Fig. 14. The minimum fluctuation is 2.3 MT and the maximum fluctuation is 2.8 MT.

The deviation from the target CT tonnage to be produced in each period based on the deterministic model is shown in Fig. 20. The average difference between the maximum CT tonnage produced and the target CT tonnage in each period is 1.7 MT, and the average difference between the minimum CT tonnage produced and the target CT tonnage in each period is 1.2 MT.

The histogram of CT tonnages produced in each period based on the reject percent simulation is presented in Fig. 21. The CT tonnage varies between 116 MT and 118.6 MT in this period.

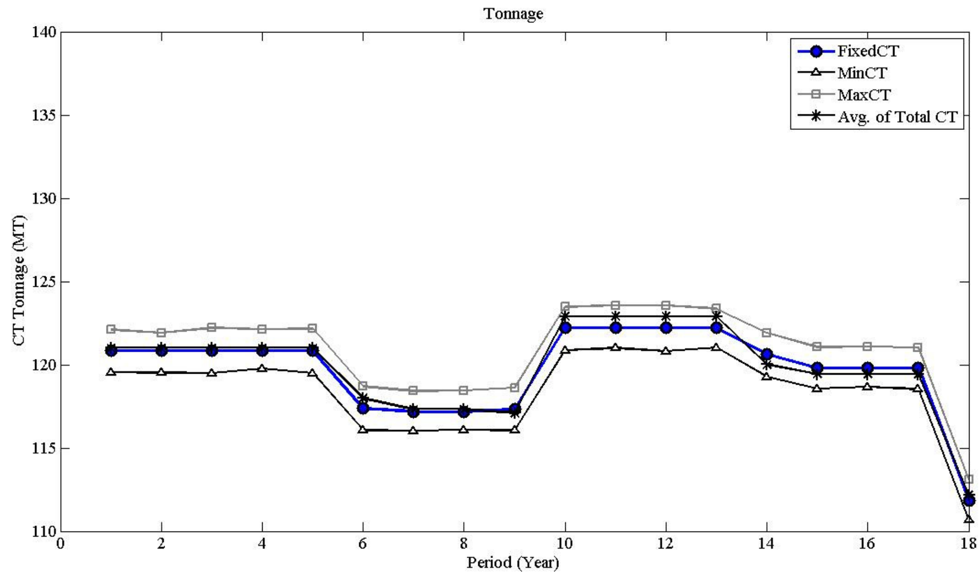

Fig. 20 – Minimum, maximum and CT tonnages produced based on the deterministic model and the average of total CT produced in each period (output of 100 runs for reject percent simulation)

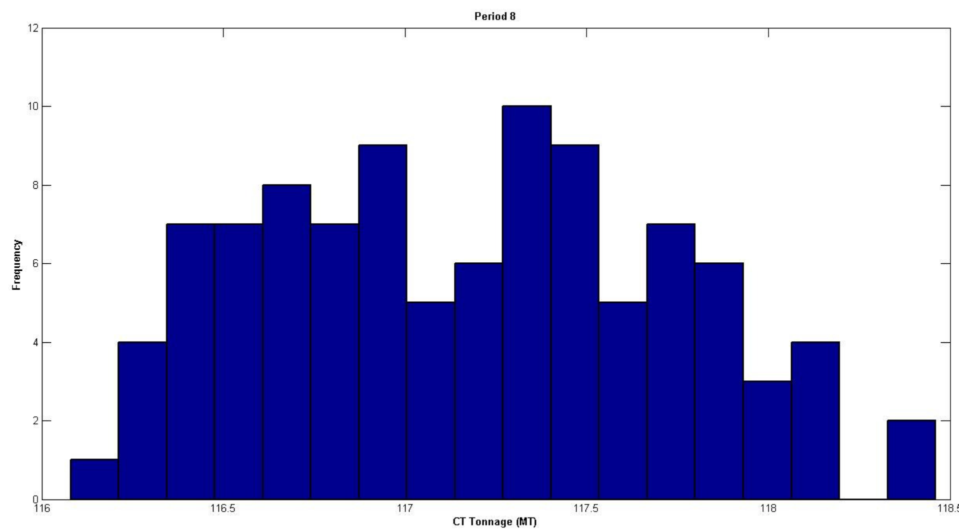

Fig. 21 – Histogram of CT tonnages produced in period 8

(output of 100 runs for reject percent simulation)

4.4.2. Sand Reject Percent

In this set of simulation runs, it is assumed that the only uncertain input to the CT calculation process is sand reject percent. Therefore, other variable inputs such as reject percent, target SFR in pipe and on-spec CT to Tremie are assumed to remain constant during the mine life.

The average CT tonnage produced based on 100 runs for sand reject percent simulation is presented in Fig. 22. Box plots and CT tonnages fluctuations in each period are shown in Fig. 23. Maximum fluctuation is 3.4 MT, minimum fluctuation is 2.4 MT and the average fluctuation is 2.9 MT. According to Fig. 23, the average difference between the maximum CT tonnage and the target CT tonnage to be produced in each period is 1.7 MT.

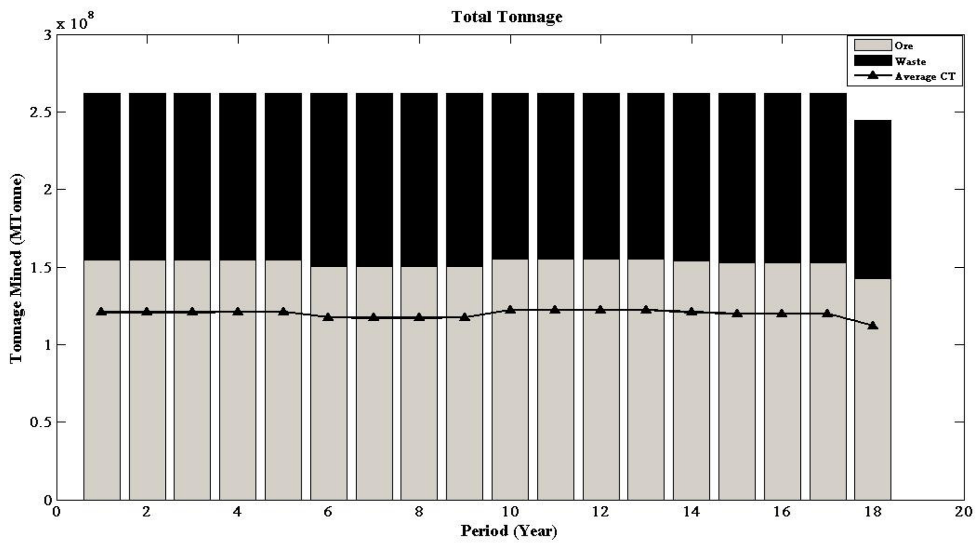

Fig. 22 – Ore tonnage, waste tonnage and average CT tonnage produced in each period (output of 100 runs for sand reject percent simulation)

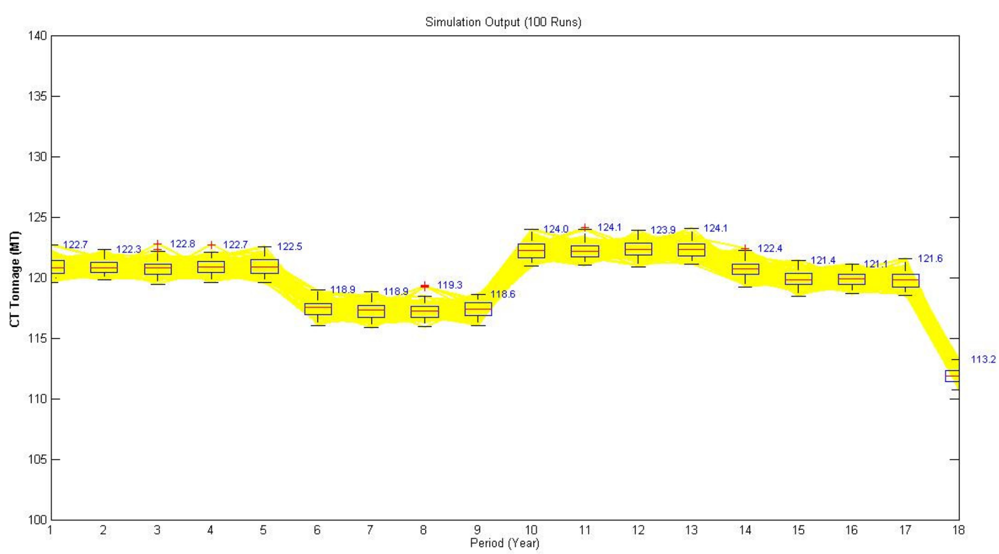

Fig. 23 – Box plots and fluctuation in CT tonnages produced in each period (based on 100 runs for sand reject percent simulation)

Deviations of the output of sand reject percent simulation from the target CT tonnages predicted to be produced in each period, based on the deterministic model, are shown in Fig. 24. The maximum difference between the two models is occurred in period 8 (2.1 MT). Histogram of CT tonnages in this period is presented in Fig. 25. Based on this histogram, the CT tonnage in this period varies between 116 MT and 119.3 MT.

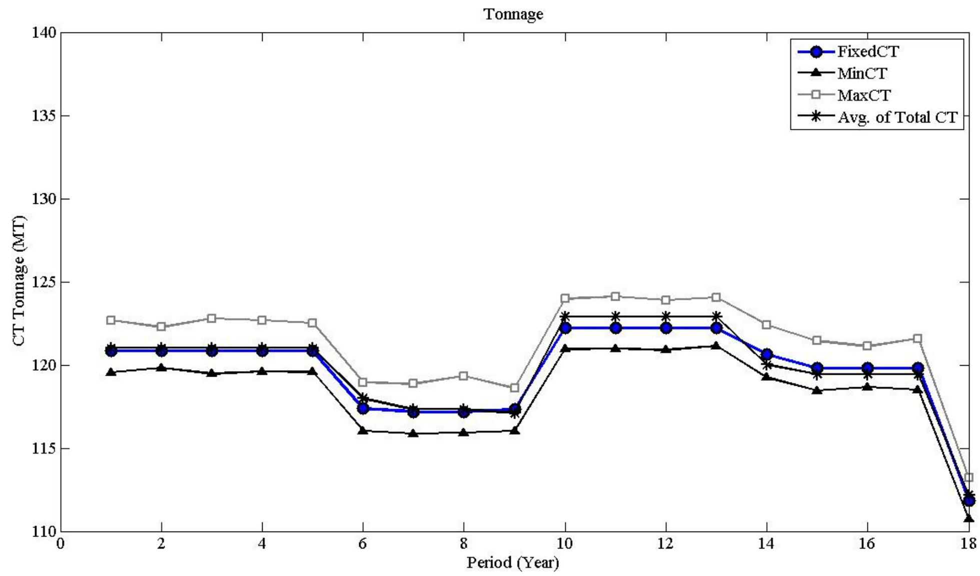

Fig. 24 – Minimum, maximum and target CT tonnages produced based on the deterministic model and the average of total CT produced in each period (output of 100 runs for sand reject percent simulation)

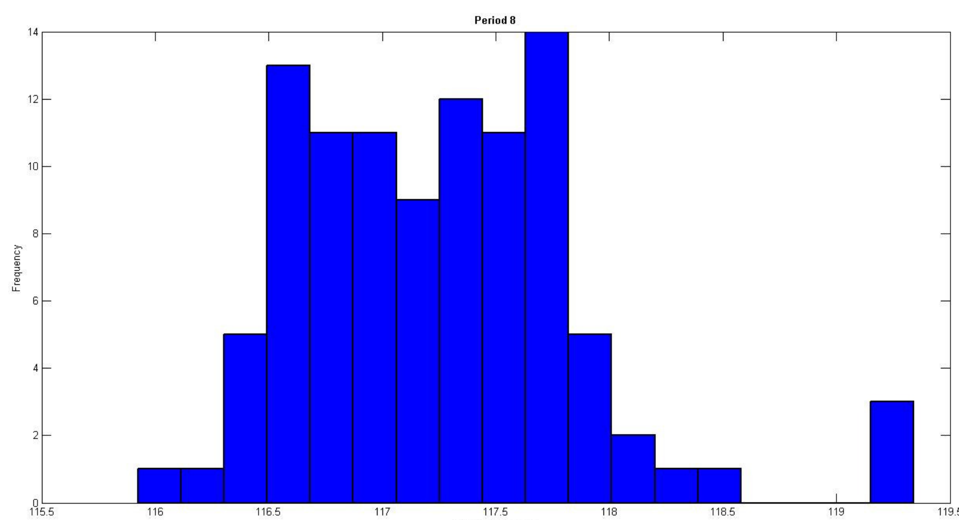

Fig. 25 – Histogram of CT tonnages produced in period 8

(output of 100 runs for sand reject percent simulation)

4.4.3. Target SFR in Pipe

In this part of the sensitivity analysis, the uncertainties associated with the target SFR in pipe should be captured. As it was mentioned before, a uniform distribution with mean of 4.25 and the truncation minimum and maximum of 4.0 and 4.5 is assigned to this variable input. Other variable inputs are assumed to be constant during the mine life. Fig. 26 represents the average CT tonnage produced in each period based on the output of SFR simulation.

Box plots and fluctuations in the CT tonnages produced in each period are shown in Fig. 27. According to this figure, the average fluctuation is 2.6 MT with the maximum and minimum fluctuation of 2.7 MT and 2.4 MT respectively.

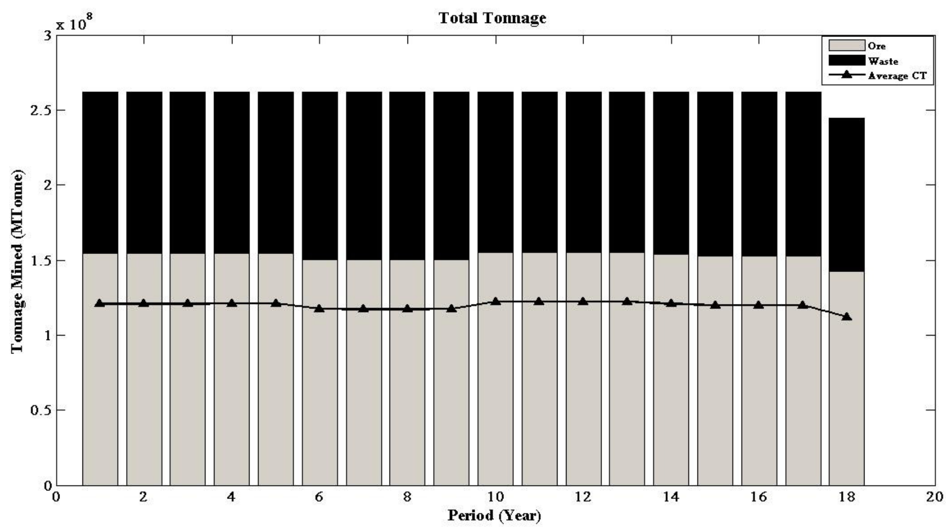

Fig. 26 – Ore tonnage, waste tonnage and average CT tonnage produced in each period (output of 100 runs for SFR simulation)

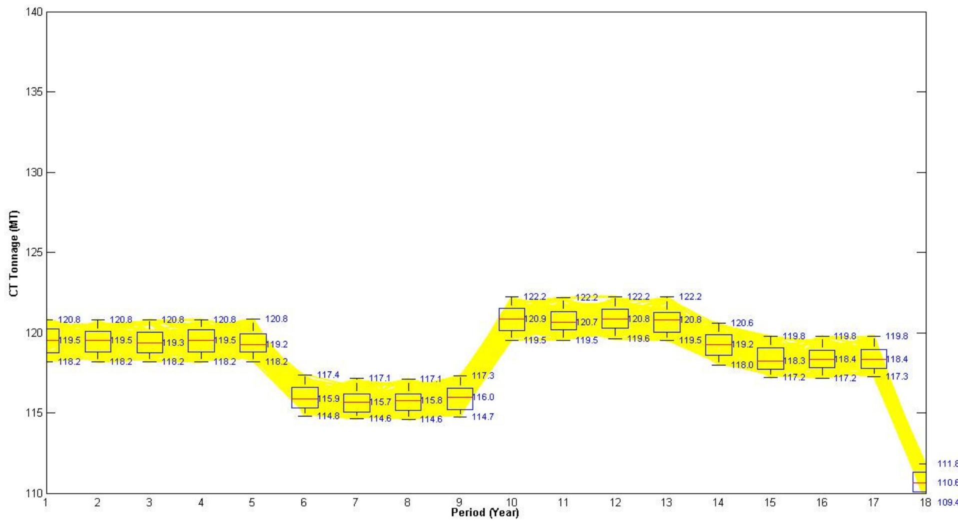

Fig. 27 – Box plots and fluctuations in CT tonnages produced

in each period(output of 100 runs for SFR simulation)

Fig. 28 compares minimum and maximum CT tonnages produced based on stochastic simulation of SFR with the target CT tonnages to be produced in each period based on the deterministic model. It can be seen from this figure that the maximum CT tonnage and the target CT tonnage lines are approximately close. According to Eq. (41) and (42) if the only variable input is SFR, when the target SFR is equal to 4.0, the maximum CT tonnage will be produced since the determinant factor is $\frac{1+SFR}{SFR}$. In other words, the maximum value for $\frac{1+SFR}{SFR}$ which is 1.25 occurs when SFR is equal to 4. When SFR is equal to 4.5, $\frac{1+SFR}{SFR}$ would be equal to 1.22 which would result in the minimum CT tonnage produced. Therefore, the maximum CT tonnage and the target CT tonnage to be produced in each period are exactly the same (which can be seen in Fig. 28).

Histogram of 100 values for CT tonnage produced in period 8 is shown in Fig. 29. Based on this figure CT tonnage in period 8 varies between 114.5 MT and 117 MT.

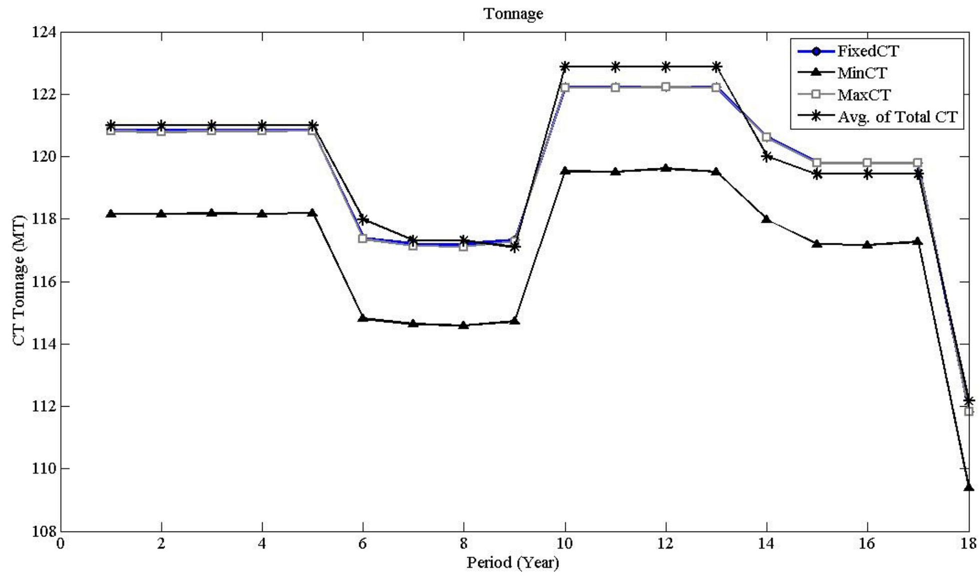

Fig. 28 – Minimum, maximum and target CT tonnages produced based on the deterministic model and bathe average of total CT produced in each period (output of 100 runs for SFR simulation)

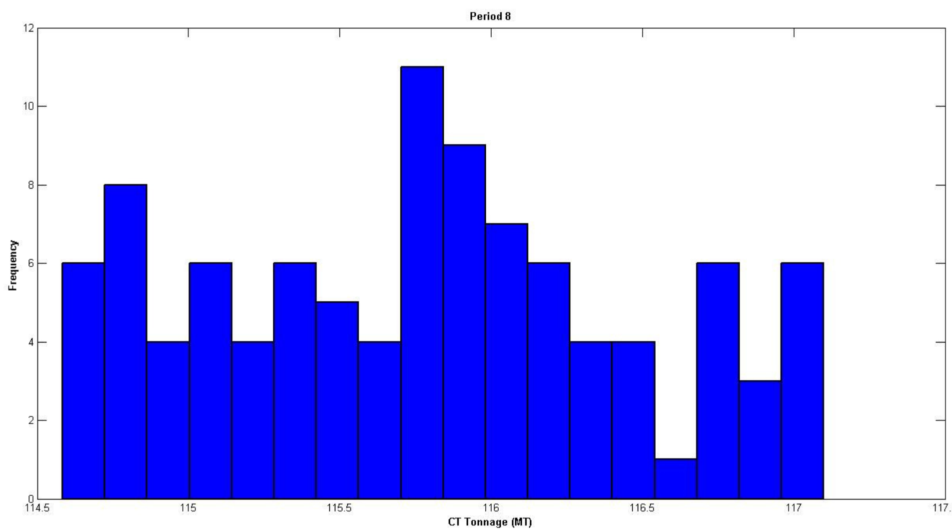

Fig. 29 – Histogram of CT tonnages produced in period 8

(output of 100 runs for SFR simulation)

4.4.4. On-Spec CT to Tremie

As it was mentioned earlier in the text, the on-spec CT to Tremie is the percentage of acceptable CT to be sent to Tremie. In this part of the sensitivity analysis, the goal is to capture the uncertainties associated with this input to the CT production process. It is expected that the total CT tonnage produced would be most sensitive to this variable input since according to Eqs. (41)

and (42) the on-spec CT to Tremie is a determinant factor and this input has a direct relation with the resulting CT tonnage.

A lognormal distribution with a minimum and maximum of 0.85 and 0.99 respectively is assigned to this input. It is assumed that other three variable inputs (reject percent, sand reject percent and the target SFR in pipe) remain constant during the mine life.

The bar chart for ore and waste tonnage and the average CT tonnage produced in each period based on on-spec simulation is presented in Fig. 30.

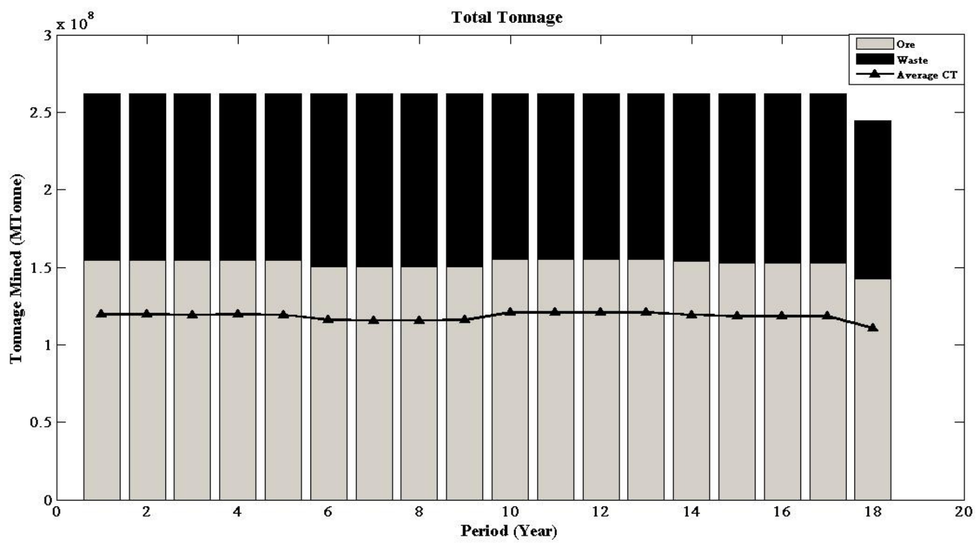

Fig. 30 – Ore tonnage, waste tonnage and average CT tonnage produced

in each period (output of 100 runs for on-spec simulation)

Fig. 31 represents the box plots and fluctuations in CT tonnages produced in each period based on the on-spec CT simulation outputs. The average fluctuation is 12.7 MT with the minimum fluctuation of 11.2 MT and the maximum fluctuation of 13.7 MT.

The difference between the maximum and minimum CT in each period based on the stochastic simulation and the target CT tonnage predicted to be produced based on the deterministic model is presented in Fig. 32. The average deviation between the maximum and the target CT tonnage is 13.7 MT and the average deviation between the minimum CT and the target CT tonnage is 1 MT. based on this graph, the minimum CT tonnage produced in each period is very close to the target CT tonnage predicted by the deterministic model. The on-spec% CT has a direct relation with the total CT tonnage, and since the truncation minimum of the lognormal distribution assigned to this input is equal to the value of this input in the deterministic model, it is reasonable to have the values for the minimum CT tonnage and the target CT tonnage very close.

The histogram of CT tonnages produced in each period based on the output of 100 runs for on-spec simulation is shown in Fig. 33. According to this figure, the CT tonnage varies between 118.5 MT and 130.9 MT for this period. The deviation from the target CT tonnage to be produced in this period is 10.5% which is equal to 12.4 MT.

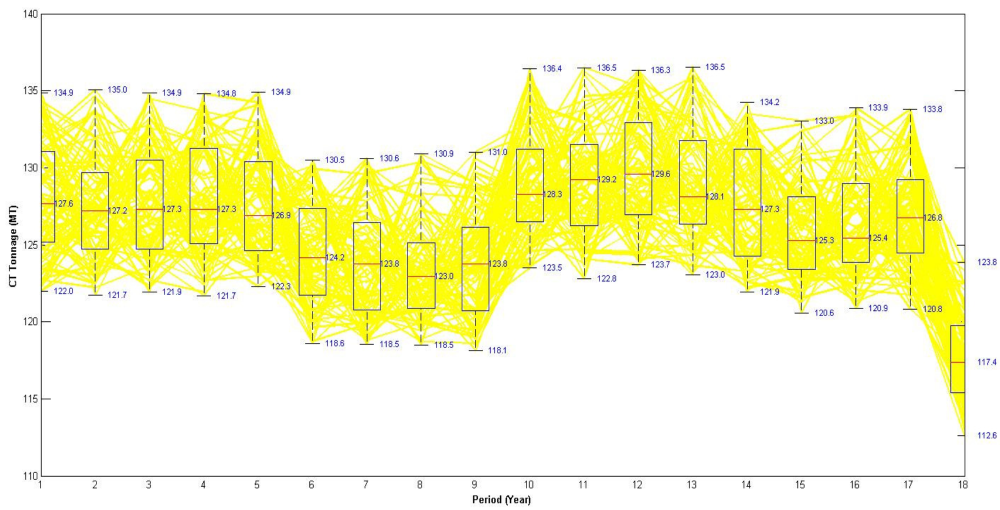

Fig. 31 – Box plots and fluctuation in CT tonnages produced in each period (output of 100 runs for on-spec simulation)

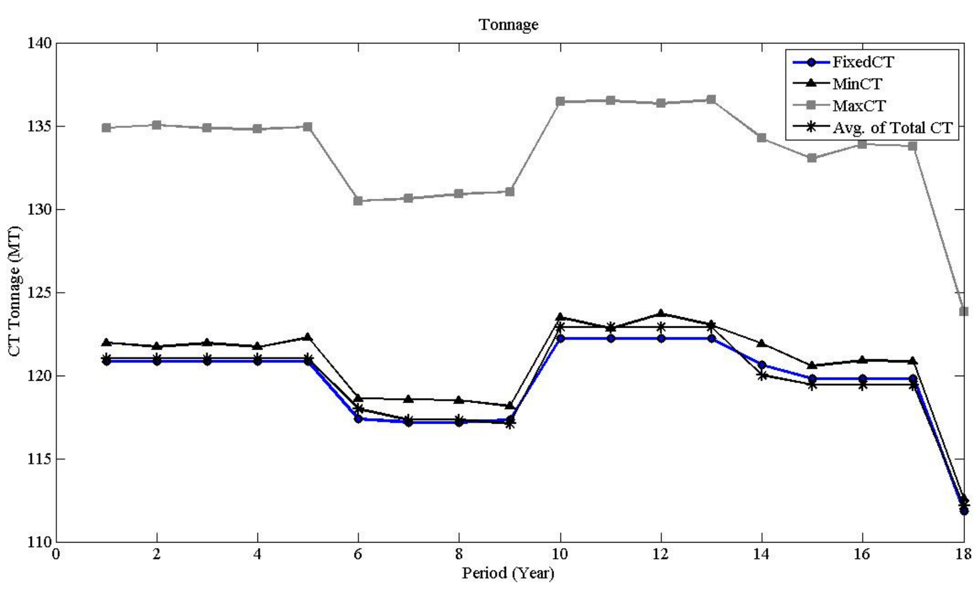

Fig. 32 – Minimum, maximum and target CT tonnages produced based on the deterministic model and the average of total CT produced in each period (output of 100 runs for on-spec simulation)

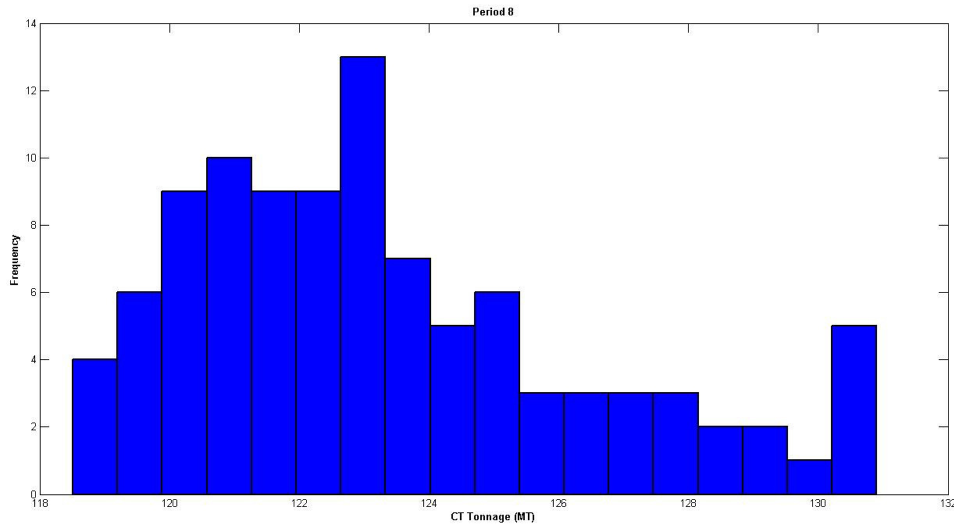

Fig. 33 – Histogram of CT tonnages produced in each period

(output of 100 runs for on-spec simulation)

4.4.5. Summary of the Sensitivity Analysis

The main motivation in running the sensitivity analysis is to find the sensitivity of the produced CT tonnage to the variable inputs. Table 9 represents the minimum, maximum and average fluctuation in the CT tonnages produced in four sets of simulation runs. According to this graph, the on-spec CT to Tremie simulation showed the greatest fluctuation in the CT tonnages produced in each period and reject percent simulation resulted in producing the lowest fluctuation.

Table 9 – Minimum, maximum and average fluctuation in the CT tonnages produced based on four simulations

Variable input	Minimum fluctuation (MT)	Maximum fluctuation (MT)	Average fluctuation (MT)
Reject percent	2.3	2.8	2.5
Sand reject percent	2.4	3.4	2.9
SFR	2.4	2.7	2.6
On-spec CT to Tremie	11.2	13.7	12.7

Results of the sensitivity analysis showed that the CT tonnage produced is most sensitive to the on-spec CT% to Tremie. According to Eqs. (41) and (42), on-spec CT% has a direct relation with the total CT tonnage produced. Since this term is assumed to fluctuate between 0.85 and 0.99, the maximum fluctuations in the CT tonnages produced can be 14%. Therefore, it is reasonable to consider the on-spec CT% as the parameter which the total CT tonnage produced is most sensitive to.

Based on the information provided in Table 9, the average fluctuation in the produced CT tonnages is almost the same for both reject percent and SFR simulation. Since the average sand reject percent (50%) is considerably higher than the average reject percent (5%), the total CT tonnage produced is more sensitive to the fluctuations in the sand reject percent.

4.5. Summary and Remarks

Implementation of the CT calculation code on a large-scale oil sands model has been presented in this chapter. The long-term mining schedule is provided using the Whittle software and the resulting mining sequence file is sent to the CT calculation model. The output of this model provides information on CT tonnages produced for each block, CT tonnages produced for each period and the total CT tonnage expected to be produced at the end of the mine life.

In the second part of this chapter, a stochastic simulation model is developed to capture the uncertainties associated with the CT production process. Prior to running the specified simulation model, confidence interval and number of replications required to obtain the desired confidence interval are estimated.

Finally, sensitivity analysis is done on the simulation outputs to capture the sensitivity of the CT tonnages produced to the variable inputs in this process.

Chapter 5

Summary, Conclusions and Recommendations

This chapter is concerned with summary of research, contributions of research, conclusions and recommendations for future work.

5.1 Summary of Research

This research is motivated by the challenges associated with the current oil sands tailings management techniques in being in compliance with the directive 074 regulations. The major issues with these oil sands tailings management strategies can be summarized as the lack of a direct relation between the long-term mine plans and the final tailings produced downstream and not considering the uncertainties associated with the oil sands production process in reporting the expected CT to be produced at the end of the mine life. The key parameters in this research are:

1. Developing a linkage between the long-term and short-term mine plans and the final CT produced during each period and at the end of the mine life.
2. Considering the uncertainties associated with the CT production process in reporting the final CT tonnage produced at the end of the mine life.

Subsequent to constructing mass-balance equations and mathematical formulations, code has been developed to implement these formulations on oil sands large-scale data.

In the second part of this research, a stochastic simulation model has been developed to capture the uncertainties associated with the CT production process. In running the simulation model, it was assumed that reject percent, sand reject percent, target SFR in pipe and on-spec CT sent to Tremie are the four uncertain inputs to the CT calculation model.

Sensitivity analysis has been done on the output of the simulation to capture the sensitivity of the produced CT tonnage to different variable inputs. In each set of simulation runs it was assumed that only one input is variable and other three inputs remain constant during the mine life.

5.2. Summary of Research Methodology

In order to obtain the mass-balance relation between the ore feed and the mass of CT, a comprehensive study on all of the different factors affecting the CT production process has been conducted. A VBA code is developed to implement the CT calculations on the mining sequence file. This code is provided in Appendix A. This code takes the block by block information provided in parcel and header lines and transfers it to the CT calculation equations and provides the information such as ore tonnage, economic block value (EBV), block bitumen, block fines, ore value, solid content and last but not least the CT tonnage produced for each block. The mass-balance equations provided in Chapter 3 are employed to develop this model. To verify the CT calculation model, a case study of large-scale oil sands data with 864 drillholes was carried out. This is followed by creating the block model and sending it to the Whittle software to develop the mining production schedule. The resulting mining sequence file was sent to the CT calculation model to develop the CT production schedule. Fig. 34 illustrates the research summary and models which have been developed and implemented.

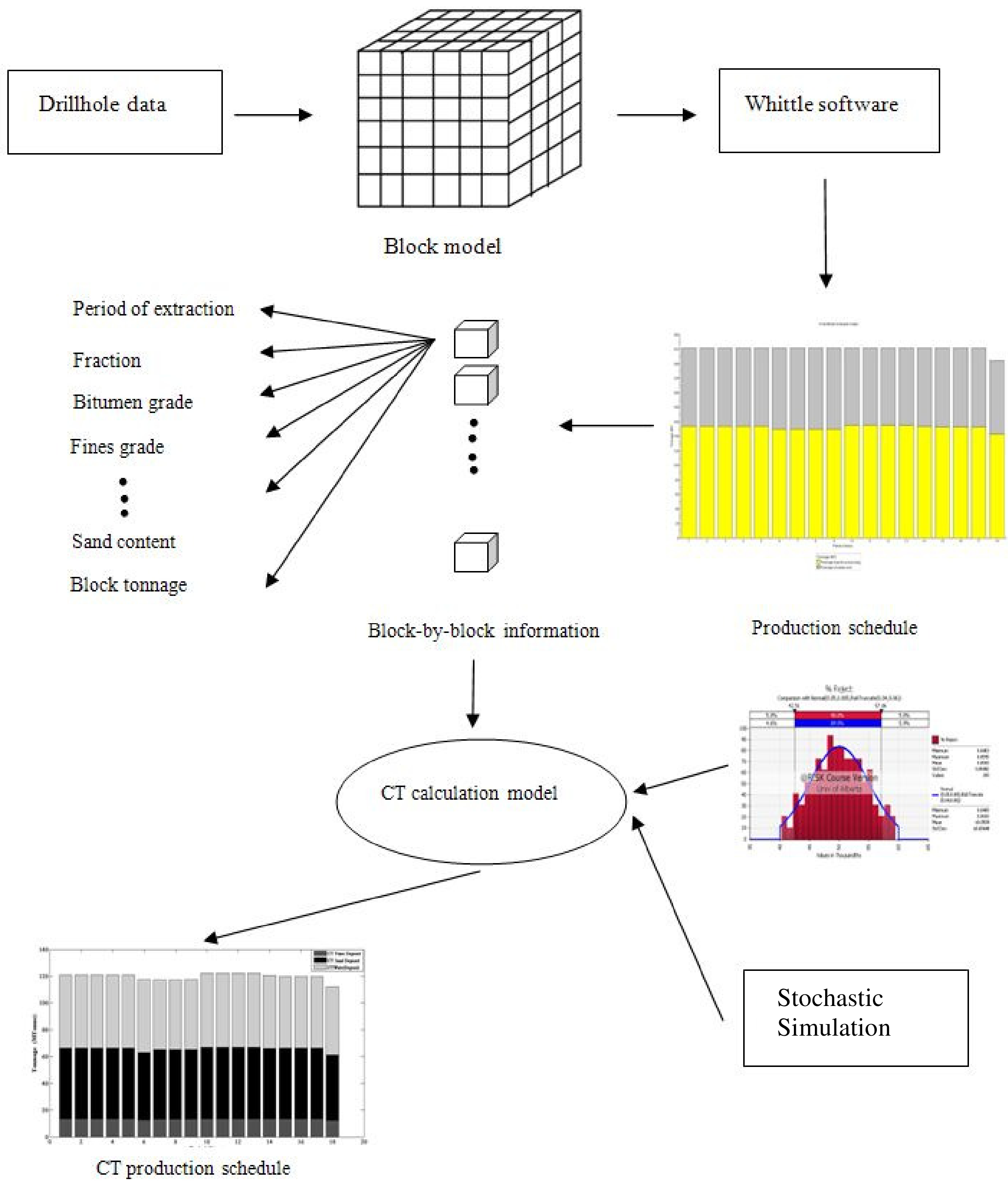

Fig. 34 – Research summary and models developed

5.3. Contributions of Research

This research has developed mathematical formulations and simulation models, which assist in prediction of the expected value of the quality and quantity of CT produced at the end of the oil sands production process. The following constitute the major contributions of this research.

1. The research has developed the mathematical formulations and mass-balance equations to relate the oil sands ore tonnage to the CT tonnage produced at the end of the oil sands production process. Providing a linkage between the oil sands long-term mine plans and the final CT produced downstream contributes in the development of current oil sands waste management techniques.
2. CT calculation model can be employed in modifying and re-evaluating current oil sands long-term mine plans based on the deposition area constraint and the amount of CT which is expected to be produced based on the mine plans.
3. The methodology presented in this research contributes enormously to the oil sands production process to be in compliance with the regulations set by directive 074.
4. The stochastic simulation model provided in this research based on the Monte Carlo simulation technique can be employed to assess and quantify uncertainties with the quantity and quality of CT produced.
5. The stochastic simulation methodology provided in this research can be used to overcome some of the environmental challenges caused by under-estimating the CT tonnages to be produced during each period and at the end of the mine life.

5.4. Scope and Limitations of the study

In developing the CT calculation mode, the desired CT solid percent is assumed to be 55% fixed. The percentage of sand sent to the underflow stream is set to be 93%. It should be noted that these numbers are selected based on Suncor's spreadsheet.

The following assumptions are made in developing the mathematical model for the CT production process:

1. The MFT is available for the CT process during the mine life and the solid percent for MFT is fixed at 30.
2. The percentage of sand being sent to underflow stream from the cyclone is 93.
3. The desired CT solid percent is 55.
4. The desired underflow stream has a sand content of 65%, fines content of 5% and water content of 30%.

It should be considered that this study has some limitations due to the assumptions that have been made in developing the stochastic simulation model. In other words, in order to assign proper distributions to capture the variability of the uncertain inputs, historical data from operations should be gathered and the distributions should be fitted on the real data. It should be noted that these distributions may be different based on several operational factors.

5.5. Conclusions

All of the research objectives outlined in Chapter 1, have been achieved within the research scope. The following conclusions were obtained from simulation and sensitivity analysis results:

1. Simulation of four input variables (reject percent, sand reject percent, target SFR in pipe and on-spec CT to Tremie showed that the average fluctuation in the CT tonnages produced was 14.3 MT. this fluctuation is significantly high and might cause serious problems especially in case of having storage area limitations.
2. The fluctuation in the CT tonnages produced should be considered in predicting the total CT tonnage to be produced at the end of each period and at the end of the mine life in order to be in compliance with the regulations set by directive 074.
3. Sensitivity analysis showed that the total mass of CT produced is most sensitive to the on-spec CT sent to Tremie. The average fluctuation in the CT tonnages produced in each period as a result of variations in on-spec CT to Tremie was 12.7 MT.
4. The on-spec CT sent to Tremie has a direct relation with the CT tonnage. When this input varies between 0.85 and 0.99 during the mine life, there should be a high fluctuation in the produced CT tonnages.
5. CT tonnage is least sensitive to the fluctuations in the reject percent. The average fluctuation of the CT tonnages produced in each period assuming that reject percent is the only variable input was 2.5 MT.
6. Since the average sand reject percent (50%) is considerably higher than the average reject percent (5%), the total CT tonnage produced is more sensitive to the fluctuations in the sand reject percent than the fluctuations in the reject percent.

5.6. Recommendations for Further Research

The following recommendations could significantly improve the proposed stochastic simulation model and add to the body of knowledge in this research domain.

- In considering the uncertainties in the stochastic simulation model, it was assumed that only four inputs are variable during the mine life. For further research it is recommended to study all other uncertainties associated with the CT production process. Capturing all the probable risks in this process can result in having a more realistic model.

- The proposed CT calculation model can be employed to modify and re-evaluate the long-term mine plans based on the storage area limitations prior to starting the mining process. In other words, the maximum acceptable CT tonnage can be a constraint and the CT calculation model can be employed to modify the long-term mine plans based on this specified constraint.

Appendix A – VBA Code

```
Public finesGrade As Double
Public bitumenGrade As Double
Public OreFeed As Double
Public CTProduced As Double
Public SandPercentFeed As Double
Public FinesPercentFeed As Double
Public SandContentFeed As Double
Public FinesContentFeed As Double
Public OreTonnage As Double
Public CTFinesDeposit As Double
Public CTSandDeposit As Double
Public CTWaterDeposit As Double
Public Period As Integer
Public BitumenInFroth As Double
--------------------------------------------------------------------------------------------------------------------------------------------------------------
Private Sub CommandButton1_Click()
```

The code reads the Whittle Mining Sequence File

The Economic Block Value (EBV) and the Economic Parcel Value (EPV) are added to each line

The code has an output file

1- a file that just includes the Block information (BlockOutputMSQ.dat)

Filename

```
Dim inputFile As String
Dim BlockOutput As String
Dim numDistributions As Long
Dim NumIterationstoRun As Long
Dim tempworksheet As Worksheet
Dim distributionRange As Range
Dim distributionRange2 As Range
Dim distributionRange3 As Range
Dim distributionRange4 As Range
Dim outputCell As Range
Dim outputCell2 As Range
Dim outputCell3 As Range
Dim outputCell4 As Range
Dim inputCell As Range
--------------------------------------------------------------------------------------------------------------------------------------------------------------
```

Common Dialog settings

```
CommonDialog1.CancelError = True
```

On Error GoTo CancelButton

CommonDialog1.Filter = "All files (*.*) |*.*"

Use ShowOpen Method to show the common open file dialog

CommonDialog1.ShowOpen

inputFile = CommonDialog1.Filename

For jLoop = 1 To 100

Open inputFile For Input As #1

The input file format information

INFORMATION ABOUT THE HEADER LINE IN WHITTLE MSQ FILE in order of precedence

Header Line

XI YI ZI #Parcels MCAF PCAF BlockTonnage intPeriod(Year) dblBlockFraction intPushBackNum

1- IX = block index in X direction, easting; 2- IY = block index in Y direction, northing; 3 -IZ = block index in Z direction, levels

Dim IX As Integer, IY As Integer, IZ As Integer

4- #Parcels - number of parcel lines

Dim NumberParcel As Integer

Positional mining and processing Cost Adjustment Factor (CAF)

5- MCAF = mining cost adjustment factor ; 6- PCAF = processing cost adjustment factor

Dim MCAF As Double, PCAF As Double

7- total tonnage of the block

Dim BlockTonnage As Double

8- intPeriod - period that the block is going to be extracted (in this case year)

Dim Period As Integer

9- dblBlockFraction - Fraction of block extracted in the period

Dim BlockFraction As Double'

10- intPushBackNum - Pushback to which the block belongs

Dim PushBackNum As Integer

INFORMATION ABOUT THE PARCEL LINE IN WHITTLE MSQ FILE in order of precedence

XI YI ZI RockType ParcelTonnes Bitumen(%) Fines(%) ParcelDestination ParcelFraction

1- IX = block index in X direction, easting; 2- IY = block index in Y direction, northing ; 3- IZ = block index in Z direction, levels

Dim IX As Integer, IY As Integer, IZ As Integer these variables are defined before

4- Rock Type as alphanumeric value defined by string

ReDim RockType(1) As Variant

5- Parcel tonnes must be positive

ReDim ParcelTonnes(1) As Double

Quantity of element 1 to 10 in the parcel

In this case it is Bitumen, and Fines in order 1 to 3

ReDim Bitumen(1) As Double, Fines(1) As Double

ReDim ParcelDestination(1) As Variant

ReDim ParcelFraction(1) As Variant

11 th Column And onward

Second allocation unit defined like above two fields (Char + Double)

Total number of allocation units cannot exceed the maximum number of the processes plus one.

ReDim StockPileParcelDestination(1) As Variant

ReDim StockPileParcelFraction(1) As Double

Dim parcelDest As String, spParcelDest As String

Dim RockCode As Variant

NOTE: the Whittle MSQ file has some lines that mark a new increment

The format is (! Increment 1)

These lines needed to be recognized and omitted from the out files

----

Output file format are as follows:

(BlockOutputMSQ.dat)

IX, IY, IZ, X, Y, Z, MCAF, PCAF, BlockTonnage, BlockVal, blockBitumen, blockFines, bitumenGrade, finesGrade, oreTonnage,

wasteTonnage, oreValue, Period(Year), destination, fraction ore, destination stockpile, fraction sp, PushBackNum, WaterContent,

SolidContent, FinesFeed, SandFeed, OreFeed, CT produced

NOTE: the values of blockBitumen, blockFines, are Block values

----

Variables used in code

Dim EBV As Double ' economic block value

ReDim EPV(1) As Double ' economic parcel value

Dim blockBitumen As Double, blockFines As Double

Define variables for the grades

Dim WaterContent As Double

Dim SolidContent As Double

Dim varTempParcel As Variant

Dim varTempBlock As Variant

Dim blockStrLine As String, parcelStrLine As String

Dim NumberOfElements As Integer

Seting the values to zero initilize

sumOreParcelTonnes = 0

sumWasteParcelTonnes = 0

unknownWasteTonnes = 0

unknownWasteCosts = 0

wasteCosts = 0

EBV = 0

BlockTonange = 0

BlockVal = 0

blockBitumen = 0

blockFines = 0

bitumenGrade = 0

finesGrade = 0

WaterContent = 0

SolidContent = 0

FinesFeed = 0

SandFeed = 0

OreTonnage = 0

OreFeed = 0

wasteTonnage = 0

oreValue = 0

CTProduced = 0

CTFinesDeposit = 0

CTSandDeposit = 0

Code starts here

Get the filelocation and name

BlockOutput = "C:\BlockMSQ.dat"

Open BlockOutput For Output As #2

Write the header line to BlockOutputMSQ.dat

IX, IY, IZ, X, Y, Z, MCAF, PCAF, BlockTonnage, EBV, blockBitumen, blockFines, oreTonnage, wasteTonnage, oreValue, Period(Year),

destination, fraction ore, destination stockpile, fraction sp, PushBackNum

Write #2, "IX", "IY", "IZ", "X", "Y", "Z", "MCAF", "PCAF", "RockType", "BlockTonange", "EBV", "blockBitumen", "blockFines" , "bitumenGrade", "finesGrade", "oreTonnage", "oreValue", "Period", "Destination", "Fraction", "DestinationSP", "FractionSP", "PushBackNum", "WaterContent", "SolidContent", "FinesContentFeed", "FinesPercentFeed", "SandContentFeed", "SandPercentFeed", "CTproduced", "CTFinesDEposit", "CTSandDeposit"

Read the file till end of the file

Simulation to get the reject percent

On Error GoTo exitpoint

Application.EnableCancelKey = xlErrorHandler

Application.DisplayAlerts = False

Application.EnableEvents = False

numDistributions = 1

NumIterationstoRun = 100

Creating a temporary worksheet for the simulation

Set tempworksheet = ThisWorkbook.Worksheets.Add()

Set distributionRange = tempworksheet.Range("A1").Resize(numDistributions)

Set distributionRange2 = tempworksheet.Range("E1").Resize(numDistributions)

Set distributionRange3 = tempworksheet.Range("H1").Resize(numDistributions)

Set distributionRange4 = tempworksheet.Range("K1").Resize(numDistributions)

Defining the distributions for the simulation for reject percent, sand reject percent, target SFR in pipe and on-spec CT% to Tremie

distributionRange.Formula = Worksheets("CTCalculation").Cells(1, 2).Formula

distributionRange2.Formula = Worksheets("CTCalculation").Cells(4, 2).Formula

distributionRange3.Formula = Worksheets("CTCalculation").Cells(1, 5).Formula

distributionRange4.Formula = Worksheets("CTCalculation").Cells(2, 24).Formula

Setting up the output cells in the temporary worksheet

Set outputCell = tempworksheet.Range("B1")

Set outputCell2 = tempworksheet.Range("F1")

Set outputCell3 = tempworksheet.Range("I1")

```
Set outputCell4 = tempworksheet.Range("L1")
outputCell.Formula = "=Riskoutput()+sum(" & distributionRange.Address & ")"
outputCell2.Formula = "=Riskoutput()+sum(" & distributionRange2.Address & ")"
outputCell3.Formula = "=Riskoutput()+sum(" & distributionRange3.Address & ")"
outputCell4.Formula = "=Riskoutput()+sum(" & distributionRange4.Address & ")"
With Risk.Simulation.Settings
LoadFromWorkbook ThisWorkbook
NumIterations = NumIterationstoRun
AutomaticResultsDisplay = RiskNoAutomaticResults
End With
```

Running the simulation

```
Risk.Simulation.Start
Dim sampleData() As Double
With Risk.Simulation.Results.GetSimulatedOutput(outputCell)
a = Risk.Simulation.Results.GetSimulatedOutput(outputCell).GetSampleData(sampleData, False)
For iLoop = 1 To NumIterationstoRun
Range("C" + Format(iLoop)).Formula = sampleData(iLoop)
Next
End With
Dim sampleData2() As Double
With Risk.Simulation.Results.GetSimulatedOutput(outputCell2)
a = Risk.Simulation.Results.GetSimulatedOutput(outputCell2).GetSampleData(sampleData2, False)
For iLoop = 1 To NumIterationstoRun
Range("G" + Format(iLoop)).Formula = sampleData2(iLoop)
Next
End With
Dim sampleData3() As Double
With Risk.Simulation.Results.GetSimulatedOutput(outputCell3)
a = Risk.Simulation.Results.GetSimulatedOutput(outputCell3).GetSampleData(sampleData3, False)
For iLoop = 1 To NumIterationstoRun
Range("J" + Format(iLoop)).Formula = sampleData3(iLoop)
Next
End With
Dim sampleData4() As Double
With Risk.Simulation.Results.GetSimulatedOutput(outputCell4)
a = Risk.Simulation.Results.GetSimulatedOutput(outputCell4).GetSampleData(sampleData4, False)
For iLoop = 1 To NumIterationstoRun
Range("M" + Format(iLoop)).Formula = sampleData4(iLoop)
Next
End With
exitpoint:
If Err = 0 Then
Else
```

MsgBox Err.Description: Err.Clear

End If

Do Until EOF(1)

Read the first line of data

IX, IY, IZ, NumberParcel, MCAF, PCAF, BlockTonnage, Period, BlockFraction, PushBackNum

Note: if the first block is air block it will have 9 elements. the PushBackNum is omitted

IX, IY, IZ, NumberParcel, MCAF, PCAF, BlockTonnage, Period, BlockFraction

If a new increment is started the code will start reading a new line

nextIteration:

Line Input #1, blockStrLine

varTempBlock = Split(blockStrLine, ",")

NumberOfElements = UBound(varTempBlock)

If it reads an exclamation mark showing the next increment.

When parsing the file, the !increment is divided into 3 fields

If NumberOfElements = 2 Then

counter = counter + 1

Write #2, "!", counter

GoTo nextIteration

End If

For j = 0 To NumberOfElements

Select Case j

Case 0

IX = varTempBlock(0)

Case 1

IY = varTempBlock(1)

Case 2

IZ = varTempBlock(2)

Case 3

NumberParcel = varTempBlock(3)

Case 4

MCAF = varTempBlock(4)

Case 5

PCAF = varTempBlock(5)

Case 6

BlockTonnage = varTempBlock(6)

Case 7

Period = varTempBlock(7)

Case 8

BlockFraction = varTempBlock(8)

Case 9

PushBackNum = varTempBlock(9)

End Select

Next j

Redefining the EPV, RockType, ParcelTonnes, Bitumen, Fines, charParcelDestination, and dblParcelFraction arrays

ReDim EPV(NumberParcel) As Double

ReDim RockType(NumberParcel) As Variant

ReDim ParcelTonnes(NumberParcel) As Double

ReDim Bitumen(NumberParcel) As Double, Fines(NumberParcel) As Double

ReDim ParcelDestination(NumberParcel) As Variant

ReDim ParcelFraction(NumberParcel) As Variant

ReDim StockPileParcelDestination(NumberParcel) As Variant

ReDim StockPileParcelFraction(NumberParcel) As Double

If the number of parcels and the tonnage are zero they are air blocks

If ((NumberParcel = 0) And (BlockTonnage = 0)) Then

Calculate the coordinates based on the excel worksheet data

X = Worksheets("Origin").Cells(2, 2) + (IX * Worksheets("Origin").Cells(2, 4))

Y = Worksheets("Origin").Cells(3, 2) + (IY * Worksheets("Origin").Cells(3, 4))

Z = Worksheets("Origin").Cells(4, 2) + (IZ * Worksheets("Origin").Cells(4, 4))

Write the block information to BlockOutputMSQ.dat

IX, IY, IZ, X, Y, Z, MCAF, PCAF, BlockTonnage, EBV, blockBitumen, blockFines, 'bitumenGrade, finesGrade, oreTonnage, oreValue, Period, Destination, Fraction, DestinationSP, FractionSP, PushBackNum

Write #2, IX, IY, IZ, X, Y, Z, MCAF, PCAF, 0#, 0#, 0#, 0#, 0#, 0#, 0#, 0#, 0#, 0#, 0#, Period, 0#, 0#, 0#, PushBackNum

If the block contains parcels and elements

ElseIf ((NumberParcel <> 0) And (BlockTonnage <> 0)) Then

The for loop reads all the pracels in each block and calulates the total tonnage of block and element

For i = 0 To NumberParcel - 1

Reads the parcel line data

IX, IY, IZ, RockType(i), ParcelTonnes(i), Bitumen(i), Fines(i), ParcelDestination(i), ParcelFraction(i), StockPileParcelDestination(i), StockPileParcelFraction(i)

Line Input #1, parcelStrLine

varTempParcel = Split(parcelStrLine, ",")

NumberOfElements = UBound(varTempParcel)

For j = 0 To NumberOfElements

Select Case j

Case 0

IX = varTempParcel(0)

Case 1

IY = varTempParcel(1)

Case 2

IZ = varTempParcel(2)

Case 3

RockType(i) = varTempParcel(3)

Case 4

ParcelTonnes(i) = varTempParcel(4)

Case 5

Bitumen(i) = varTempParcel(5)

Case 6

Fines(i) = varTempParcel(6)

Case 7

ParcelDestination(i) = varTempParcel(7)

Case 8

ParcelFraction(i) = varTempParcel(8)

Case 9

StockPileParcelDestination(i) = varTempParcel(9)

Case 10

StockPileParcelFraction(i) = varTempParcel(10)

End Select

Next j

Coordinates = origin + block Index * block dimension

X = Worksheets("Origin").Cells(2, 2) + (IX * Worksheets("Origin").Cells(2, 4))

Y = Worksheets("Origin").Cells(3, 2) + (IY * Worksheets("Origin").Cells(3, 4))

Z = Worksheets("Origin").Cells(4, 2) + (IZ * Worksheets("Origin").Cells(4, 4))

If the grade of ore is greater than the cut-off grade

If (Bitumen(i) / ParcelTonnes(i)) >= 7 Then

EPV = economic parcel value if ore

(Bitumen amount of ore * mining recovery * processing recovery * selling price ($/unit))+ (- total tonnage of ore (tonnes) * mining recovery * Processing Cost - Blocktonnage * mining costs)

total Bitumen in each block, summing up the parcel values

Cells (11, 2)= selling price

Cells (8, 2) = mining recovery

Cells (10, 2)= processing recovery

Cells (9, 2) = processing costs

Cells (7, 2) = mining costs

This is revenue minus just the processing costs. Mining costs are not included at this stage. to make a decision based on the marginal cut-off

EPV(i) = (Bitumen(i) * Worksheets("Origin").Cells(11, 2) * Worksheets("Origin").Cells(8, 2) * Worksheets("Origin").Cells(10, 2)) - (ParcelTonnes(i) * Worksheets("Origin").Cells(9, 2))

If the parcel is ore

In other words this implicitly checks to see if the grade of ore is above the cutoff

If (EPV(i) > (-ParcelTonnes(i) * Worksheets("Origin").Cells(7, 2))) Then

Summing up the revenue of ore minuse processing cost

oreValue = oreValue + EPV(i)

Deduct the mining cost of the parcel and update EPV(i)

EPV(i) = EPV(i) + (-ParcelTonnes(i) * Worksheets("Origin").Cells(7, 2))

Cells(8, 2)is the mining recovery

Summing up the economic parcel values

This is the ore value after the deduction of mining cost

oreValueMining = oreValueMining + EPV(i)

Summing up the Bitumen values times the mining recovery

blockBitumen = blockBitumen + (Bitumen(i) * Worksheets("Origin").Cells(8, 2))

Summing up the P values

blockFines = blockFines + (Fines(i) * Worksheets("Origin").Cells(8, 2))

Summing up the S values

Summing up the tonnage of ore parcels. any parcel that generates a positive cash flow

This is going to be used to calculate the grade of ore and other elements

sumOreParcelTonnes = sumOreParcelTonnes + (ParcelTonnes(i) * Worksheets("Origin").Cells(8, 2))

If the pacel is waste

Else

Economic parcel value if waste

Cells (7, 2) = mining costs

EPV(i) = -ParcelTonnes(i) * Worksheets("Origin").Cells(7, 2)

sumWasteParcelTonnes = sumWasteParcelTonnes + ParcelTonnes(i)

Summing up the economic parcel values for waste

wasteCosts = wasteCosts + EPV(i)

End If

If the block is waste

ElseIf (Bitumen(i) / ParcelTonnes(i)) < 7 Then

Economic parcel value if waste

Cells (7, 2) = mining costs

EPV(i) = -ParcelTonnes(i) * Worksheets("Origin").Cells(7, 2)

sumWasteParcelTonnes = sumWasteParcelTonnes + ParcelTonnes(i)

Summing up the economic parcel values for waste

wasteCosts = wasteCosts + EPV(i)

End If 'Bitumen if

parcelDest = ParcelDestination(i)

parcelFrac = ParcelFraction(i)

spParcelDest = StockPileParcelDestination(i)

spParcelFrac = StockPileParcelFraction(i)

RockCode = RockType(i)

Next i ' for loop for the Parcels

The tonnage of unknown waste in the block

unknownWasteTonnes = BlockTonnage - sumWasteParcelTonnes - sumOreParcelTonnes

If unknownWasteTonnes < 0 Then

unknownWasteTonnes = 0

End If

unknownWasteCosts = -unknownWasteTonnes * Worksheets("Origin").Cells(7, 2)

This is the total profit or costs of extracting the block

totalWasteCosts = (wasteCosts + unknownWasteCosts)

BlockVal = oreValue + totalWasteCosts

If there is any ore blocks calcualte the grade

If sumOreParcelTonnes > 0 Then

calculate the grade of each element in the block

bitumenGrade = (blockBitumen / 100) / sumOreParcelTonnes

finesGrade = (blockFines / 100) / sumOreParcelTonnes

OreTonnage = sumOreParcelTonnes

OreFeed = OreTonnage * BlockFraction

End If

Calling the CT calculation function to calculate the CT tonnage for each block

Call UploadCTData(tempworksheet)

resultOutput = "C:\ResultMSQ" & jLoop & ".dat"

Open resultOutput For Append As #3

Write #3, CTProduced, Period, Destination

Close #3

wasteTonnage = sumWasteParcelTonnes + unknownWasteTonnes

If (OreTonnage + wasteTonnage) <> BlockTonnage Then

BlockTonnage = OreTonnage + wasteTonnage

End If

This is the cost of mining all the block as waste

miningCost = -BlockTonnage * Cells(7, 2)

If OreTonnage <> 0 Then

Write #2, IX, IY, IZ, X, Y, Z, MCAF, PCAF, RockCode, OreTonnage, BlockVal, blockBitumen, blockFines , bitumenGrade, finesGrade, OreTonnage, oreValue, Period, "MILL", BlockFraction, spParcelDest, spParcelFrac, PushBackNum , WaterContent, SolidContent, FinesContentFeed, FinesPercentFeed, SandContentFeed, SandPercentFeed, CTProduced, CTFinesDeposit, CTSandDeposit

End If

If wasteTonnage <> 0 Then

Write #2, IX, IY, IZ, X, Y, Z, MCAF, PCAF, RockCode, wasteTonnage, BlockVal, blockBitumen, blockFines, bitumenGrade, finesGrade, 0, 0, Period, "-np-", BlockFraction, spParcelDest, spParcelFrac, PushBackNum, WaterContent, SolidContent, FinesContentFeed, FinesPercentFeed, SandContentFeed, SandPercentFeed, CTProduced, CTFinesDeposit, CTSandDeposit

End If

Reseting the values to zero for next block

BlockTonange = 0

BlockVal = 0

blockBitumen = 0

blockFines = 0

bitumenGrade = 0

finesGrade = 0

WaterContent = 0

SolidContent = 0

FinesFeed = 0

SandFeed = 0

OreTonnage = 0

OreFeed = 0

SandContentFeed = 0

FinesContentFeed = 0

OreTonnage = 0

wasteTonnage = 0

oreValue = 0

CTProduced = 0

CTFinesDeposit = 0

CTSandDeposit = 0

CTWaterDeposit = 0

BitumenInFroth = 0

sumOreParcelTonnes = 0

sumWasteParcelTonnes = 0

unknownWasteTonnes = 0

unknownWasteCosts = 0

wasteCosts = 0

M = 0

N = 0

P = 0

W = 0

V = 0

W1 = 0

W2 = 0

W3 = 0

CTProduced = 0

RejectPercent = 0

SFRInPipe = 0

OnSpecCTtoTremie = 0

SandReject = 0

SandPercentFeed = 0

FinesPercentFeed = 0

End If

If the number of parcels and the tonnage are zero they are air blocks

Loop

Do until EOF

Close #1

Close the file

Close #2

deleteWorksheets

Next

MsgBox ("Done!")

CancelButton:

Exit Sub

End Sub

Sub UploadCTData(tempworksheet)

Uploading data from the CT calculations inputs'

Defining reject properties'

Dim RejectPercent As Double

Dim FinesReject As Double

Dim SandReject As Double

Dim WaterReject As Double

Dim WaterContent As Double

Defining Under Flow Properties'

Dim SFRInPipe As Double

Dim SandInUF As Double

Dim FinesInUF As Double

Dim WaterInUF As Double

Dim SandToUF As Double

Dim Recovery As Double

Defining SET Properties'

Dim SETSand As Double

Dim SETBitumen As Double

Dim OnSpecCTtoTremie As Double

Defining Cell Properties'

Dim CellEfficiency As Double

Dim PhysicalCapture As Double

Dim CellVolume As Double

Dim CellDryDensity As Double

Dim M As Double, N As Double, W As Double, P As Double, L As Double, V As Double, W1 As Double, W2 As Double

Dim W3 As Double

Dim CTSolids As Double

Dim FinesInSolids As Double

Dim MFTSolidsPercent As Double

Sampling from the simulation output for four defined input variables

RejectPercent = tempworksheet.Range("C" + Format(Period))

SandReject = tempworksheet.Range("G" + Format(Period))

SFRInPipe = tempworksheet.Range("J" + Format(Period))

OnSpecCTtoTremie = tempworksheet.Range("M" + Format(Period))

RejectPercent = Worksheets("CTCalculation").Cells(1, 2)

Reading from the spreadsheet

FinesReject = Worksheets("CTCalculation").Cells(2, 2)

WaterReject = Worksheets("CTCalculation").Cells(3, 2)

FinesReject = Worksheets("CTCalculation").Cells(2, 2)

SandInUF = Worksheets("CTCalculation").Cells(2, 8)

FinesInUF = Worksheets("CTCalculation").Cells(2, 10)

WaterInUF = Worksheets("CTCalculation").Cells(2, 12)

SandToUF = Worksheets("CTCalculation").Cells(2, 14)

SETSand = Worksheets("CTCalculation").Cells(2, 17)

SETBitumen = Worksheets("CTCalculation").Cells(2, 19)

CellEfficiency = Worksheets("CTCalculation").Cells(2, 27)

PhysicalCapture = Worksheets("CTCalculation").Cells(2, 29)

CellVolume = Worksheets("CTCalculation").Cells(2, 31)

CellDryDensity = Worksheets("CTCalculation").Cells(2, 33)

CTSolids = Worksheets("CTCalculation").Cells(2, 36)

FinesInSolids = Worksheets("CTCalculation").Cells(2, 39)

Recovery = Worksheets("CTCalculation").Cells(2, 21)

MFTSolidsPercent = Worksheets("CTCalculation").Cells(2, 42)

WaterContent = (0.1875 * finesGrade * 100) + 2

SolidContent = 100 - (bitumenGrade * 100) - WaterContent

FinesPercentFeed = finesGrade * SolidContent

SandPercentFeed = (100 - (bitumenGrade * 100) - FinesPercentFeed - WaterContent) / 100

FinesContentFeed = OreTonnage * FinesPercentFeed

SandContentFeed = OreTonnage * SandPercentFeed

BitumenInFroth = bitumenGrade * Recovery

Calculate the CT produced at the end of the production

If OreFeed > 0 Then

Breaking the ore feed tonnage into 1000 tonnes portions

L = Round(OreFeed / 1000)

W1 = (1 - MFTSolidsPercent) / MFTSolidsPercent

W2 = (1 / SFRInPipe) - (FinesInUF / SandInUF)

W3 = (WaterInUF / SandInUF)

W = OnSpecCTtoTremie * ((1 + SFRInPipe) / SFRInPipe) * (1 / CTSolids)

N = ((CellVolume * CellDryDensity * (1 - FinesInSolids)) / (CellEfficiency * PhysicalCapture))

For j = 1 To L

M = ((SandPercentFeed * 1000) - (RejectPercent * SandReject * 1000) - ((BitumenInFroth * 1000 / SETBitumen) * SETSand)) * SandToUF

P = 1 - (N / M)

CTFinesDeposit = CTFinesDeposit + (OnSpecCTtoTremie * M * P / SFRInPipe)

CTWaterDeposit = CTWaterDeposit + (OnSpecCTtoTremie * ((W1 * W2) + W3) * M * P)

Next j

CTSandDeposit = CTFinesDeposit * 4

If (((CTFinesDeposit + CTSandDeposit) / 0.85) / CTSolids) * (1 - CTSolids) - CTWaterDeposit < 0 Then

For kloop = 1 To L

CTProduced = CTProduced + (((1 + SFRInPipe) / SFRInPipe) + ((W1 * W2) + W3) * M * P)

Next kloop

Else

For mloop = 1 To L

CTProduced = CTProduced + (W * M * P)

Next mloop

End If

V = (L * 1000) - OreFeed

If V > 0 Then

M = ((SandPercentFeed * V) - (RejectPercent * SandReject * V) - ((BitumenInFroth * V / SETBitumen) * SETSand)) * SandToUF

CTProduced = CTProduced - (W * M * P)

CTFinesDeposit = CTFinesDeposit - (OnSpecCTtoTremie * M * P)

```
End If
If V <= 0 Then
V = Abs(V)
M = ((SandPercentFeed * V) - (RejectPercent * SandReject * V) - ((BitumenInFroth * V / SETBitumen) * SETSand)) * SandToUF
CTProduced = CTProduced + (W * M * P)
CTFinesDeposit = CTFinesDeposit + (OnSpecCTtoTremie * M * P)
End If
CTSandDeposit = CTFinesDeposit * 4
End If
If CTProduced < 0 Then
CTProduced = 0
End If
End Sub
Private Sub RaiseCustomError(ByVal p_ErrorText As String)
Err.Raise 513, "@RISK Macro Example", p_ErrorText
End Sub
Public Sub deleteWorksheets()
Application.DisplayAlerts = False
For iLoop = ActiveWorkbook.Worksheets.Count To 2 Step -1
If Not (ActiveWorkbook.Worksheets(iLoop).Name = "origin") And Not (ActiveWorkbook.Worksheets(iLoop).Name = "CTCalculation") Then
ActiveWorkbook.Worksheets(iLoop).Delete
End If
Next
Application.DisplayAlerts = True
End Sub
```

Appendix B – MATLAB Code

```
outputFileName=[];
 CT=[];
 CTproduced=zeros(18,1);
 for i=1:100
     outputFileName=['ResultMSQ' num2str(i) '.dat'];
     B=load(outputFileName);
     data=[B];
    for j=1:18
 for k=1:64584
     if data(k,2)==j
       CTproduced(j,1)=CTproduced(j,1)+data(k,1);
    end

 end
    end
  CT=[CT,CTproduced];
    CTproduced=zeros(18,1);
end
xlsread CTOREWASTE.xlsx;
Periods=[1;2;3;4;5;6;7;8;9;10;11;12;13;14;15;16;17;18];
CTOREWASTE=ans;
 CT=[Periods,CTOREWASTE,CT];
X=CT(:,3);
X2=CT(:,4);
Y=[X,X2];
X3=CT(:,1);
Y1=CT(:,2);
B=[];
B2=[];
for h=1:18
    for d=5:104
      B(h,d-4)=(CT(h,d)/1000000);
       B2(h,d-4)=(CT(h,d));
    end
end

AverageCT=[];
VarCT=[];
MinCT=[];
MaxCT=[];
STDEVCT=[];
MD=[];
for i=1:18
    AverageCT(i,1)=mean(B(i,:));
    VarCT(i,1)=var(B(i,:));
    MinCT(i,1)=min(B(i,:));
    MaxCT(i,1)=max(B(i,:));
    STDEVCT(i,1)=std(B2(i,:));
    MD(i,1)=(median(B2(i,:)));
end


for mloop=5:104
 mG=plot(CT(:,mloop)/1000000);
set(mG,'Color','yellow','LineWidth',1.5);
hold on;
end
xlabel('Period (Year)');
ylabel('CT Tonnage (MT)');
title('Simulation Output (100 Runs)');
bP=CT(:,5:104);
CP=bP';
tP=CP./1000000;
MD=MD./1000000;
MD=MD';
MaxCT=MaxCT';
```

```
MinCT=MinCT';
testbp=boxplot(tP,'plotstyle','traditional');
for c=1:18
    text(c+0.25,MD(1,c),num2str(MD(1,c),'%.1f'),'Color','blue','fontsize',7);
    text(c+0.25,MaxCT(1,c),num2str(MaxCT(1,c),'%.1f'),'Color','blue','fontsize',7);
    text(c+0.25,MinCT(1,c),num2str(MinCT(1,c),'%.1f'),'Color','blue','fontsize',7);
end
set(testbp,'linewidth',1);
axis([1 18 100 140]);
hold off;
MinCT=MinCT';
MaxCT=MaxCT';
createBar(Y,...
                'Period (Year)',...
               'Tonnage Mined (MTonne)',...
                'Total Tonnage ');
hold on;
KG=plot(AverageCT.*1000000);
set (KG,'Color','Green','LineWidth',2);
h1=legend('Ore','Waste','Average CT');
hold off;
createPlot(X3,AverageCT,'Period (Year)','CT Tonnage (MT)','Tonnage');
hold on;
FG=plot(X3,MinCT(:,1));
set(FG,'Color','black','LineWidth',2)
hold on;
CTMax=plot(X3,MaxCT(:,1));
legend('AverageCT','MinCT','MaxCT');
set(CTMax,'Color','red','LineWidth',2);
axis([0 18 110 140]);
hold off
bp1=boxplot(tP,'plotstyle','traditional');
set(bp1,'linewidth',1.5);
axis([1 18 100 140]);
xlabel('Period (Year)');
ylabel('CT Tonnage (MT)');
axis([1 18 100 140]);
createPlot(X3,CT(:,2)./1000000,'Period (Year)','CT Tonnage (MT)','Tonnage');
hold on;
FG=plot(X3,MinCT(:,1));
set(FG,'Color','black','LineWidth',2)
hold on;
CTMax=plot(X3,MaxCT(:,1));
legend('FixedCT','MinCT','MaxCT');
set(CTMax,'Color','red','LineWidth',2)
hold off
ATest=CT(8,5:104)./1000000;
 tP1=tP(:,8);
boxplot(tP1,'Orientation','horizontal');
axis([100 140 0 5]);
hold on;
hist(ATest,18);
hold on;
xlabel('CT Tonnage (MT)');
title('Period #8');
h=findobj(gca,'Type','patch');
set(h, 'FaceColor','blue','EdgeColor','black');
 bp8=boxplot(tP1,'Orientation','horizontal');
 set(bp8,'linewidth',1.5);
 axis([100 140 0 2]);
 xlabel('CT Tonnage (MT)');
 hold off;
```

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