University of Alberta

Modeling and Simulation of An At-Face Slurry Process for Oil Sands

by

Andrea Scaffo-Migliaro ©

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ABSTRACT

AFS (At-Face Slurry) technology is a mobile surface mining system concept to produce and transport oil sands slurry from a mining production face to join a final fixed pipeline or hydrotransport train. AFS technology provides a direct interface between the mine face and hydrotransport system with the added benefit of eliminating the use of haulage trucks. A second benefit of AFS technology is preliminary conditioning of oil sand slurry before hydrotransport.

Understanding the interaction between production and reliability processes in the oil sand industry is crucial for effective and well-informed operational decision-making. Relatively little emphasis has been placed on modeling efforts that concern both perspectives. This work focuses on modeling an AFS system incorporating production with reliability issues under the imposed effect of uncertainty. It aims to provide a model-based framework for future optimization studies of the operation of the AFS technology.

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Finally, I deeply thank Pamela Harding for her unconditional support, understanding and encouragement. Many thanks to my parents, for believing in me; and to my friends, that helped me get here.

I sincerely hope this work is just the beginning of new discoveries and understanding of new technologies to be applied in the oil sands industry.

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1.1 *Oil Sands Industry*

The oil sands of northern Alberta contain the biggest known reserve of oil in the world. An estimated 1.7 to 2.5 trillion barrels of bitumen are trapped in a complex mixture of sand, water and clay in which the percentage of bitumen ranges from 1% to 20%. The oil saturated sand left over from ancient rivers is found in three main deposits, as shown in Figure 1: Peace River, Cold Lake and Athabasca areas. The Athabasca deposit is the largest and closest to the surface, accounting for the large-scale oil sands development around Fort McMurray [Oil Sands story]

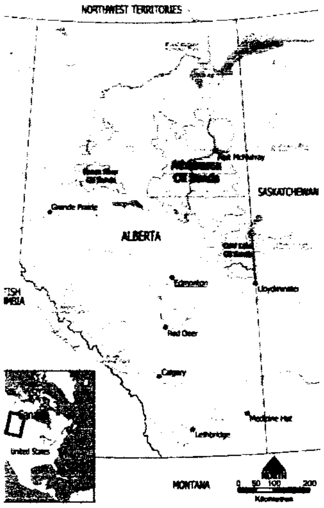
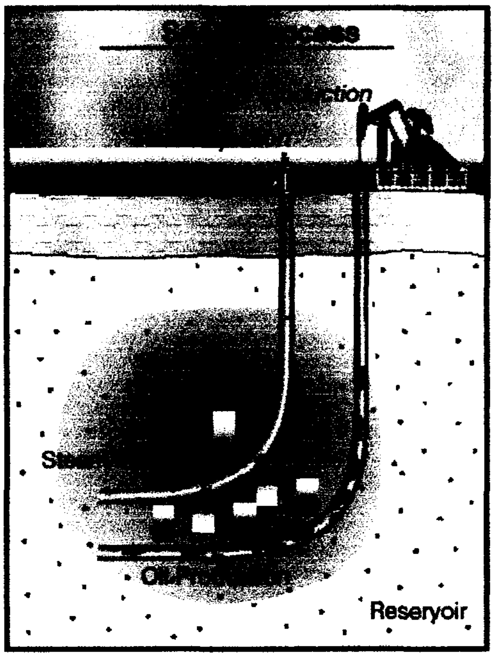


Figure 1 - Alberta's oil sand deposits [Alberta Oil sands]

Currently, in the Athabasca deposit, oil is recovered from the oil sands in a wide variety of methods through mining and extraction processes. Production is carried out through surface mining and extraction or in-situ methods, depending on the depth of the orebody. On the extraction side, bitumen is recovered by variations of the original hot-water separation process pioneered by Karl Clark, with treatment of the bitumen / water froth to reduce the water and solids content. Some companies in the area use both truck-shovel mining and SAGD (Steam Assisted Gravity Drainage) processes. Figure 2 shows a schematic of the SAGD Process. New in-situ processes are also emerging, for example, THAI (Toe-to-heel air injection).



Source: PetroCanada

Figure 2 – Schematic of SAGD Process

1.2 Background of Oil Sands Mining at Syncrude

Syncrude Canada Ltd. has been mining oil sands in the Athabasca deposit since 1977 at its Mildred Lake Mine. The first method introduced for mining oil sands was a combination of dragline / bucket-wheel-reclaimer / conveyor technology. The last dragline and bucket-wheel retired at the beginning of 2006, representing the end of an era. In 1991, production shifted to a different method that proved to be more economical by using large shovels and trucks to mine both ore and overburden. The main driving factors for the change were the large amount of pre-stripping required by the dragline system and the flexibility of mobile equipment. In 1997 the introduction of hydrotransport technology for pipelining oil sand slurry proved to be a success because it was capable of transporting ore with higher efficiency and reduced costs compared to the original method and to truck-shovel haulage to a central plant. Results from pilot scale testing showed that ore processing begins in the pipeline itself, which means that when the ore reaches the extraction plant bitumen is already released from the oil sand matrix and aerated [AFS Technology].

1.2.1 The Syncrude process

Oil sand mined by truck-and-shovel at Syncrude's Mildred Lake and Aurora mines is transported via hydrotransport to a series of process units that extract bitumen from the oil sand. The oil sand is "slurried" by adding hot water and caustic soda to condition it for bitumen separation, in either tumblers (large rotating drums), cyclofeeders or mixing boxes. From the tumblers, the slurry is discharged onto vibrating screens where large material such as rocks and lumps of clay are rejected. Oil sand is also converted into slurry in cyclofeeders, which employ fixed screens for classification, or mixing boxes followed by vibrating screens. Slurry is fed into Primary Separation Vessels (PSV), where the bitumen floats to the surface as froth. Underflow streams are further treated to recover more bitumen. Froth is deaerated and treated to minimize the water and solids going to the upgrader; froth is diluted with naptha and is either put through inclined plate settlers or two stages of centrifuges to remove water and solids. Next, three upgrading units – the fluid cokers, the Vacuum Distillation Unit (VDU), and the LC-Finer – break down the bitumen into light gas oil (LGO), heavy gas oil (HGO), and naphtha. These three products are routed to hydrotreaters to remove sulphur and nitrogen and are blended to produce the crude oil called Syncrude Sweet Premium [Pure Energy]. Figure 3 shows a schematic of the above-mentioned process.

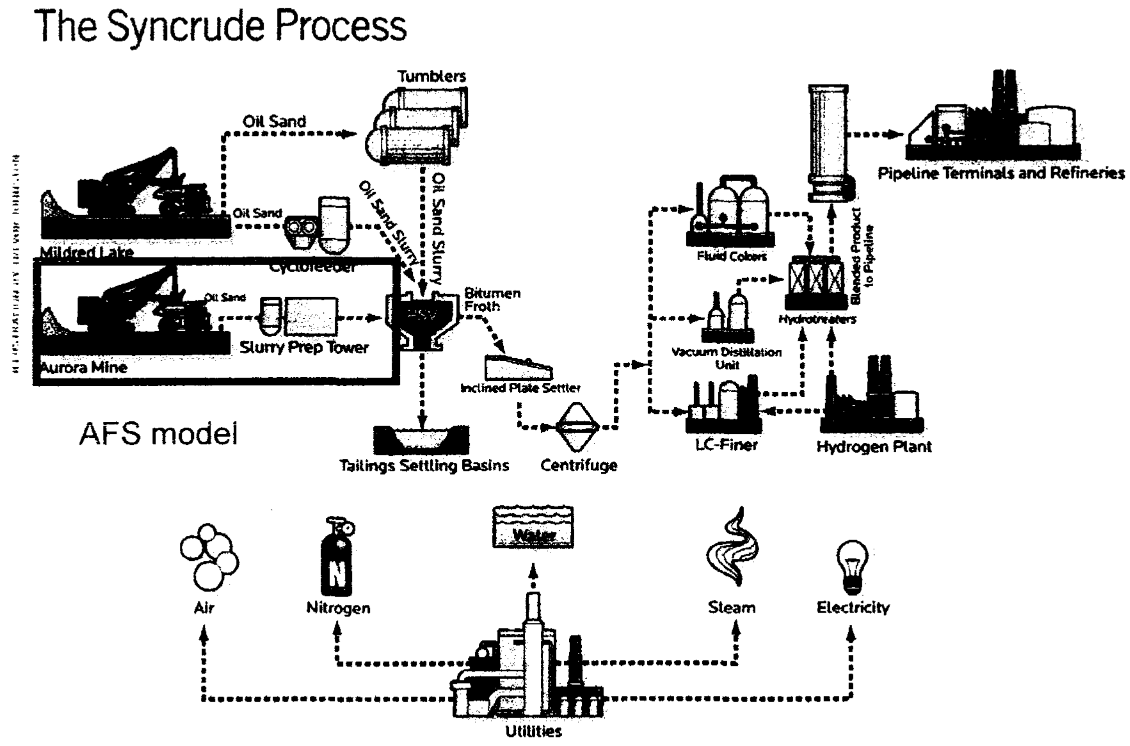


Figure 3 - The Syncrude process [Pure Energy]

The at-face slurry (AFS) model simulates the process steps from the ore face, starting at the shovel, up to the hydrotransport line that goes into the PSV. The AFS part of the process is indicated in the rectangle in Figure 3.

1.3 At-Face Slurry Technology

The cost of oil sands bitumen production by means of truck and shovel operations is expected to increase significantly with increasing haulage distances. Relocating slurry preparation systems and installing longer pipelines mitigate this cost, but even relocating in-pit slurry preparation systems is of high cost. The capital and operating costs associated with the use of haul trucks account for over 25% of bitumen production cost. As haul distances increase, more trucks are required for a given production rate. The requirement for more haul trucks to meet production targets will result in higher production costs. The current challenges of worldwide tire shortage and engine reliability are new ingredients in the economic equation behind AFS as a means to reduce haulage costs. Low reliability and premature failure of 793 Haul Truck engines and components, has led to unacceptable levels of fleet downtime for maintenance and repair. Resulting in an average total service life of units only achieving 7000 to 10000 hours. Improved lubrication practices leading to better engine reliability and service life are being studied [Maintenance Technology Institute].

Oil sands deposits in the Athabasca formation are characterized by different lithofacies, interburden waste pockets, overburden, and displaced deposits, all of which affect extraction performance. In major fault zones within this formation, orebodies can be displaced as far as 20 meters, making it extremely difficult for the extraction process. Current operations allow for interburden waste bodies of

5 meters or less in thickness to be mined as part of the ore, resulting in dilution and additional cost for handling and processing waste materials. Excessive variability in feedstock affects extraction separation performance. Appropriate production schedules allowing for continuous ore extraction from multiple concurrent faces are needed to achieve targets while enhancing flexibility and efficiency. Design, planning and modifications of pit layouts for selective mining of heterogeneous ore and extraction of displaced deposits significantly increase the cost of extracting oil from the oil sands. In addition, the need for reducing greenhouse gases like CO_2 and other exhaust pollutants from diesel engines warrants the use of a more efficient, less costly and environmentally friendly technology.

At-face slurry (AFS) technology will extract oil sands using a combination of continuous processes and discretely operating mining equipment operated in appropriate mining sequence. This technology introduces design, operating and maintenance challenges, as will be illustrated in this thesis work.

Figure 3 shows the current Syncrude process, which includes a high level depiction of what AFS involves, with the exception of haulage trucks. Figure 4 depicts a schematic of the AFS process, as described in this work.

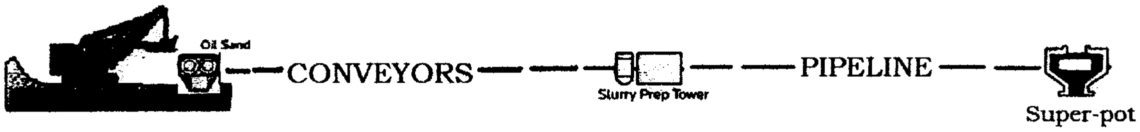


Figure 4 - Schematic of AFS process

The configuration of the modified open pit layouts must accommodate the dimensions and complexity of the AFS system. The technology must also be flexible to respond to changes in its operating requirements and accommodate its limitations. One of the biggest challenges in an existing operation is to design, develop and implement robust and efficient technology to meet production targets, while maintaining a reliable and safe operation. If implemented, AFS technology is estimated to reduce mining production costs by about 20% compared to conventional truck-shovel methods [AFS technology].

The use of shovels as primary excavators delineates the need for flexible and mobile material transport units to accommodate horizontal and vertical displacements on a mining bench while following the excavation process.

The AFS technology must withstand the harsh mining environment of the oil sands, and account for the variability of the ore. In winter, when ground temperatures fall below -10°C, the ore becomes hard and brittle. On the other hand, in hot-summer temperatures, the ore is sticky and hard to manage, binding to bins and hoppers, and difficult to drive on because it is so soft. The viscosity of Athabasca bitumen changes about 1 million times in the range of working temperatures from -30°C to +30°C [University of Alberta Geotechnical Centre].

Productivity of the AFS system also depends on the design and configuration of flexible pipelines, slurry flow characteristics, energy losses in the pipelines and pipeline degradation.

Equipment maintenance, operational environment as well as design of each component affect the overall reliability of the system. The effectiveness of maintenance is an important factor in determining how long the equipment operates after repairs are performed. For example, if maintenance procedures are faulty, or poor replacement parts are used, then the reliability of the equipment will decrease; and hence, the reliability of the whole system will decrease. The operational environment, including ore and slurry conditions as well as operator practices significantly influence equipment reliability. Where there is a known operating environment and proper practice, the design of the equipment determines its maximum achievable reliability [Reliability Analysis].

The School of Mining and Petroleum Engineering of the University of Alberta sponsored by NSERC, and Syncrude Canada Ltd. joined efforts to develop a concept for a robust and efficient AFS technology for the extraction of oil from the oil sands. A three-year project was conducted in order to investigate the feasibility of such technology within Syncrude leases [AFS Technology].

The study carried out by the University of Alberta and more in-depth research performed by Syncrude indicated that a more operational perspective of the AFS technology is required. The present work addresses this need for model-based understanding of AFS operability. The development of a model from both the production and reliability points of view will mimic realistic scenarios for the AFS technology for both engineering analysis and operation decision analysis.

There has been previous work on simulation models to understand different combinations of equipment and processes. For example, a probabilistic discrete event simulation program was developed and used to provide production volumes and statistics to assist in the selection and sizing of key elements of the integrated operation of the mining and hydrotransport equipment, from the mining face to the extraction plant for the North Mine [Hydrotransport system simulation]. Also, an At-Face Slurrying model was developed by D. W. Ellis & Associates Ltd. to simulate the operations of a proposed system from the mine to extraction. Through the analysis of various cases defined by the user in an input file, equipment configuration and operating strategies for different AFS options can be compared and evaluated [AFS Simulation]. The limitations of this model are given by the fact that the study was performed more than seven years ago and technology has changed since that time. Also, the goal of this model is to compare three viable options rather than achieving a thorough understanding of a specific model. Another limitation of this model is given by the fact that even though regular maintenance events are accounted for, the fluctuations driven by production that affect reliability are not reflected in the system. For example, changes in ore quality can affect pump and pipe wear and this will require more maintenance events.

The whole AFS system as presented in this work has not been implemented anywhere in the world yet, the oil sands industry will be the first industry where it will be implemented.

1.4 Objective of the Present Work

The main goal of this thesis work is to address the lack of understanding of how an at-face slurry system will be operated and controlled, and also to understand the system behavior through the interaction of downstream and upstream processes along the system.

The present state of mining process development and automation results from past research and development efforts focusing almost exclusively on individual machines rather than on an overall automation strategy. Although essential to the natural progression from mechanization to automation, this machine-centered approach has lead to the introduction of advanced mining equipment, which operates in isolation because it lacks the capability to interact effectively and safely with other equipment and personnel. As progressively more complex systems are required for mining operations, the problem of *integration* is becoming a logistic colossus, which can no longer be harnessed with temporary solutions. Hence, the need to gain a more global perspective has become apparent and research efforts are being addressed to analyze operability and functionality in a more integrated way [Robotic Mining].

The need for high productivity, coupled with a harsh physical environment that pushes equipment to the limits of its design, results in a high-stress work environment that can make cooperation between operations and R&M (Reliability and Maintenance) departments quite challenging. It cannot be overstated that the most significant improvements are based on better communications through shared information [Mine Operations and Maintenance]. In an operational system, a symbiosis between operations and maintenance is vital for a successful operation, and the AFS model is not an exception.

Large bulk mining operations are moving to shovels and trucks for ore fragmentation and material handling. For integrated operations with effective operational control, the mining sequence and downstream mineral processes must be in tune. There are recognized competitive advantages to integrated operations, but this value comes only to organizations that have tight operational control in integrated operations. Integration is achieved by cutting excess capacity and intermediate inventory, which makes processes more coupled. This coupling causes disturbances that ripple through the operation. Decision makers in such organizations need to understand what affects their part of the operation, and they need effective methods for dealing with other groups and departments when they make decisions that have broad consequences. Discrete-event modeling is a powerful tool for representing these industrial activities, and for developing methods to improve them [Truck-shovel Mining Operations].

The above statements delineate the need for an *integrated* model that incorporates *production* and *reliability* constraints to optimize the design and ultimately provide guidance in the operational decision making of a mining system. The objective of this thesis work is to provide a model that accounts for all these issues in an AFS system.

A model-based framework for AFS simulation that adds reliability issues to the traditional production concepts will be introduced, for example, scheduled downtime generated due to pipe wear from the actual operation.

Chapter 2 introduces the fundamentals of modeling and simulation and includes information on the package selected for developing the model. It also includes theoretical background for the model. Chapter 3 provides a detailed description of the AFS model at a high level. Chapter 4 describes each module in detail; a list of assumptions and decision variables used for the model is also included. In the hydrotransport module, an introduction to wear rates as defined for this model is explained. Chapter 5 gives examples of how the model was used for analysis, and shows how the system is affected by production issues as well as reliability concerns. Chapter 6 provides conclusions and recommendations for improving the AFS model that has been developed. The Appendix gives more detail for the entire model as defined in a commercial simulation package.

2 LITERATURE REVIEW

2.1 Modeling

The most basic concept of this investigation is that of a system. The primary definition of system as given by the Webster's Dictionary is: "a regularly interacting or interdependent group of items forming a unified whole" [Webster's Dictionary].

A system is a collection of elements used to perform a process. A process is a collection of activities that creates an output based on one or more inputs. Thus, systems encompass processes but also include the resources and controls for carrying out processes. In process design, the focus is on *what* is being performed while in systems design the emphasis is on the details of *how*, *where* and *when* the process is performed. Defining the process generally comes first, followed by the design of the system. Each one, however, can have an influence on the other [Simulation Made Easy]. At the most basic level, a system is made up of entities, activities, resources and controls, as shown in Figure 5.

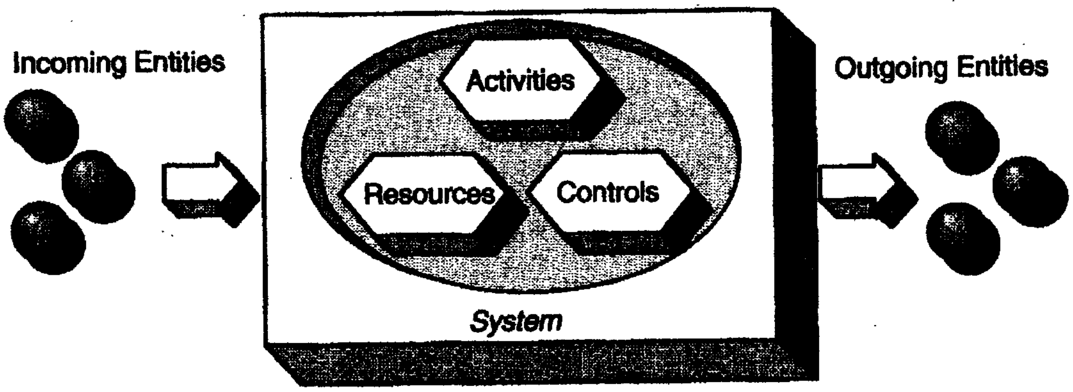


Figure 5 – Elements of a system [Simulation made easy]

An entity is an elementary, a complex, or a structural unit in a model that is generated by a dedicated-model creating procedure and can be distinguished from any other entity or entities by its type and parameters. An entity describes an object or some feature of it. There are several general expectations of the handling of entities in modeling packages, which are expected to include all necessary procedures to create, combine, modify, and delete the specified entities [Modeling and Problem Solving].

Frequently, the phenomena occurring in the real world are multifaceted, interrelated, and difficult to understand. In order to deal with these phenomena, we abstract from details and attempt to concentrate on the larger picture – a particular set of features of the real world or the structure that underlies the processes that lead to the observed outcomes. Models are such abstractions of reality. Models force us to face the results of the structural and dynamic assumptions we have made in our abstractions. Modeling can be a never-ending process – we build, revise, compare, and change models. With each cycle, our understanding of the reality improves [Simulation Made Easy].

Some models represent a particular phenomenon at a point in time and are classified as *static*. Other models compare some phenomena at different points in time. This is like using a series of snapshots to make inferences about the system's path from one point in time to another without modeling that process; this category of models is called *comparative static models*. Some models describe and analyze the very processes by which a particular phenomenon is created. The latter type of model is a dynamic model, which attempts to capture and represent the change in real or simulated time and takes into account that the model components are constantly evolving as a result of previous actions [Dynamic Modeling]. In some cases, a system exhibits a limited number of cyclic behaviors, referred to as an eigen value system.

Some models are *prescriptive*; that is, they determine an optimal policy. Linear programming models are prescriptive because the solution to a linear program suggests the best course of action that a decision maker should take. Other models are *descriptive*; they simply describe relationships and provide information for evaluation. Descriptive models are used to explain the behavior of systems, to predict future events as inputs to planning processes, and to assist decision makers in choosing the best solution or system design. Models can also be *deterministic* or *probabilistic*. In a deterministic model, all data is known, or assumed to be known with certainty; mathematical models belong to this category. In a probabilistic model, some data are described by probabilistic distributions.

Finally, models may be *discrete, continuous or hybrid* [Simulation and Risk Analysis]. The state of a model is given by the collection of variables necessary to describe the system at a particular time, relative to the objectives of the study. A discrete model is one for which the state variables change instantaneously at separated points in time. A bank is an example of a discrete system because state variables (for example, the number of customers in the bank) change only when a customer arrives or when a customer finishes being served and departs. A continuous model is one for which the state variables change continuously with respect to time. An airplane moving through the air is an example of a continuous system because state variables such as position and velocity can change continuously with respect to time. Since some systems are neither completely discrete nor completely continuous, the need may arise to construct a model with aspects of both discrete-event and continuous models resulting in a hybrid or combined discrete-continuous model [Simulation Modeling and Analysis].

Models are sketches of real systems and are not designed to show all of the systems' many facets; they aid us in understanding complicated systems by simplifying them. Models study cause and effect; they are causal, as in the case of systems with a dynamic response. The modeler specifies initial conditions and relations among these elements. The model then describes how each condition will change in response to changes in the others. The initial conditions selected by the modeler could be actual measurements or estimates. Then the modeler must decide on the boundaries of the system and choose the appropriate level of detail. The components of a model are expected to interact with each other. Such interactions engender feedback processes [Dynamic Modeling for Business Management].

Much of the art of system dynamics modeling is discovering and representing the feedback processes, which, along with stock and flow structures, time delays, and non-linearity, determine the dynamics of the system. There is an immense range of different feedback processes and other structures to be mastered before one can understand the dynamics of complex systems. In fact, the most complex behaviors usually arise from the interactions (feedbacks) among the components of the system, not from the complexity of the individual components themselves. All dynamics arise from the interaction of just two types of feedback loops, positive (or self-reinforcing) and negative (or self-correcting loops). Positive loops tend to reinforce or amplify whatever is happening in the system. Negative loops counteract and oppose change. Either type of loop can be good or bad, depending on which way it is operating. Though there are only two types of feedback loops, models may easily contain thousand of loops, of both types, coupled to one another with multiple time delays, non-linearity, and accumulations. The dynamics of all systems arise from the interactions of these networks of feedbacks. When multiple loops interact, it is not easy to determine what the dynamics will be [Business Dynamics].

The first step of the model building approach is the development of a purpose for modeling that is based on a stated problem or project goal, an abstraction from reality. Based on this purpose, the boundaries of the system and the level of detail are established. Desired performance and design alternatives can be considered as part of the model or as inputs to it. Assessments of design alternatives in terms of specified performance measures are the model outputs. Typically, the assessment process requires iterations of definitions and designs. In fact, the entire model building approach is usually performed iteratively. When recommendations can be made based on the assessment of alternatives, an implementation phase is initiated [Simulation with Visual SLAM]. A pictorial view of the model building approach used in this work is depicted in Figure 6. The approach just described is not the only model building approach but it is the one used for building the AFS model.

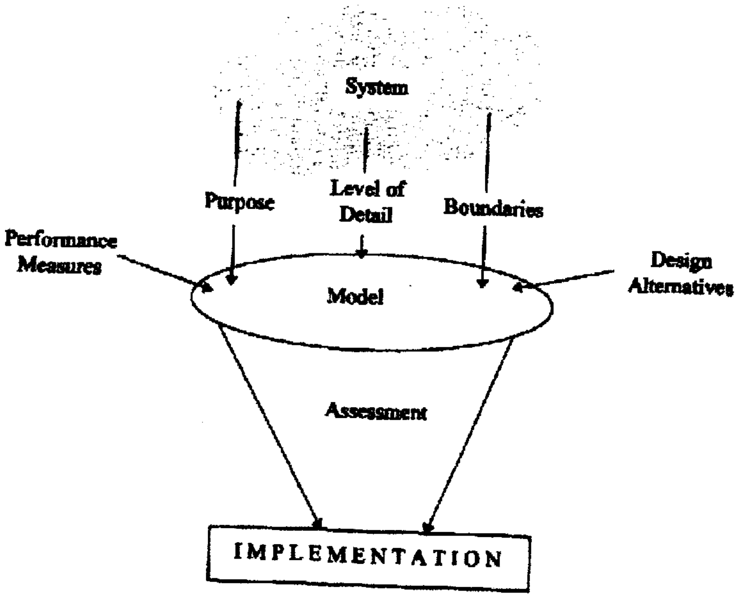


Figure 6 - Model building approach [Simulation with Visual Slam and AweSim]

2.2 Structure and behavior of dynamic systems

The feedback structure of a system generates its behavior. Most dynamics observed in the real world are examples of a small set of basic pattern or modes of behavior. Three of these modes are fundamental: exponential growth, goal seeking, and oscillation. Each of these modes is generated by a particular underlying feedback structure. Positive feedback processes generate exponential growth, goal seeking is generated by negative feedback, and oscillation is generated by negative feedback with delays. More complex patterns of behavior such as S-shaped growth, growth with overshoot, as well as overshoot and collapse result from the non-linear interaction of these basic feedback structures. Figure 7 shows the common modes of behavior in dynamic systems [Business Dynamics].

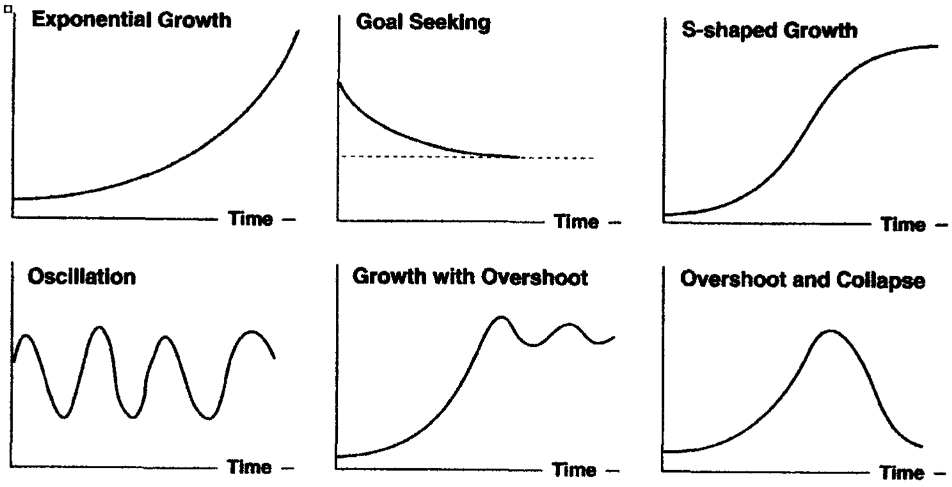


Figure 7 – Common modes of behavior in dynamic systems [Business dynamics]

The principle that the structure of a system generates its behavior leads to a useful heuristic to help modelers discover the feedback loop structure of a system. Whenever a particular pattern of behavior is observed, the dominant basic feedback structure during the period covered by the data is identified. Observing that a variable of interest has been fluctuating, for example, implies the existence of (at least) one negative feedback loop with significant time delays, which manifests itself as a second-order, under-damped dynamic system that helps to guide the search of particular structures, decision processes, and time delays that compromise the negative loop. While this heuristic is useful as an aid to the initial conceptualization process it can also be used as a way of identifying possible bottlenecks and potential limits of the model [Business Dynamics].

2.3 Engineering Analysis and Modeling

A new scene of engineering has emerged in computer systems. It is called the virtual world and it gives a new and enhanced quality to engineering. The virtual world for engineering is constituted of interrelated descriptions of objects as parts, assemblies, kinematics, analysis results, manufacturing processes, production equipment, manufacturing tools, instruments, etc. Elements of the descriptions are entities and their attributes. The structure of the descriptions is defined as the relationships between entities, or their attributes. Construction of a virtual world in the course of engineering activities starts from ideas about the system to be modeled and the engineering objects to be included in it. Typically, objects and their structures are defined. The basic approach to construction may be top-down, bottom-up, or mixed. Following a pure top-down approach, modeling starts with the definition of a structure, and then objects are created for elements of the structure. Following a pure bottom-up approach, first objects are created and then their structure is defined. A mixed approach represents everyday practice where some objects are available at the start, then structure is defined, and finally remaining objects are created according to the structure. Examples for predefined elements can be units of computers, integrated circuits, fasteners, bearings, and other standard elements of mechanical and other engineering systems. Typical structures can be predefined, stored, retrieved, and adapted for individual tasks [Modeling and Problem Solving].

2.4 Simulation modeling

In developing a simulation model, an analyst needs to select a conceptual framework for describing the system to be modeled. This framework contains a ***world view*** within which the system functional relationships are perceived and described. If a modeler is employing a simulation language, the world view will normally be implicit within the language. However, if the modeler chooses to select a general-purpose language such as FORTRAN, C or C++, the perspective for organizing the system description and solving the resulting equations is the responsibility of the modeler. In either case, the worldview employed by the modeler provides a conceptual mechanism for articulating the system description [Simulation with Visual SLAM]. Commercial simulation software will be used to implement the AFS technology model.

Simulation is a modeling technique in which the cause-and-effect relationships of a system are captured in a computer model, which then becomes capable of generating the same behavior that would occur in the actual system. A simulation model should be viewed essentially as a *what-if* tool that allows a designer or manager or trainee to experiment with alternative designs and operating strategies to see what impact those decisions have on overall system performance. As an experimental tool, simulation is used to test the effectiveness of a particular design and does not, in itself, solve a problem or optimize a design. It helps evaluate a solution and provides insight into problem areas rather than generating a solution [Simulation Made Easy].

Applying object-oriented concepts to simulation has been considered in the past as a key factor to ensure the efficiency of both the modeling process and the generation of software that is modular and easy to modify. An object-oriented simulation approach may be better exploited when a hierarchy of the main components of a system is defined [Object-Oriented]. Modeling a system through the definition of a class hierarchy is one of the characteristics of object-oriented simulation.

An object-oriented simulation model is usually composed of a set of objects or classes of objects that represent the entities involved. In turn, each class is characterized by specific attributes that determine the behaviors of the entities. During simulation, instances of the different classes are generated, and the whole system behavior results from the parallel execution of the instances.

Discrete-event simulation allows a comprehensive and detailed description of the system behavior by identifying the events that start and/or end activities and by linking them with cause-effect relations. Transient behavior during transitions is assumed to be unimportant. In other words, object-oriented simulation specifies the whole system behavior as the evolution of such processes and their interactions.

Continuous simulation concerns the modeling over time of a system by a simplified representation in which the state variables change continuously with respect to time. Typically, continuous simulation models involve differential equations that give relationships for the rates of change of the state variables with time. If the differential equations are particularly simple, they can be solved analytically to give the values of the state variables for all values of time as a function of the values of the state variables at time 0. However, for most continuous models analytic solutions to the set of differential equations are not possible, and so numerical analysis techniques (for example, Runge-Kutta integration) are used to integrate the differential equations numerically, given specific values for the state variables at time 0 [Simulation Modeling and Analysis].

There is a plethora of simulation packages available on the market. Simulators are data-driven packages that require little or no programming. It seems desirable to combine the ease of use of simulation packages with the flexibility of languages [What Users Want].

The benefits of developing a simulation model can accrue in two major areas:

- The process of developing a model of a system often provides insight into some of the major issues, which impact the design of a system and ultimately its operation

- Having an operational model of the system can give a quantitative basis for making many of the cost/performance trade-off decisions that are part of all development projects

The study of dynamical systems has focused, for the most part, on the two distinctive areas of continuous-time dynamical systems and discrete-event systems. The former are typically modeled and analyzed based on differential or difference equations to capture "real-time" behavior while the latter are considered within the context of finite automaton or machines to capture logical-time behavior. Interest has emerged recently in terms of considering the dynamical behavior of systems that combine these two classes. These systems are referred to as hybrid (dynamical) systems. In addition, real-world models involve both logical-time constraints as well as real-time ones. There has been no agreement on an appropriate, simple, yet sufficiently rich model for hybrid systems. Models ought to be closely linked to the physical or real-world situation that they represent [Hybrid Systems].

The stochastic and dynamic nature of the AFS system makes it very difficult to model its operation using analytical models. With simulation, model inputs can be based on appropriate probability distributions that characterize the input variables. Also, simulation allows for easy addition of detail into the model as more information about the system is obtained.

A simulation model is an abstraction of the system. To build a model, it is necessary to visualize how the system can be translated into a model using the constructs that are available in the product being used. There are usually several ways in which particular system characteristics can be represented in a discrete-event simulation model, such as: entities, resources, movement of entities and resources, entities routing, entity processes, entity arrivals, resource availability schedules, resource downtime and repairs, special decision logic, to name a few. Entities are the items processed through the system and they may be of different types and have different characteristics such as speed, size, condition, etc. Entities might get split into other entities or get combined into a single entity. They may arrive from outside of the system or be created from within the system. Resources are used to directly or indirectly support the processing of entities in the system. In simulation, we are generally interested in how resources are utilized and how entity flow is constrained as a result of waiting for resources to become available [Simulation Made Easy].

The primary purpose of most simulation studies is the approximation of prescribed system parameters with the objective of identifying parameter values that optimize some system performance measures. If some of the input processes driving a simulation are random, then the output data are also random and runs of the simulation program can only produce estimates of system performance measures. Unfortunately, a simulation run does not usually produce independent, identically distributed observations; therefore classical statistical techniques are not directly applicable to the analysis of simulation output. There are two types of simulations with regard to output analysis:

1. Finite-horizon simulations: where the simulation starts in a specific state, such as the empty and idle state, and is run until some terminating event occurs. The output process is not expected to achieve any steady-state behavior and the value of any parameter estimated from the output data will depend upon the initial conditions. An example is the simulation of a building evacuation.

2. Steady-state simulations: in which the purpose is the study of the long-run behavior of the system of interest. A performance measure of a system is called a steady-state parameter if it is a characteristic of the equilibrium

distribution of an output stochastic process. The value of a steady-state parameter does not depend upon the initial conditions. An example is the simulation of a continuously operating communication system where the objective is the computation of the mean delay of a data packet [Advanced Methods for Simulation Output Analysis].

AFS is based on the assumptions of steady-state process conditions. However, the validation of its output is outside the scope of this thesis.

2.4.1 Simulation package selection

Up until the 1990s, it was most appropriate to classify simulation software into two classes: simulation languages and simulators. Simulation languages were characterized as being flexible, but difficult to use. Simulators, on the other hand, were characterized as being easy to use, but inflexible. Since that time, significant advancements have taken place in simulation product offerings. Some general-purpose simulation languages have added specialized modeling constructs making them easier to use, while some of the more specialized simulators have added general programming extensions making them more flexible. In fact, some simulation products that were classified as simulators in the 1980s are now more flexible than some of the traditional simulation languages. The most popular simulation tools today combine powerful industry-specific constructs with flexible programming capabilities, all accessible from an intuitive graphical user interface [Simulation Made Easy].

After some research on available simulation packages the choice was made to use AweSim under the unified modeling framework of Visual Slam. AweSim comes with specialized elements for specific processes such as queues, servers and decision points. Discrete and continuous changes can be modeled with this tool. It also provides integrating capabilities to store, retrieve, browse and communicate with externally written applications. AweSim is built in Visual Basic and C/C++, so programs written in these languages are easily incorporated into its architecture. AweSim supports problem resolution within a project structure. A simple first model was developed using AweSim.

However when the model needed to be more robust and the need for hierarchical modeling was a must, AweSim proved to be quite limited.

Extend (Imagine That Inc.) simulation environment provides the tools and capability to create powerful hierarchical dynamic models. Overall, Extend provides a full array of building blocks, animation capabilities for enhanced presentation and easy communication of the model. The unlimited hierarchical decomposition to make complex systems easy to build and understand is quite useful. The large variety of libraries that provide an extensive set of iconic building blocks for modeling is definitely an asset.

Extend OR (Operations Research) is an object-oriented environment for dynamic modeling which allows the building of discrete, continuous and hybrid systems. There are three types of documents in Extend: models, libraries and text files.

A model in Extend is composed of components (blocks) with connections between them. A block specifies an action or process.

A library is a repository of blocks. Extend OR contains libraries with well-defined functionality, for instance the manufacturing library is a toolkit for modeling discrete industrial and commercial processes.

Text files store data in a form that can be read by almost any application; these files are especially useful for importing large amounts of data into a model (for example a spreadsheet) or for exporting model data to another application for further analysis or for presentation purposes.

Extend's iconic building-block paradigm allows for rapid model building. The use of hierarchical blocks, as well as built-in libraries and performance calculations facilitates comprehensive model building starting from a basic model and adding complexity in later phases.

Extend also allows for flexibility and custom made functionality by using its own developing language – ModL – a language that is very similar to C. The development of specific and powerful block building is an added feature of this package.

The original model developed in AweSim was transferred into Extend OR (Operations Research). Chapter 4 makes reference to the model developed with Extend OR.

2.5 Reliability

Reliability is the probability that a system will perform its intended functions satisfactorily for at least a given period of time when used under stated conditions. A system can be characterized as a group of stages or subsystems integrated to perform one or more specified operational functions. Recent progress in science and technology has made today's engineering systems more powerful than ever. The increasing level of sophistication in high-tech industrial processes implies that reliability problems not only will continue to exist but also are likely to require ever more complex solutions. The importance of reliability at all stages of modern engineering processes, including design, manufacture, distribution, and operation, can hardly be overstated [Optimal Reliability Modeling].

Quality control procedures are developed to make judgments on both measurements and attributes. Measurements can be related to physical characteristics such as wall thickness, distance between holes, electrical resistance, and reflectivity of a polished surface. Attribute analysis, on the other hand, is concerned with whether an item possesses or does not possess some described characteristic such as a stated size (yes/no) or a stated degree of quality (acceptable versus defective product). Reliability theory is a subset of quality control, in that the characteristic studied is not some instantly available dimensional measurement but the length of life of the item. Because of the long time periods necessary to gather life data, it is a far more expensive and involved process than simple size measurement. The analyst may study these data more intensively in order to extract as much information as possible. In short, the quality control function deals primarily with new products under inspection. Reliability deals with products in service [A Primer of Reliability Theory].

Reliability is generally concerned with failures during the life of an item, product or machine. We therefore need to understand why items fail. Reliability is an aspect of engineering uncertainty. Whether an item works for a particular period is a question that can be answered as a probability [Practical Reliability Engineering].

The primary goal of the reliability engineer has always been to find the best way to increase system reliability. Kuo et al provided a list of accepted principles for this purpose: (1) keeping the system as simple as is compatible with the performance requirements; (2) increase the reliability of the components in the system; (3) using parallel redundancy for the less reliable components; (4) using standby redundancy, which is switched to active components when failure occurs; (5) using repair maintenance where failed components are replaced; (6) using preventive maintenance such that components are replaced by new ones whenever they fail or at some fixed interval, whichever comes first; (7) using better arrangements for exchangeable components; (8) using large safety factors or a product improvement management program; and (9) using burn-in for components that have high infant mortality [Optimal Reliability Modeling].

For repairable items, reliability is the probability that no failure will occur in the period of interest, for example, during the mean time between rotations on a straight pipe.

A physical asset is put into service to fulfill a specific function. By maintaining the asset we make sure it continues to perform its intended function(s) to an acceptable standard of performance. If for any reason, the asset is unable to achieve that level of performance, we will consider it to have failed.

Two categories of actions can be taken to deal with failures: *proactive tasks*, which are tasks undertaken before a failure occurs, in order to prevent the item from falling into a failed state; and *default actions* that deal with the failed state and are chosen when it is not possible to identify an effective proactive task [RCM].

A proactive task is worth doing if it reduces the consequences of failure enough to justify the direct and indirect costs of doing the task.

Any physical asset that is required to fulfill a function will be subjected to a variety of stresses that deteriorate the asset by lowering its resistance to stress. Eventually this resistance drops to the point at which the asset can no longer deliver the desired performance. Generally, there is a relationship between the rate of deterioration and the age of an item. In fact, there are three sets of ways in which the probability of failure can increase as an item gets older. These are shown in Figure 8. The characteristic shared by patterns A and B is that they both display a point at which there is a rapid increase in the conditional probability of failure. Pattern C shows a steady increase in the probability of failure, but no distinct wear-out zone where the probability increases rapidly.

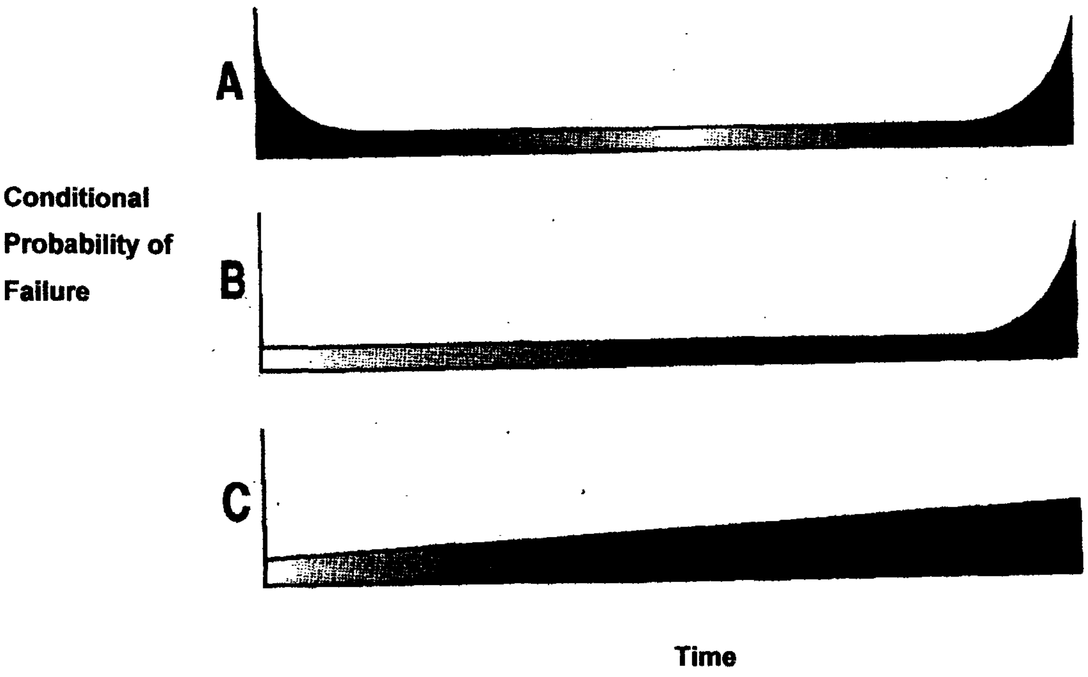


Figure 8 – Age related failures [RCM]

In general, age related failure patterns apply to items, which are simple, or to complex items with a dominant failure mode. In practice, they are commonly found under conditions of direct wear (most often where process equipment comes into direct contact with the product). They are also associated with fatigue, corrosion, oxidation and evaporation. Examples of these include pump impellers and inner surfaces of pipelines.

Failure modes that conform to Patterns A or B in Figure 8 become more likely to occur after the end of the useful life as shown in Figure 9. If an item or component is one of those which survive to the end of its life, it is possible to remove it from service before it enters the wear-out zone and take some sort of action either to prevent it from failing, or at least to reduce the consequences of the failure. This is the intent to achieve a reliable AFS system. However, the model also accounts for default actions as in the case of unscheduled downtime.

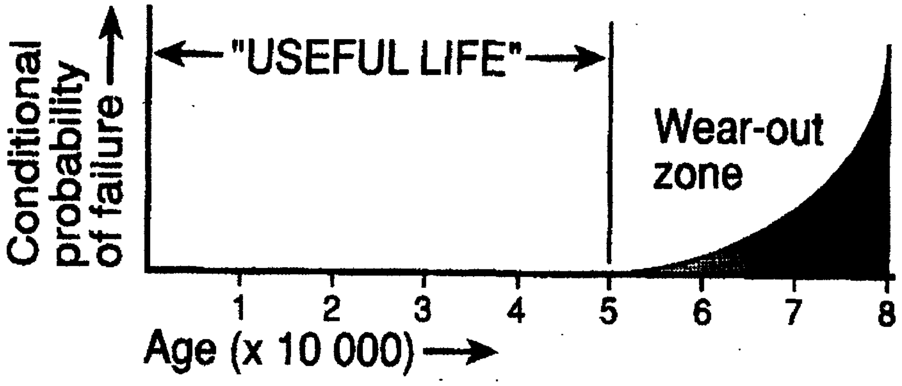


Figure 9 - Conditional probability of failure and useful life [RCM]

Preventive maintenance can reduce failures and emergency repairs. It promotes equipment awareness and disciplined inspection. At the same point, there is a balance between the cost of emergencies and that of proactive maintenance [Uptime]. Figure 10 shows the concept of an optimum minimum cost of maintenance based on the two above-mentioned scenarios. From experience in hydrotransport and tailings pipe reliability at Syncrude, it can be stated that pipes and pumps do actually benefit from age-related routine maintenance, component change-outs, and machine overhauls based on use and/or elapsed time.

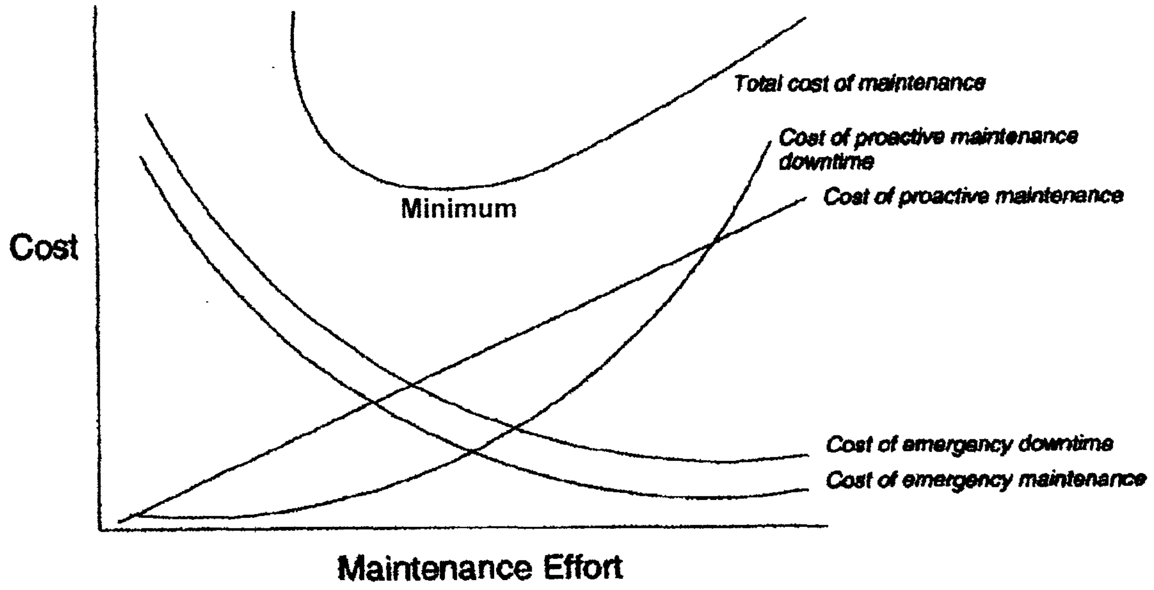


Figure 10 - Total cost of Maintenance [Uptime]

2.6 Multi-component systems

Most systems are a combination of several or many components. For most systems, then, it may be necessary or convenient to compute the system reliability from the individual component reliabilities. The simplest configuration is the *series* system, in which all components must function correctly for the system to function correctly. Schematically it is represented in Figure 11, wherein the symbol C_i indicating the *i*th component. The system reliability for systems in series has the form given in Equation 1

Rsys = P(system works) [Equation 1]

$$= P(\text{all components work})$$

$$= P(C_1 \text{ works})\, P(C_2 \text{ works} \mid C_1 \text{ works}) \ldots P(C_n \text{ works} \mid C_1, \ldots, C_{n-1} \text{ work}),$$

where P(system works) is the probability that the system works and P(C_2 works | C_1 works) is the probability that C_2 works given that C_1 works.

Figure 11 – A series system [A Primer of Reliability Theory]

Equation 1 allows for the possible dependence of one component on another – usually a realistic assumption. It is convenient, however, to assume independence between the various components; this can sometimes be done appropriately, especially if the components that are likely to fail together are regarded as a single unit. When the simplifying assumption of independence can be made, Equation 1 becomes

$$R = R_{sys} = P(C_1 \text{ works})\, P(C_2 \text{ works}) \ldots P(C_n \text{ works}) \qquad \text{[Equation 2]}$$

$$= R_1 R_2 \ldots R_n$$

The consequence of Equation 2 is that a series system is much less reliable than any of its individual elements. The more components in the system, the less reliable the system becomes [A Primer of Reliability Theory]. The AFS system is a series system.

The production level and operating costs of mines depend directly on good business organization, while the economics of the overall process is a function of operating and material costs. Maintenance costs of a mine are a significant part of the total costs, therefore any improvement of the machine output or the maintenance would bring about tangible savings. It must be recognized that the smooth functioning of the equipment is fundamental to the productivity of the operation. Failures and repairs are random quantities, which make the calculation of the system capacity so complex that it can be calculated only with difficulty by classical methods. This can be overcome by reliability theory, the first phase of the mathematical modeling being the determination of the distribution functions of the random quantities. For the transition from the operational state into the inoperative state and vice versa, a special type of Markov random process is used. The states of the system are time-dependent, and since the periods of failure or operation are random quantities, the state of the system in time *t* is also a random quantity. Markov chains are among the simplest kinds of random relationships; they are important in practical applications because they describe random processes in which the probability of future states does not depend on past states. The analysis of the system's capacity is of great relevance for increasing productivity, reducing operational costs, and improving the overall economics of the operation. Determining the reliability parameters for all components of the system before calculating the system's production capacity is a very important theoretical and practical question, which has not yet been scientifically and thoroughly defined [Continuous Mining Reliability].

The first attempt to deal with the reliability of the AFS as a whole is performed by dealing with each component's reliability. The influence of process variability on the reliability of the AFS system is beyond the scope of the present work. The assumptions about individual component reliability needs to be evaluated for the overall system, thus the need for a model and the need to do scenario analysis because individual probability distributions are not well known in advance.

The following assumptions were made for the AFS model:

- All components are relevant and improvement of component performance does not degrade the performance of the system
- The system and its components may be in only of two possible states, working or failed

- The states of the components are independent random variables (each component is assigned failed or working state that is independent of the state of other components)

2.7 Wear in slurry transport

The useful life of most slurry transport equipment is limited by erosive wear of the wetted passages. As a result, wear performance must often be evaluated in connection with the design or operation of the slurry system. In simplest terms, erosive wear amounts to the progressive removal of material from a solid surface. In practice, the mechanisms by which erosion occurs are diverse. As the factors affecting wear performance are manifold, and the gamut of slurry applications broad, a good deal of wear-performance evaluation has occurred post facto, when the system is already in operation. A body of experience and insight gathered by this method has accumulated over time, and much of the current design for wear performance of slurry systems is based on this experience.

The major erosive mechanisms are sliding abrasion and particle impact. The sliding-abrasion mode of wear typically involves a bed of contact-load particles bearing against a surface and moving tangent to it, as illustrated in Figure 12.

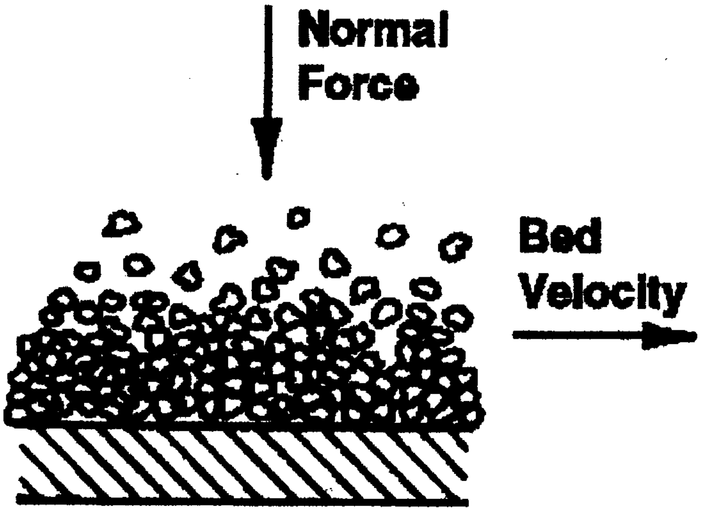


Figure 12 – Erosion by sliding abrasion [Slurry transport]

In pipelines, the stress normal to the surface primarily is caused by gravity. The normal stress is enhanced when the flow streamlines are curved, as in an elbow; and is also prevalent in pump casings where sliding abrasion tends to dominate in most areas. The second type of wear is the particle-impact mode, which occurs where individual particles strike the wearing surface at an angle, despite the fact that the fluid component of the slurry is moving along the surface (see Figure 13). Removal of material over time occurs through small-scale deformation, cutting, fatigue cracking, or a combination of these, and thus depends on the properties of both the wearing surface and the particles. Ductile materials tend to exhibit erosion primarily by deformation and cutting, with the specific type depending on the angularity of the eroding particles. Brittle or hardened materials tend to exhibit fatigue-cracking erosion under repeated particle impacts. For a given slurry, the erosion rate depends on properties of the wearing surface: hardness, ductility, toughness and microstructure. The mean impact velocity and mean angle of impact of the solids are also important variables, as are particle characteristics such as size, shape and hardness, and the concentration of solids near the surface [Slurry Transport].

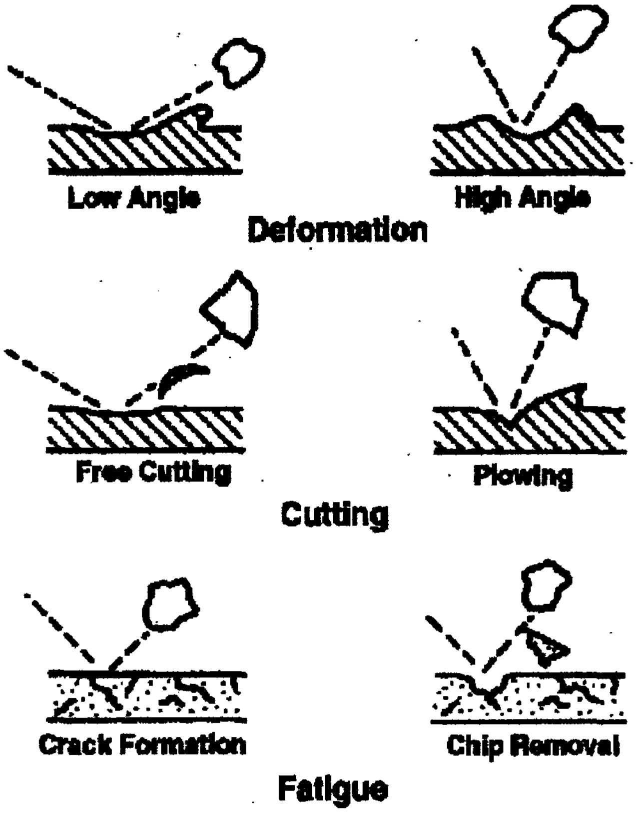


Figure 13 – Mechanisms of particle-impact erosion [Slurry transport]

Wear in slurry transport applications is primarily caused by the solids transported through the slurry, but in addition to erosion, cavitation and corrosion may also occur. Cavitation occurs on surfaces where pressure differences cause formation and collapse of vapor cavities. When the cavities collapse in high-pressure zones, shocks will be generated, causing localized deformation or pitting damage on the surface. In a corrosive slurry system, corrosion occurs when two or more electrochemical reactions take place on a wearing surface. On the attacked surface layer the corrosion products are usually loose, soft and easily removed by erosion from the slurry stream. In a combined erosion-corrosion situation, either erosion or corrosion can be the dominant factor. In most slurry transport applications, erosion is the control factor, and corrosion may be difficult to identify as it often occurs together with particle erosion, which may have a masking effect. It is not uncommon for the combined corrosion-erosion effect to be more severe than the sum of the individual effects. This situation occurs when the particulate erosion accelerates the corrosion by removing the surface corrosion products, allowing the fluid access to a fresh surface [Slurry transport].

In 1997-98, work was initiated to investigate the premature failure of one of five tailings pipelines at Syncrude. These lines had always operated under the assumption that erosion was the primary damage mechanism resulting in metal loss. The tailings system transports 55-weight % sand in recycle cooling water and operates at a temperature of approximately 55° C. Due to an initial assessment, it was believed that corrosion was a significant factor in the damage mechanism. Field-testing was performed and it showed that corrosion was a significant factor in the overall damage mechanism (erosion/corrosion). The introduction of the hydrotransport process has resulted in new material performance issues that require a re-assessment of how to best protect components from various damage mechanisms [Improving Reliability at Syncrude].

Wear testing is critical for the prediction and control of wear in slurry handling equipment such as pipelines and pumps. Abrasive/erosive wear is a complex process which may be affected significantly by a number of variables including the volume concentration of the solids, the velocity and impact angle of the eroding particles, the abrasiveness of the eroding solids and the properties that determine the wear resistance of the target surface. The availability of high-speed computers with ample memory has encouraged many research workers to develop numerical algorithms for analyzing flow and wear in pumps and other components of slurry pipeline systems. Numerical simulation of fluid and particulate flow entails the transformation of the governing partial differential equations of motion into discrete form. However, one should not infer that numerical analysis is a panacea for all flow and wear problems; and major obstacles exist which must be overcome in constructing models which can serve as effective tools for predicting wear [Slurry Transport].

2.8 Other Damage Mechanisms affecting Surface Mining and Material Handling Equipment and Systems

Some examples of damage mechanisms in surface mining and material handling equipment are described below, based on experience at Syncrude:

- In shovels and ancillary equipment (loaders, etc.): tooth damage or loss, structural cracks, lost track pads, electrical system outage (or fueling for diesel-hydraulics)
- In crusher and screens: damaged or worn teeth or segments, damaged or worn screens (if used), plugging (with ore or tramp metal)
- In apron feeder: worn or damaged pans or chains, motor / transmission drive failures, plugging, VFD (variable frequency drive) controller fault
- In transfer conveyor: worn or ripped belt, motor / transmission drive failures, structural cracking

The proposed model for the AFS technology is simplified and it does not include the failure modes described in this section in an attempt to try to understand the system as a whole without getting into a lot of detail.

2.9 Optimization

Optimization is a useful technique to automatically find the best answer to a problem. The *problem* is usually stated as the *Objective function*; equivalent to a cost or profit equation which the modeler is trying to minimize or maximize. Most optimization algorithms that can solve stochastic models use an initial population of possible solutions. One solution approach is to run the model several times, averaging the samples, and sorting the solutions. The best solution set of parameters is used to derive slightly different solutions that might be better. Each new derived solution is called a generation. This process continues for enough generations until there are probably no better solutions in sight, and then it terminates, setting up the model with the best one found.

The problem with all optimization algorithms stems from the inability to tell when the best solution has been found, or even if the best solution has even been attempted. A good approach is to allow the optimization to continue for a long enough time and check to see if the population of solutions converges [Extend v6].

One way of applying optimization into a model is by means of linear programming in order to determine the values of decision variables that maximize or minimize a linear objective function, where the decision variables are subject to linear constraints. In a linear programming problem, the set of feasible points is determined by a set of linear equations and/or inequalities. Linear programming methods provide a way of choosing the best feasible point among the many possible feasible points [Introduction to Optimization]. Later in the thesis, an example of linear optimization for the shovel module in the AFS system will be introduced.

3 SYSTEM MODEL

The model proposed in this work will aid in the development of the concept for a compact / no reject / simple / semi-mobile slurry preparation facility. The configuration includes a bin, apron feeder, a wet secondary crusher, a mix box, and a pump box on transport crawlers. The benefits of such a configuration are given by its mobility, cost effectiveness and high mechanical availability as well as suitable well-conditioned slurry for the Primary Separation Vessel feed distributor.

Figure 14 displays the configuration of the wet crushing and the mix box arrangement to achieve the above-mentioned goals.

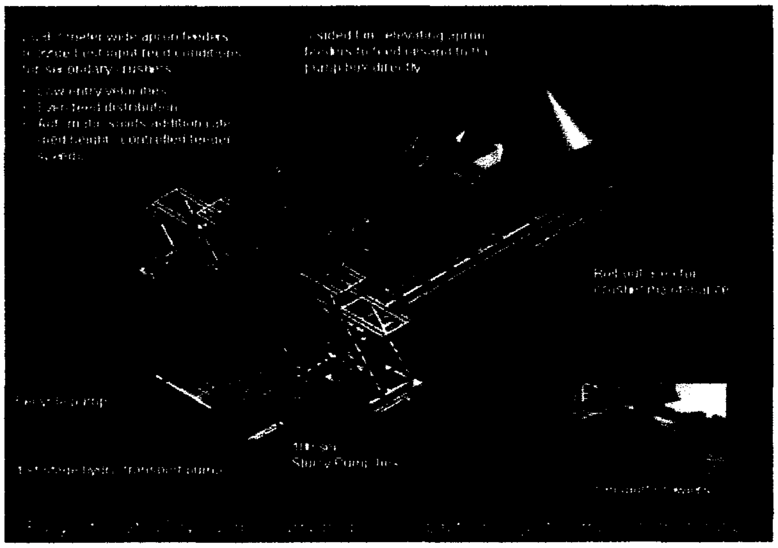


Figure 14 – Wet crushing / Mixing box [Bitumen Production Development team - Syncrude]

Compact size compared to conventional towers is achieved by using compact crushers to replace wet screening equipment and secondary systems for rejects. Figure 15 compares the proposed AFS slurry prep tower to existing structures at Syncrude Canada Ltd.

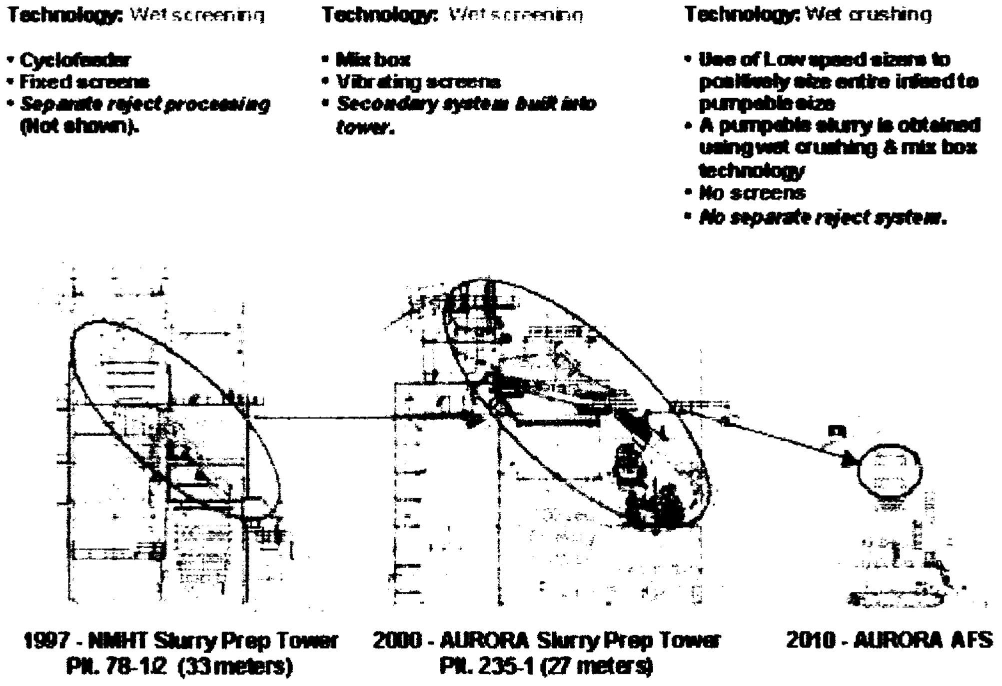


Figure 15 – AFS size comparison [Bitumen Production Development team - Syncrude]

A simplified model for the above-described configuration and the rest of the system is proposed in this thesis. The AFS system is composed of five modules that interact among each other driven by model assumptions and constraints.

Figure 16 depicts the general description of the AFS system at a high level, where the shovel is the only discrete element.

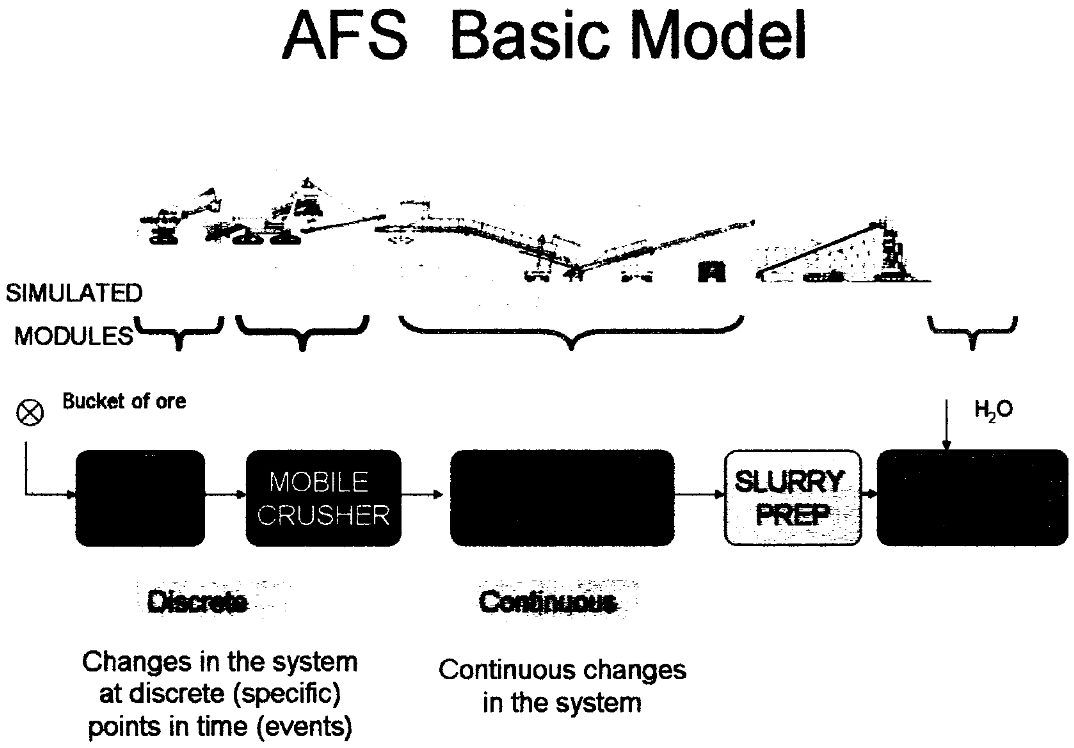


Figure 16 - High level description of AFS system

The AFS system operational equipment layout is shown in Figure 17 in two different arrangements: the top view gives an indication of how big an area it occupies, and the sectional view depicts a closer understanding of how the equipment will interact as a unit.

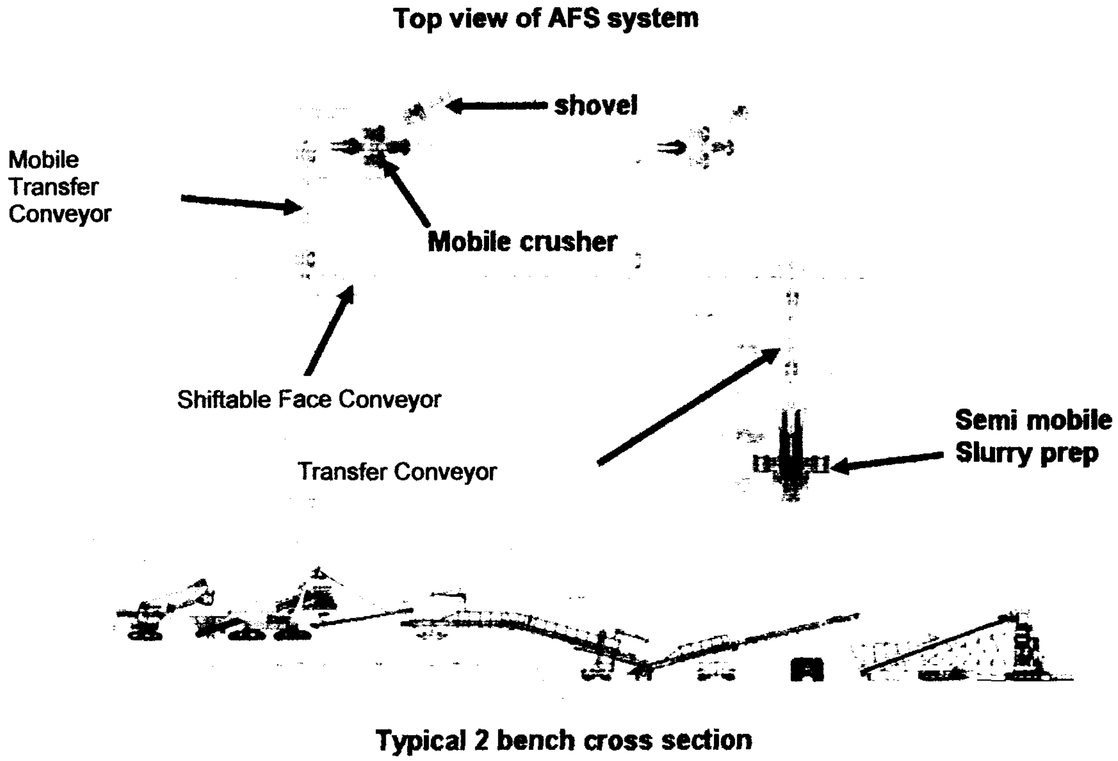


Figure 17 – AFS equipment layout [Bitumen Production Development team - Syncrude]

The model of the AFS system is basically a controlled management of delays in each module that incorporates as many different, realistic, and thorough scenarios as possible.

Three types of delays are modeled in the system, as shown below in Figure 18. If everything works as smoothly as expected, the delays will re-iterate and the whole process will be repeated again and again. However, as soon as an unexpected delay occurs, the system needs to adapt and new interactions between modules will occur, as specified in Figure 18.

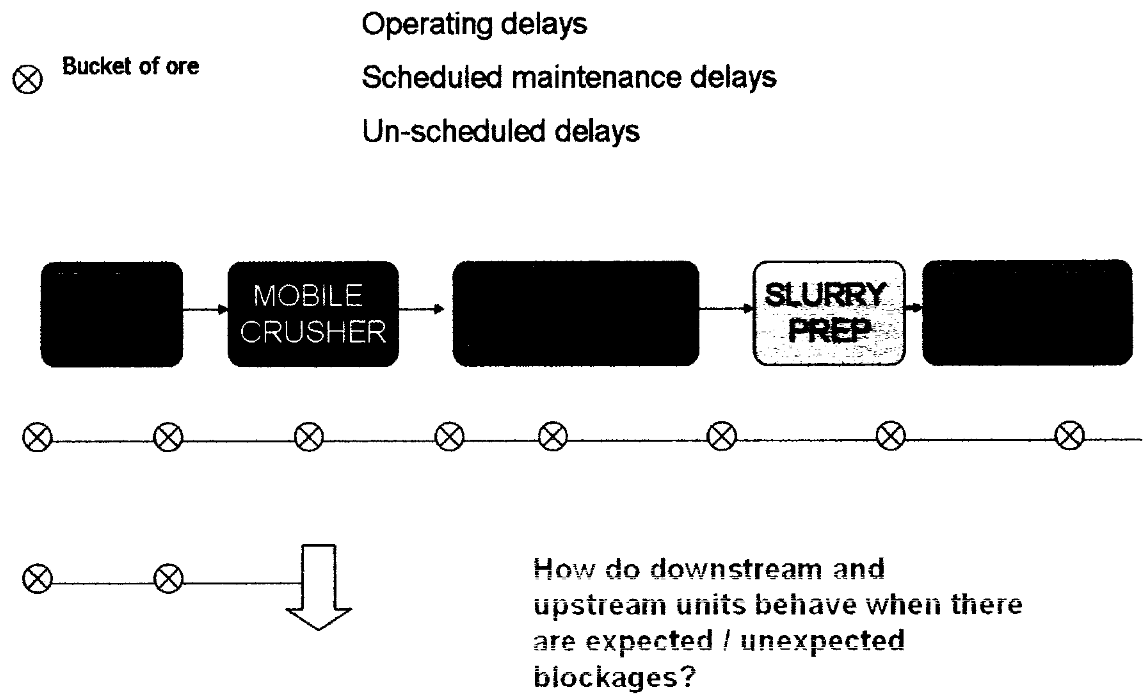


Figure 18 - System delays

The first module corresponds to a discrete system, and is given by the actions performed by the shovel while loading the mobile crusher. Figure 19 shows a schematic of the actions performed by the loading shovel, which is the only discrete, event driven module.

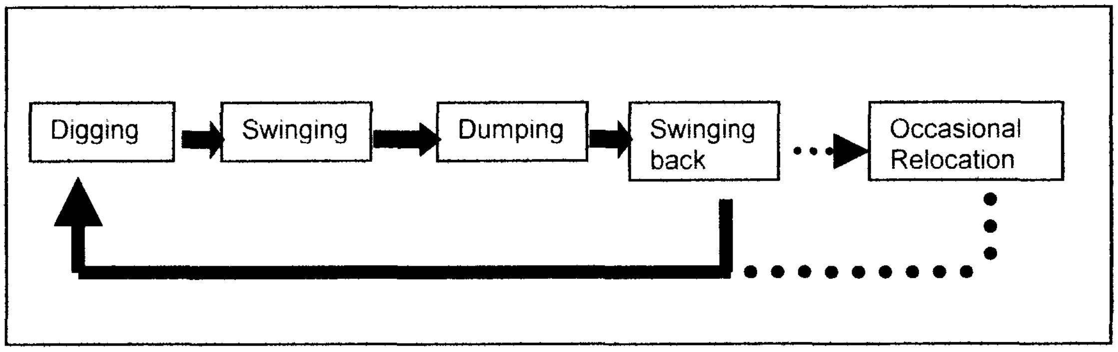


Figure 19 - Actions performed by loading shovel

The continuous modules will be represented in different states as shown in the schematic below (Figure 20). When the system is in steady state, the module's intake and discharge are both on, and the system is working between the allowable minimum and maximum volumes.

However, when a delay presents itself, two situations can occur; either both intake and discharge are off, or at least one of them is off or unavailable.

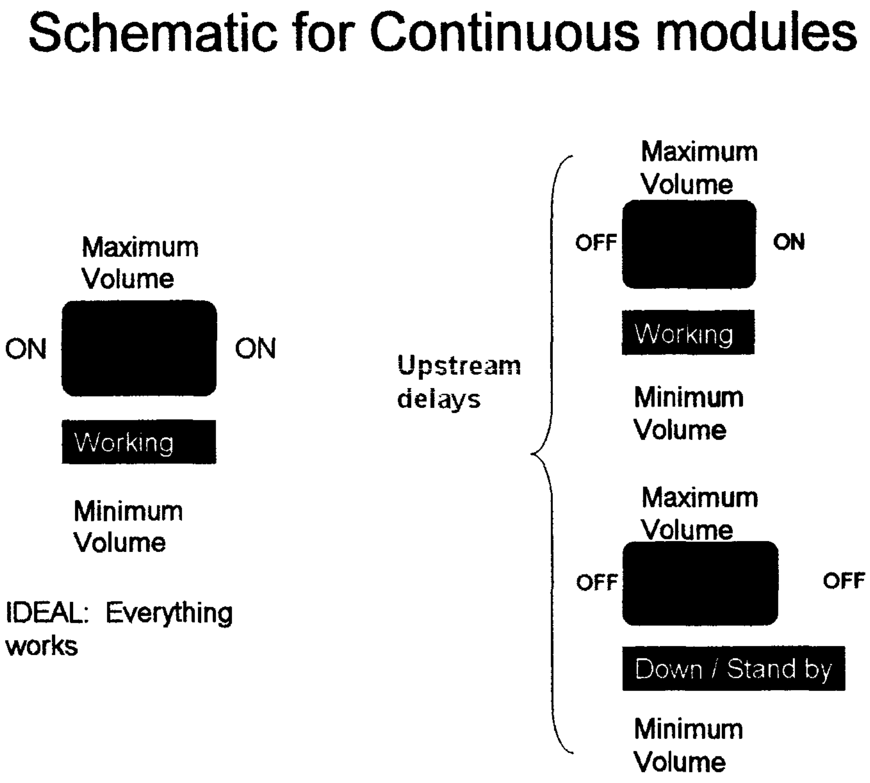


Figure 20 - Implementation of Continuous modules

The more detail described in the system, the more complex it becomes. However, this complexity allows for the identification of the weakest links in the whole system. Figure 21 shows an example of a very detailed model. This level of detail was hard to achieve because of the complexity. The biggest challenge in modeling any system is knowing what level of detail is appropriate [Simulation Modeling and Analysis].

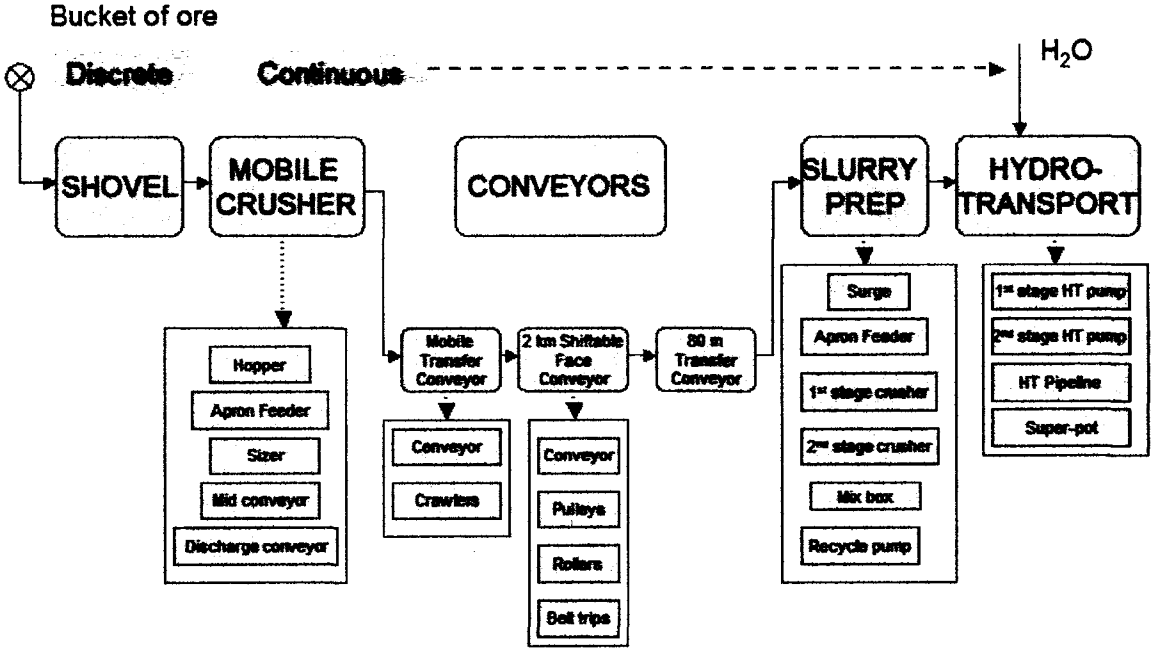


Figure 21 - Detailed AFS

Entities and resources are used in the model in order to simulate the At-Face Slurry flow of events and material. When a piece of equipment is working, for example the shovel, it is assumed that both the resource and the entity are a unit or a batch. As soon as the resource finishes moving a specific entity, the resource and the entity are disassociated. The entity keeps flowing in the system while the resource becomes available for the following entity. It is assumed that the equipment never breaks down during the activity. Figure 22 shows a schematic of how entities and resources are utilized in the modules.

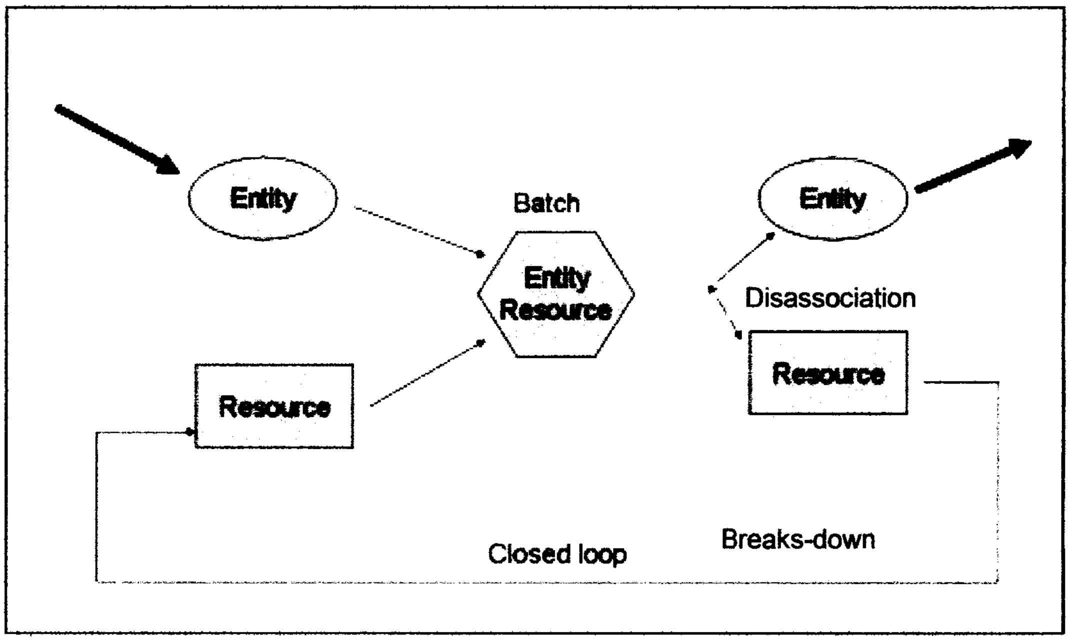


Figure 22 - Schematic of entities and resources as used in the model

4 MODEL WITH EXTEND

The model developed with Extend OR follows the same description as the one shown in Figure 16 by taking advantage of its hierarchical power. Figure 23 describes the higher level of the AFS model, as defined in Extend.

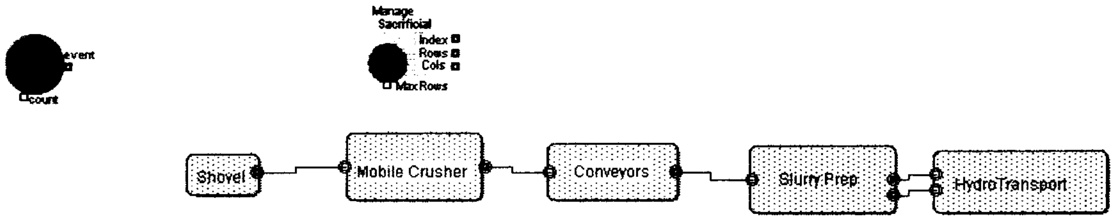


Figure 23 - First level of AFS model with Extend OR

As the hierarchy keeps building, sub-modules are created accordingly at different levels. The complete model configuration is included in the Appendix. Figure 24 shows a schematic of the whole system as defined in the AFS model.

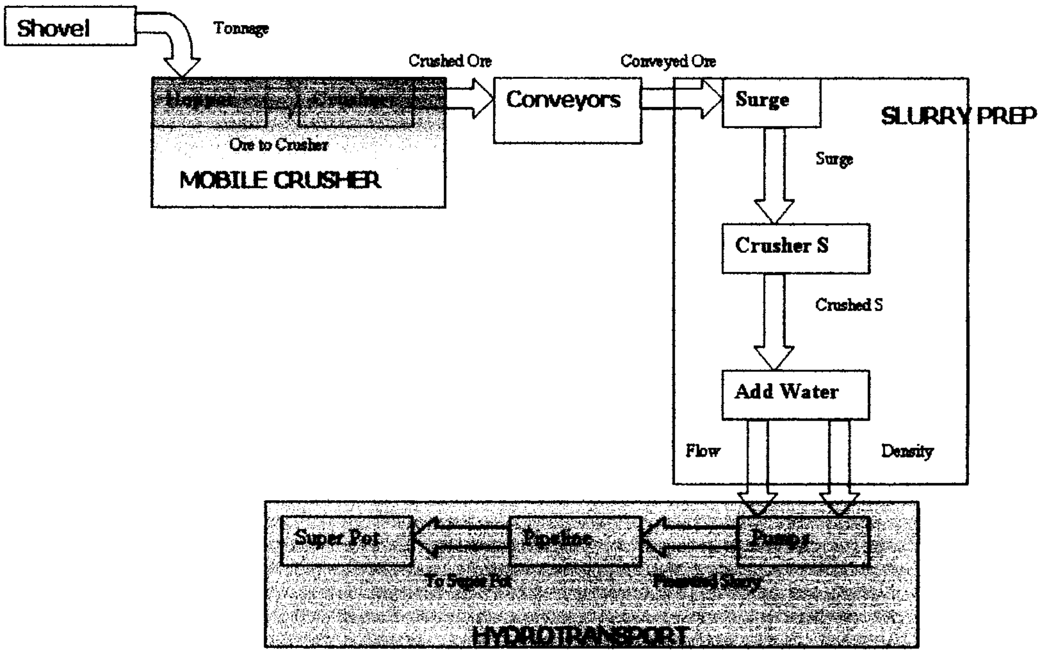


Figure 24 – AFS model

The above schematic also depicts the flow of entities among modules, which are used as needed to summarize global values, for example, the total tonnage of ore moved by the shovel. These values help in understanding the model when interpreting simulation results.

A description of each module as defined in this model follows next. Assumptions and decision variables for each module are listed. A decision variable is a variable or a resource that is defined in the model, over which the modeler has control. They can be modified for different runs. Some decision variables are assigned based on a stochastic distribution while others are given by a constant value. For the optimization case (to be displayed later), some decision variables are fixed while others are being optimized.

The decision variables selected for the AFS model allow the simulation of a more simplistic model, controlling its level of complexity. The proposed model includes enough variables to generate the three types of delays described earlier and they account for classic production issues as well as reliability concerns. For example, the calculation of real-time wear rate to account for scheduled downtime delays in the hydrotransport line. The effects of reliability on the system's production as well as the direct impact of production on system's reliability are both manipulated by means of decision variables. The frequent cause-effect relationships provide the foundation for mimicking the AFS system and understanding its operability and maintainability.

4.1 Production and Reliability

High-capacity systems demand increased reliability of operation in order to accomplish planned production in more and more complex operating conditions. The actual operational time (T_r) of a system as compared with the planned operational time (T) can be represented by the expression $T_r = T\ P_0(t)$, where $P_0(t)$ is the availability of the system. The capacity of the system is defined in Equation 3:

$$Q = Q_{teh}^{\min} T P_0(t) = Q_{teh}^{\min} T(1 - \sum_{i=1}^{m} P_i(t)),$$ **[Equation 3]**

where $Q_{teh}^{\min}$ is the technical capacity of the system (theoretical capacity in real operating conditions), which is determined by the elements having the lowest capacity, m is the number of elements within the system, $P_i(t)$ is the probability that the ith element of the system will need repair. For a coordinated mining system (without bottlenecks), the capacity is determined on the basis of the excavator's theoretical capacity, which is a function of its physical design and operating kinematics when working in real operating conditions [Continuous Mining Reliability].

Statistical research has shown that the occurrence of failures is a regular phenomenon. The curve of failure occurrence shows relatively high values during the initial operation – the 'running in' of the system or its elements. There is a gradual decline to an almost constant level of failure in the second phase, when the system operates normally. The third phase, the ageing of the system, is marked by a gradual increase in the failure rate [Continuous Mining Reliability]. The model proposed for the AFS is assumed to be in the second phase described above.

Each one of the modules described below includes a description of its expected behavior as well as considerations and assumptions made on the model to account for production and reliability issues.

4.2 Shovel module

The flowing entity through the module is the bucket of ore that the shovel loads at the mining face and dumps at the hopper of the mobile crusher unit. While the shovel is actually loading the ore, the entity (ore) and the resource (shovel) are combined and working as a unit. As soon as the ore is dumped into the hopper, the ore keeps flowing through the system and the shovel is freed up to continue moving on its cycle. Repositioning along the ore face (when required) is included in the returning time and it is included the shovel's cycle time. Running hours are accumulated accordingly, since each action takes a specific completion time. After a pre-determined number of run hours, the shovel goes down for scheduled maintenance, which makes it unavailable for any other action. At the end of the maintenance delay, the shovel becomes available and ready to work again. Only operating hours drive the shovel reliability, this assumption was chosen in order to simplify the overall model.

The amount of ore accumulated by the shovel is summed up in order to be able to estimate when the shovel needs to move along an ore block in order to keep production flowing. When a block of ore gets depleted, the shovel needs to move to the next available block. Moving along the ore block is considered to be a short move and it occurs more often than a long move, which occurs when the shovel needs to move to a different ore block. Each move has a different duration based on a statistical distribution, and they account as operating delays. Other types of operating delays exist but are not included in this model, as specified in the assumptions listed below. The working time of the shovel is given by that time during which the shovel is dumping into the hopper.

Ore characteristics are pre-defined in this module. Therefore, particle size distribution, grade and fines are defined and passed over other levels of the model to be used when necessary.

Shovel production as tonnage of ore moved is also accumulated at this level. The use of global arrays makes possible the flow of information between hierarchy levels. For example, shovel production is passed over to the hopper in order to account for its increments in time.

The following assumptions were made for the shovel module:

- Only one shovel is used for the model
- No shifts or breaks are included
- No ore blending is included

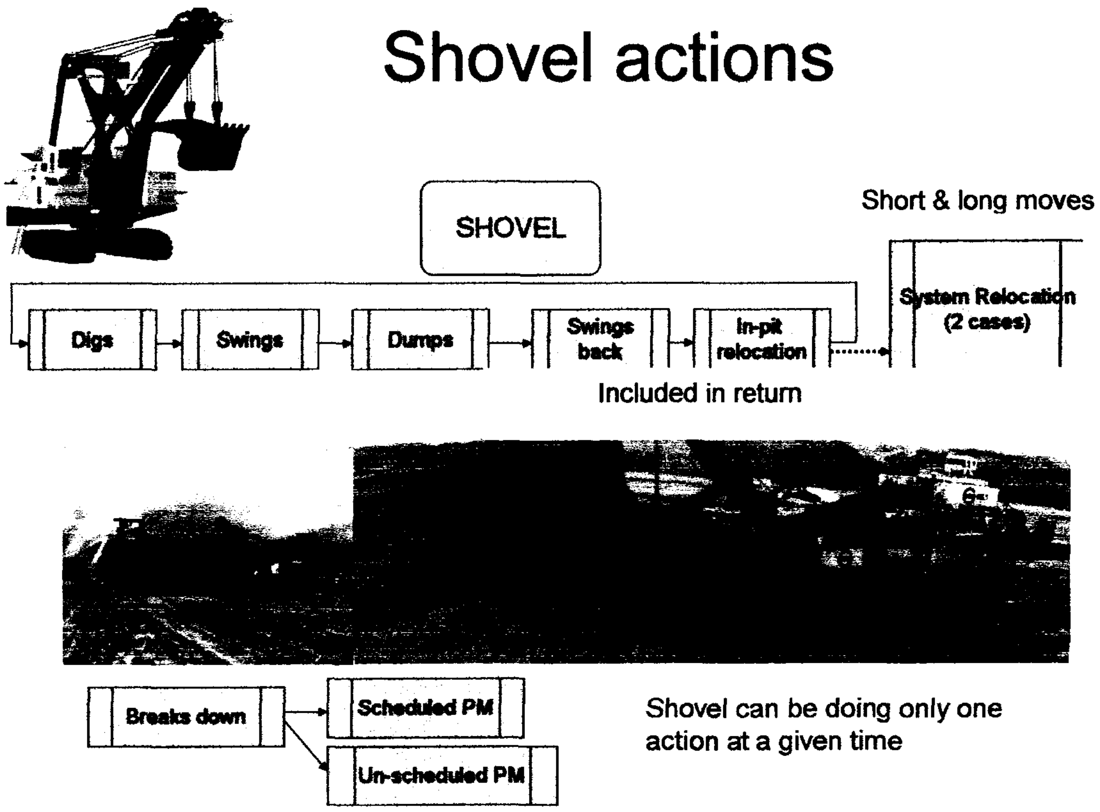
- Ore is assumed to have unlimited availability
- No weather restrictions are accounted for
- No differences are made for winter / summer ore characteristics
- No unscheduled downtime is considered
- Shovel cycle time includes: digging, swinging, dumping and returning to the face (only working time)
- Face repositioning is included in the return
- No idle time is considered
- No delays due to shift changes are included
- Ore carried back in the shovel's bucket is disregarded
- Long and short moves are considered to be down time (operating delays)

The decision variables for the shovel module are the following:

- Bucket size: cubic meters of ore loaded through each shovel dump, it is then converted into tonnage
- Duration of each shovel activity: loading, swinging, dumping and returning to the face
- Shovel cycle time: sum of the time the shovel spent loading, swinging, dumping and returning in each cycle
- Ore characteristics: psd (particle size distribution), grade and fines
- Shovel maintenance duration: time it takes to repair the shovel

- Moved tonnage: used to generate short or long moves along the ore block or to another ore block, moves are generated after the shovel moved a specific amount of ore
- Duration of each move (short or long): time it takes the shovel to move because of a long or a short move

Figure 25 shows a more detailed schematic of the actions implemented in the shovel module.



Shovel actions

SHOVEL

Short & long moves

Digs

Swings

Dumps

Swings back

In-pit relocation

System Relocation (2 cases)

Included in return

Breaks down

Scheduled PM

Un-scheduled PM

Shovel can be doing only one action at a given time

Figure 25 - Detailed schematic of actions performed by the shovel

4.3 Mobile crusher

The mobile crusher as a unit is composed of sub-units or modules: hopper and crusher. Apron feeder and transport crawlers are left outside the proposed model. The function of this module is the following: ore arrives into the hopper and gets crushed. As stated before, a more detailed model allows for a deeper understanding of the bottlenecks of each unit. Figure 26 displays the configuration of the mobile crusher.

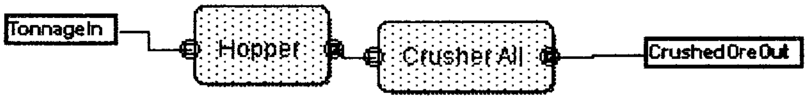


Figure 26 - Mobile crusher module configuration

4.3.1 Hopper

The hopper works as a reservoir of ore, which goes up as soon as ore gets dumped by the shovel and down when ore flows towards the crusher. The hopper is simulated as a continuous flow of ore. No mixing of ore is implemented in the model. In order to prevent overflow of ore or lack of ore for the crusher, a valve in on/off position is set up at each side of the hopper. Therefore, when the hopper is full, the input valve closes ensuring the shovel stops working if necessary. On the other side, if the storage is getting to its minimum capacity, the output valve is closed in order to stop the flow of ore into the AFS system.

Extend provides blocks for continuous modeling that use a finite number of equal steps to mimic time increments. When discrete events – like the shovel loading the hopper - feed a continuous block, as for example, a holding tank, the continuous block withdraws flow as soon as flow enters the tank and not at any other time. This condition will actually affect the continuous flow of dry feed from the hopper because it will be done only at discrete events. The AFS model was optimized by introducing a dummy input at a constant interval with zero actual feed which produces a withdrawal from the holding tank. In summary, the holding tank behaves more like a reservoir. See the Appendix for details on the hopper block.

4.3.2 Crusher

The crusher is modeled as a continuous flow with two distinct sub-levels: apron feeder and the actual crusher. The apron feeder is modeled as a conveyor and the crusher is modeled as a machine block.

The following assumptions apply for the mobile crusher module:

- Crusher goes down due to unscheduled downtime
- Crusher does not include planned maintenance
- The apron feeder is modeled as a conveyor block
- No shutdowns are included for the hopper

The decision variables defined for this module are the following:

- Hopper output to the crusher: provides an output profile that changes over time
- Apron feeder delay at the crusher: time it takes for the ore to move through the apron feeder
- Crusher time between failures and time to repair: time between failures and time to repair at the crusher, given by assumed distributions
- Duration of the crusher activity: actual time it takes to crush the ore
- Output of crushed ore: tonnage of ore crushed that is going to be included in the slurry

No failure modes are included at either the hopper or the crusher; therefore, no delays driven by reliability are included in this module. This decision was made to keep the model as simple as possible. Some of the failure modes that can be included were described in Chapter 2.

4.4 Conveyors

The configuration of this module is shown in Figure 27. Three different conveyors are included in this level: mobile transfer, shiftable face and transfer conveyors, as stated in the detailed AFS model. The main differences between them are given by their length and speed.

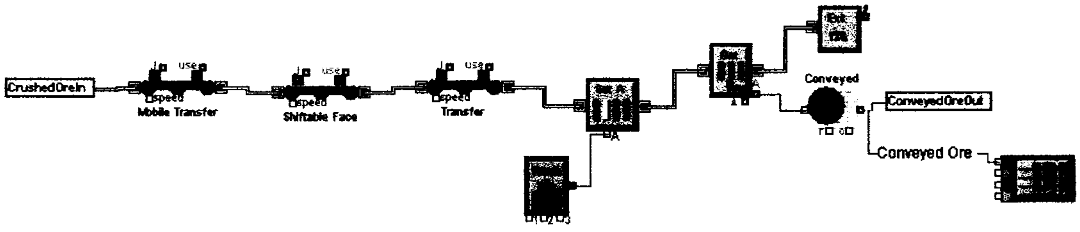


Figure 27 - Conveyors module

The following assumptions were made for the conveyors module:

- If any of the three conveyors overflows the system will stop

- The delay of the conveyor belt block is dependent on the length, speed and capacity

The following decision variables were defined in the conveyors module:

- Delay at each conveyor: time it takes for the ore to run through each conveyor
- Output capacity of the conveyors: tonnage of ore moved through each conveyor

No failure modes are included at either type of conveyor; therefore, no delays driven by reliability are included in this module. This decision was made to keep the model as simple as possible. Some of the failure modes that can be included were described in Chapter 2.

4.5 Slurry preparation

The slurry preparation module consists of 3 sub-modules: the surge, the slurry crusher, and the water addition station, as shown in Figure 28.

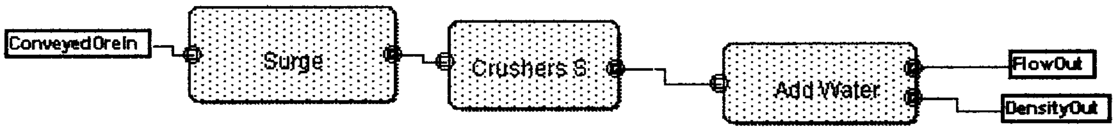


Figure 28 - Slurry preparation module

4.5.1 Surge

The surge is modeled in the same way as the hopper described earlier, with differences in storage capacity, input flow and output flow.

4.5.2 Crusher

The crusher at the slurry preparation module is modeled in a similar fashion as the crusher in the mobile crusher module described earlier. The output flow in this case is the crushed dry flow.

4.5.3 Water Addition

This is a detailed sub-module that involves the water addition to the dry flow in order to initiate the hydrotransport process (see Appendix).

The assumptions made for the slurry preparation module are the following:

- Variable flow of water is included into the slurry
- The loss of water supply is included in the model
- Density of the slurry is calculated based on the input of dry flow and water flow, no air fraction is accounted for
- The mixer is defined as a machine block
- Caustic is added to the slurry
- When the water pump is down for maintenance, the dry flow stops until the system is repaired. The blocking of the dry flow behaves as a valve (on/off position) which closes for the next entity of dry flow
- No rejects are produced from this process
- No other additives other than caustic or water are included in the model

The decision variables for the slurry preparation module are detailed below.

- Surge output to slurry crusher: provides an output profile that changes over time
- Apron feeder delay at the slurry crusher: time delay produced at the apron feeder of the crusher in the slurry preparation tower
- Duration of crusher activity: time it takes to crush the ore
- Output of crushed ore: tonnage of ore crushed at the crusher

- Amount of water pumped into the mix: cubic meters of water pumped into the slurry
- Water pump time between failures and time to repair: time between water pump failures and time it takes to repair it.
- Duration of mixer activity: time it takes for the mixing of ore and water to create the slurry
- Slurry flow output: cubic meters of slurry produced to be moved through the pipeline
- Caustic input into the mix: amount of caustic introduced into the mix
- Water temperature of the slurry: temperature of the slurry after the addition of hot water

The AFS model has the ability to control water pH by changing the caustic dosage, which eventually changes the water chemistry of the slurry mix.

The failure modes included in this module are for example, the shutdown of the water pump, which affects water availability for the slurry; also, the crusher accounts for unscheduled downtime, which eventually drives the whole system reliability. Other failure modes and related maintenance actions that can be modeled are mentioned in Chapter 2.

4.6 Hydrotransport

The oil sand from the mine operation is mixed with hot water and caustic, and this oil sand slurry is then transported by pipeline to the extraction plant where it feeds directly into the primary separation vessel [Pure Energy 2].

The success of the first large-scale pilot test of oil sand hydrotransport, the Syncrude EAPS (Extraction Auxiliary Production System) had a profound effect upon subsequent extraction plant design and operation.

The oil sands slurry is a three-phase medium composed mostly of water, sand (including clays and fines) and bitumen. Air is also part of the mix, which in this model is disregarded. The oil sands conditioning process in the AFS system is a critical link in the production / economic chain.

The properties of the slurry and the conditions of the flow determine slurry flow phenomena. Slurry properties depend upon characteristics of the involved particles such as size, size distribution, shape and density as well as properties of the fluid-particle interface determined by the compositions of the carrier fluid and solids. Flow conditions depend upon geometry of the pipe/conduits, type of flow (steady or transient) and system variables such as velocity, characteristic dimension and temperature. The oil sands slurry presents a multi-phase problem in which water, sand, bitumen and air phases co-exist with their superimposed behaviors affecting the entire system rheology [AFS Technology].

Slurry is a mixture of a given liquid and solid particles that has many of the properties of liquids. The density, as well as the viscosity of the slurry is affected by the presence of solid particles. Both weight fractions and volume fractions are generally used for describing slurry compositions.

If C_w is the mass fraction or weight fraction of the solids in a two-phase mixture containing fluid of density ρ_f and solids of density ρ_s, the mixture density ρ_m is calculated by Equation 4 [Pipeline Hydrotransport]:

$$\frac{1}{\rho_m} = \frac{C_w}{\rho_s} + \frac{1 - C_w}{\rho_f}$$

[Equation 4]

The above equation is used to calculate the density of the slurry when water is added.

The hydrotransport module as defined in the model is shown in Figure 29.

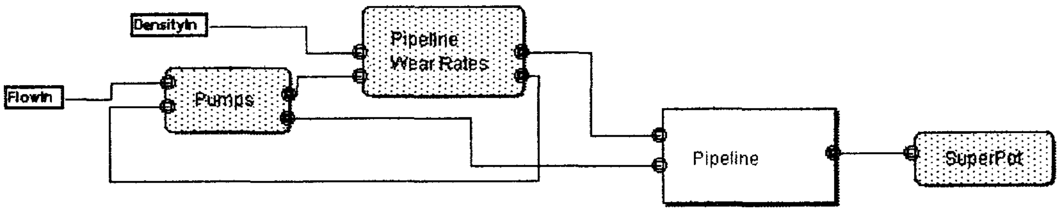


Figure 29 - Hydrotransport module detail

4.6.1 Wear rates in pipe

Wear rates are calculated as a function of particle size distribution (psd), density and slurry velocity; and are expressed as per 1000 running hours to make it more intuitive. The allowable loss in material thickness due to wear determines the useful life of the pump or pipe, after which the equipment will be in need of replacement or repair. Pump or Pipe life is calculated by means of Equation 5, where *ECAllow* stands for Erosion Corrosion allowance. Pipe life is theoretically defined from installation until replacement.

$$Pipe\_life = \frac{ECAllow}{Wear\_rate/1000}$$

[Equation 5]

The main characteristic of the pipe life calculation is given by the assumption that the same wear rate occurs at every section of the equipment during its life. For example, differences in wear rates at the bottom and at the top of a piece of pipe are counter-balanced with this assumption. The flow pattern inside the pipe is driven by gravity, keeping the heavier particles at the bottom of the pipe. From slurry pipe data collected in Syncrude, the most wear in pipes occurs at the bottom of the pipe (6 o'clock position), however, wear occurs all around the circumference of the exposed internal pipe wall. The main purpose of rotating the pipe periodically is to account for this predominant wear pattern and to increase pipe life.

The Erosion Corrosion allowance term (*ECAllow*) is defined as the available material to wear out, as shown in Equation 6.

$$ECAllow = Initial\_thickness - Disposable\_thickness \qquad \textbf{[Equation 6]}$$

where *Initial_thickness* is measured at installation, and *Disposable_thickness* is an experimental value that incorporates a safety factor value into the *Minimum_thickness* value. The latter corresponds to the minimum thickness that will hold the design pressure inside the pipe. Equation 7 shows the relation between *Disposable_thickness* and *Minimum_thickness*.

$$Disposable\_thickness = Safety\_factor * Minimum\_thickness \qquad \textbf{[Equation 7]}$$

Following industry standards, a safety factor between 2 and 3 is acceptable.

The minimum thickness in a pipe is that minimum wall thickness that will accommodate the largest stress in the pipe.

Consider a straight section of pipe filled with a pressurized liquid or slurry. The internal pressure generates three principal stresses in the pipe wall, as illustrated in Figure 30: a hoop stress σ_h (also referred to as circumferential or tangential stress), a longitudinal stress σ_l (also referred to as axial stress), and a radial stress σ_r. When the ratio of the pipe diameter to its wall thickness (24 inch diameter – d - with respect to ½ inch wall thickness – t - in this model) d/t is greater than 20, the pipe may be considered to be thin wall. In this case, the hoop stress is nearly constant through the wall thickness. The longitudinal stress is also constant through the wall and equal to half the hoop stress. The radial stress varies through the wall, from P (internal design pressure) at the inner surface of the pipe to zero at the outer surface.

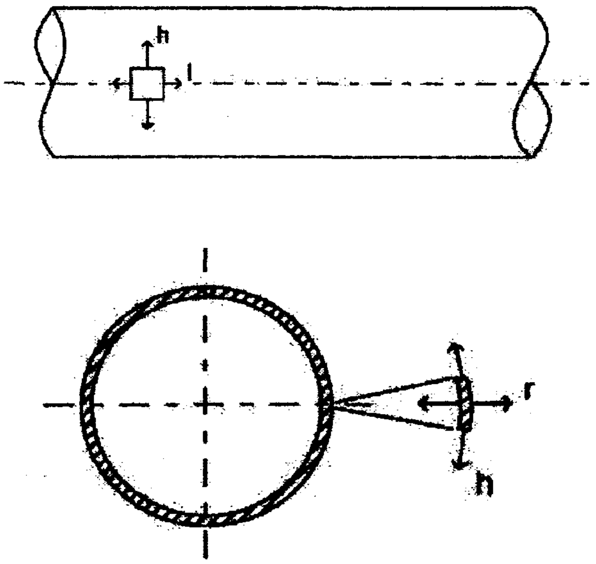


Figure 30 - Hoop (h), Longitudinal (l) and Radial (r) Stress directions [Piping Engineering]

For oil and gas pipelines, the minimum thickness of the pipe wall is obtained by assuming that the hoop stress, which is the largest stress in the pipe, must be limited to a certain allowable stress. Using the thin wall approximation and solving for thickness, the minimum thickness is calculated by means of Equation 8.

$$Minimum\_thickness = \frac{P*d}{2*\sigma_{allowable}}, \qquad \textbf{[Equation 8]}$$

where the variables are defined as follows:

P = Internal design pressure, psi

d = pipe outer diameter, in

$\sigma_{allowable}$ = allowable stress, psi

The design pressure is the pressure that, taken with the concurrent temperature, results in the thickest pipe wall. It is the highest pressure at which the piping system should operate. In practice, it is the system's pressure relief valve set pressure or rupture disc burst pressure [Piping Engineering].

For hazardous liquid pipelines (hydrocarbon, carbon dioxide, etc.), the allowable stress ($\sigma_{allowable}$) is shown in Equation 9 where E is the longitudinal weld joint factor, and S_Y is the specified lower yield stress.

$$\sigma_{allowable} = 0.72 * S_Y * E \qquad \text{[Equation 9]}$$

There are two plausible versions of the origin of 0.72 S_Y, one of which goes back to the early days of fabrication of steel line pipe and the other one is related to the fabrication tolerance and overpressure transient allowance [Piping Engineering].

The weld quality or joint efficiency factor E is a factor introduced to account for the quality of the longitudinal or spiral seam in a pipe. It is a function of the reliability and quality of fabrication and the extent of inspections performed in the pipe mill [Piping Engineering].

The calculation of wear rate identifies pipe life. It is assumed that straight spools follow a three 90° clockwise rotation strategy, which implies four intermediate lives. The mean time between rotations (MTBRot) is calculated as shown in Equation 10:

$$MTBRot = \frac{Pipe\_life}{N+1}, \qquad \textbf{[Equation 10]}$$

where N is the number of intermediate pipe rotations

The MTBRot is the run hours between rotations, each of which accounts for a planned maintenance event.

4.6.2 Wear rate in pumps

Centrifugal pumps are by far the most commonly used pump types, because of their design simplicity, high efficiency, wide range of capacity, head, smooth flow rate, as well as ease of operation and maintenance. The centrifugal pump has a simple construction, essentially comprising a volute (1) and an impeller (2) (see Figure 31). The impeller is mounted on a shaft (5), which is supported by bearings (7) assembled in a bearing housing (6). A drive coupling is mounted on the free end of the shaft. The prime mover, which is usually an electric motor, steam turbine, or an internal combustion engine, transmits the torque through the coupling. As the impeller rotates, accelerates, and displaces the fluid within itself, more fluid is drawn into the impeller to take its place (if the pump is properly primed). The impeller thus impacts kinetic energy to the fluid through mechanical action. This kinetic energy is then converted to pressure energy by the volute. The pressure of the fluid formed in the casing has to be contained and this is achieved by an appropriate sealing arrangement (4). The seals are installed in the seal housing (3).

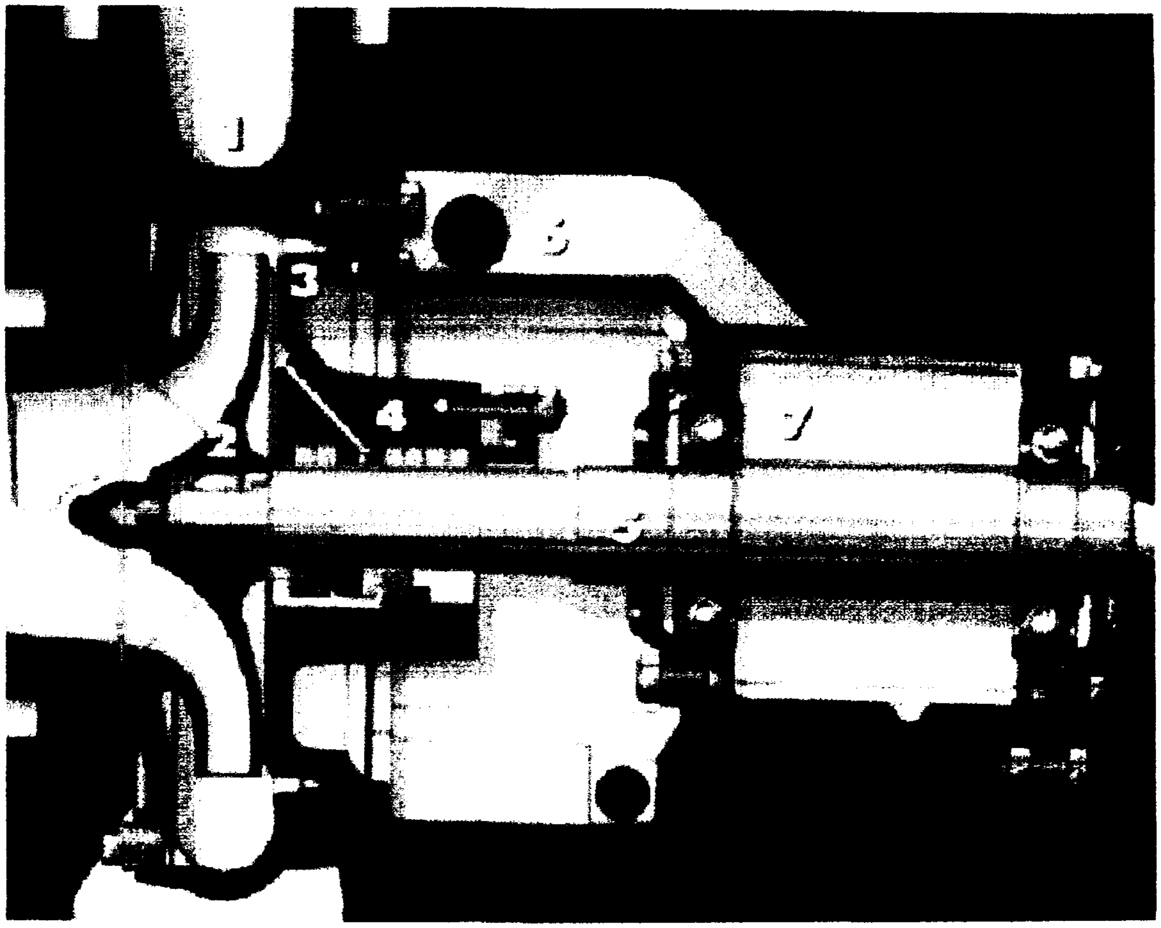


Figure 31 - Basic configuration of a centrifugal pump [Practical Centrifugal Pumps]

Pumps must be selected by matching their head discharge performance to the requirements of the piping system. Considerations of wear and ease of maintenance usually dictate that a centrifugal pump must be a single-stage machine. The number of stages refers to the number of sets of impellers and diffusers in a pump. A set forms a stage and it is usually single, dual, or multiple [Practical Centrifugal Pumps].

A single centrifugal pump cannot be used to transport slurry over a distance of more than a kilometer or so. Several pumps in series may therefore be needed for a medium length pipeline. For this configuration, the total head generated by the pumps in series is simply the sum of the heads developed by each pump at the common flow rate. To limit the pressure each pump must withstand, it is desirable to space the pumps at roughly equal distances along the pipeline [Slurry Transport].

There is also a minimum suction head constraint. This is important for pump box level control. Head loss also depends on slurry density, and deposition velocity depends on slurry particle size.

There are four techniques that should be incorporated in a PPM (Predictive and Preventive Maintenance) program. Individually, each one will provide information that gives an indication of the condition of the pump; collectively, they will provide a complete picture as to the actual condition of the pump. These include: performance monitoring, vibration monitoring, and oil and particle analysis. Over a period of time, the performance of the pumps deteriorates and it is always a debate whether to live with the problem or take the pump for an overhaul. In the first case, there is a continuous loss of revenue due to inefficient operation; for the latter, one has to incur the maintenance cost as well as opportunity cost of lost production. The basic assumption to determine the optimum time to remove a pump for an overhaul is made whether the deterioration is constant over a period of time or whether the deterioration rate increases with time. In the first case, a cash flow analysis can be done to ensure that the overhaul investment will give the required rate of return. When the deterioration rate increases with time, then the optimum time for overhaul will be when the accumulated cost of the increased power consumption equals the cost of the overhaul [Practical Centrifugal Pumps].

Wear rate in pumps is calculated exactly the same way as for pipe, with the main difference being the *ECAllow* term. For economic reasons, the material allowed to wear out is less in a pump impeller. It is much more costly to replace a pump than to replace a piece of pipe; therefore, there is no need to use up the whole impeller. Instead, the impeller can be replaced without causing any additional damage to the pump. From experience at Syncrude, impeller materials often have more wear-resistant material, but damage tends to be very local rather than general loss of material.

In real applications, breakdown of pumps is a common event. The typical failure causes are: mechanical seal failure, excessive vibrations, pump rubbing or seizure, inadequate performance (flow rate, head developed, power consumption), or leaking casing or seals. Pump maintenance is an activity to prolong the efficient run-times of the equipment and to improve its overall effectiveness. The pump is installed to perform a function under specified conditions. If a pump is observed to be in distress, it should be out of service for corrective actions immediately since to prolong maintenance can lead from primary failures to secondary failures and this consequential damage increases the downtime and maintenance costs [Practical Centrifugal pumps]. In this model, pump breakdowns are classified as unplanned or planned. The unplanned categories include all the above-mentioned typical failure causes while the planned breakdown is driven by wear rates, which are more predictable.

4.6.3 Pipeline

Continuous flow, as in the hydrotransport train in the AFS system, is modeled using discrete-event logic by converting the slurry into discrete units of measure or aggregates, such as cubic meters. An item (slurry moving through a pipe) moves from one residence to another (activities), and therefore cannot exist at two residences at once. However, when the slurry flows through the pipe, the "slurry" has residence in both resources, the previous pipe and the next pipe. One could determine points in time when each pipe was ¼ full or ½ empty, for example. One way of accounting for this is by using "aggregation" technique. These models may produce inaccurate results due to the selection of an incorrect aggregate size.

To represent the pipeline that will carry the slurry to the hydrotransport train, three main shapes are considered. A straight pipe is the basic shape. The wear rate of the other two shapes, namely elbow and sacrificial spool, is calculated in relation to the basic straight pipe. For example: an elbow wears out 2.5 faster than the straight, and the sacrificial or drop-out spool after elbows wears out 5 times faster than the straight. This section explains the mechanisms that produce these different wear rates.

The schematic of the layout used for the pipeline is displayed in Figure 32. It shows a straight pipe followed by an elbow and a drop-out spool. The pipeline is composed of numerous components that follow this lay-out. Many straight pipe components can exist before the basic unit of straight – elbow – sacrificial .

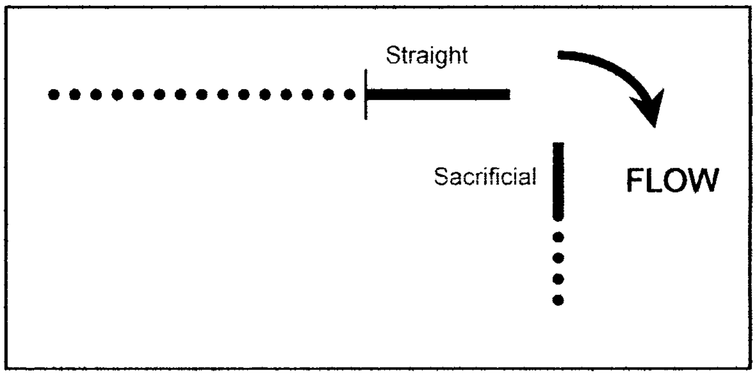


Figure 32 - Schematic of pipeline configuration

If an elbow or bend is pressurized, the hoop stress varies around the circumference. Interestingly, the largest hoop stress occurs at the *intrados* of the bend (the inner radius of the bend, 6 o'clock in Figure 33), which is also where the bending process naturally results in the thickest wall. Conversely, the smallest hoop stress occurs at the *extrados* (external radius of the bend, 12 o'clock in Figure 33), which is where the bending process naturally results in the thinnest wall. On the sides of the elbow or bend (θ = 0 or π, 3 and 9 o'clock in Figure 33) the hoop stress is the same as in a straight pipe [Piping Engineering]. Experience at Syncrude confirms the above statement, elbows wear the most at the extrados and this is the reason why a higher wear rate is assumed for elbows. In practice, elbows can be thicker or made of different material that will provide more wear resistance.

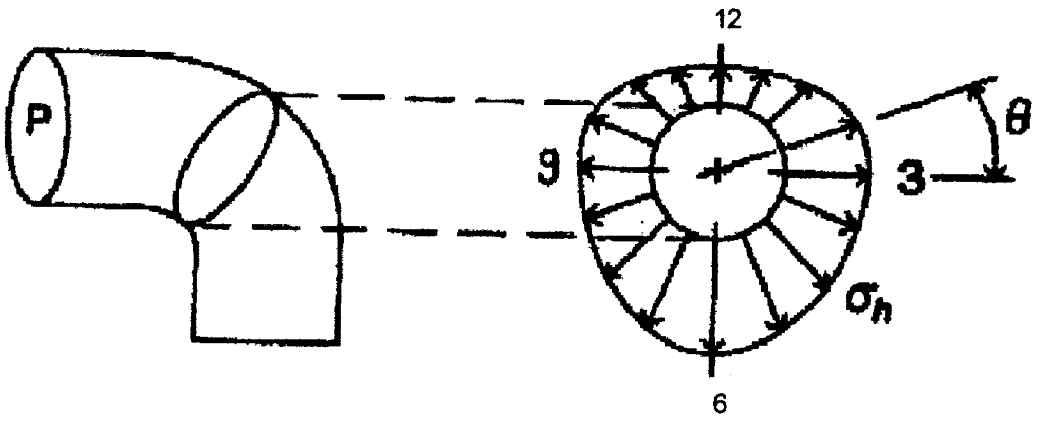


Figure 33 – Distribution of hoop stress in a pressurized elbow [Piping Engineering]

Operating experience in tailings at Syncrude has shown that approximately 40 ft of a spool after an elbow has a predominant high wear pattern all around its circumference, explaining why the relation between sacrificial spools and straight pipes is assumed to be five times.

The pipeline modeled in the AFS system is assumed to have one straight section, one elbow and one drop-out spool after the elbow.

From an asset management point of view, each pipeline component would be represented in a model of an actual AFS system. Tracking individual components can make the model extremely detailed. As an initial approximation, these three basic shapes represent all the straight spools on the line, all the elbows and all sacrificial spools. An efficient method of description is by defining each shape as a class, and assigning different attribute values to each instance.

As described earlier by means of aggregation, slurry flow and the pipe itself work as a unit as long as the slurry is flowing through the pipe, as being one whole entity. When the slurry reaches the end of the spool, both the slurry entity and pipe entity go on separate paths in the Extend model. The slurry entity keeps flowing in the system and the pipe entity accumulates run hours until the MTBRot, time at which it goes down for maintenance (refer to Figure 22). In the Extend model during pipe maintenance, the entity pipe-flow cannot exist as such, which means that the line is down.

The following assumptions were made in the hydrotransport module:

- Pipe is made of carbon steel
- 24" pipeline diameter, ½" wall = 12.7 mm
- 3 rotations of 90 degrees in straight pipes (4 lives)
- An elbow can be flipped, which means a 180CW rotation and end to end rotation (2 lives)
- Include 3 standard shapes: straight, elbow, sacrificial spool (high wear spool after elbows)
- Pumps are shut down according to running driven by wear rate
- Pump impeller is the weakest link for wear rate and it is repaired or replaced during planned maintenance
- The weakest link other than pump impeller defines unplanned maintenance on pumps. It is assumed that the impeller is not repaired during unplanned maintenance
- Each pump has similar operating performance

The decision variables for the hydrotransport module are detailed below:

- Duration of pump activity: time it takes the slurry to run through the pump
- Pump 2 time between failures and time to repair: unscheduled downtime
- Maintenance duration for each pump: time it takes to repair each pump

- Time delay for each pipeline component: time it takes the slurry to run through the pipeline component
- Duration of maintenance interventions for each pipeline component: scheduled downtime duration for each component

The reliability of the whole system is affected by the reliability of its components, as it was stated in the literature review chapter. The hydrotransport module affects the reliability of the whole system due to the detailed reliability considerations that were described at each pump as well as at the pipeline level.

4.7 Optimization with Extend

Extend's user interface simplifies setting up an optimization procedure, making it easy to add optimization to any model without using any other applications. Extend facilitates this by making the optimization algorithm available within a block that is simply added to the model. This optimizer block controls all aspects of the optimization run for the user. Extend optimization model is not limited to linear objective functions and/or constraints. The optimizer supplied with Extend uses an evolutionary algorithm to reduce the number of times it has to run the model before a solution is found. The downside to optimization is that the model will be run many times and this can take a long time with large models [Extend v6].

5 SIMULATION RESULTS AND INTERPRETATION

The unit of time chosen for the AFS model is minutes because it captures most of the delays of the system. With this level of detail, the model was able to run for one whole model month (30 days of 24 hour production) in about 6 hours on an AMD Turion 64 Mobile at 1.8 GHz and 900MB of RAM.

The main goal of this work is to develop a model that incorporates operation and reliability restrictions into an operational AFS model. The success of the model depends on how well the interaction between the modules is defined. The main focus is to create a simple and yet versatile and robust tool that accounts for these interactions. This chapter provides an understanding on how those interactions have been accounted for in the model.

A more rigorous and formal way of understanding the dynamics of the system, such a causal loop diagrams (CLD), will certainly improve the model. However, this is outside the scope of this first model.

In the case studies that follow, design parameters have been contrived for illustrative purposes in order to illustrate an integrated system behavior.

5.1 Production

To start understanding the model, consider the initial stage of the process being modeled. The shovel has three well-defined states: working, down, and stand-by. The shovel is working when it is actually loading, moving back and forth from the mining face, and dumping ore from the face into the hopper. These actions accumulate run hours and tonnage moved. These two production parameters affect the system directly, because when they reach a specific value the shovel goes down for maintenance (in the case of run hours) or the shovel is required to move (in the case of tonnage moved, once the shovel mines out an area). The stand-by activities are defined by default in the model, when the shovel is "waiting" for shovel moves, for example. Some other activities are not in the scope of this model as specified in the assumptions made for the shovel module.

The two cases mentioned above are traditional examples of how productivity affects the different delays of the system. Figure 34 displays graphical results from running the model.

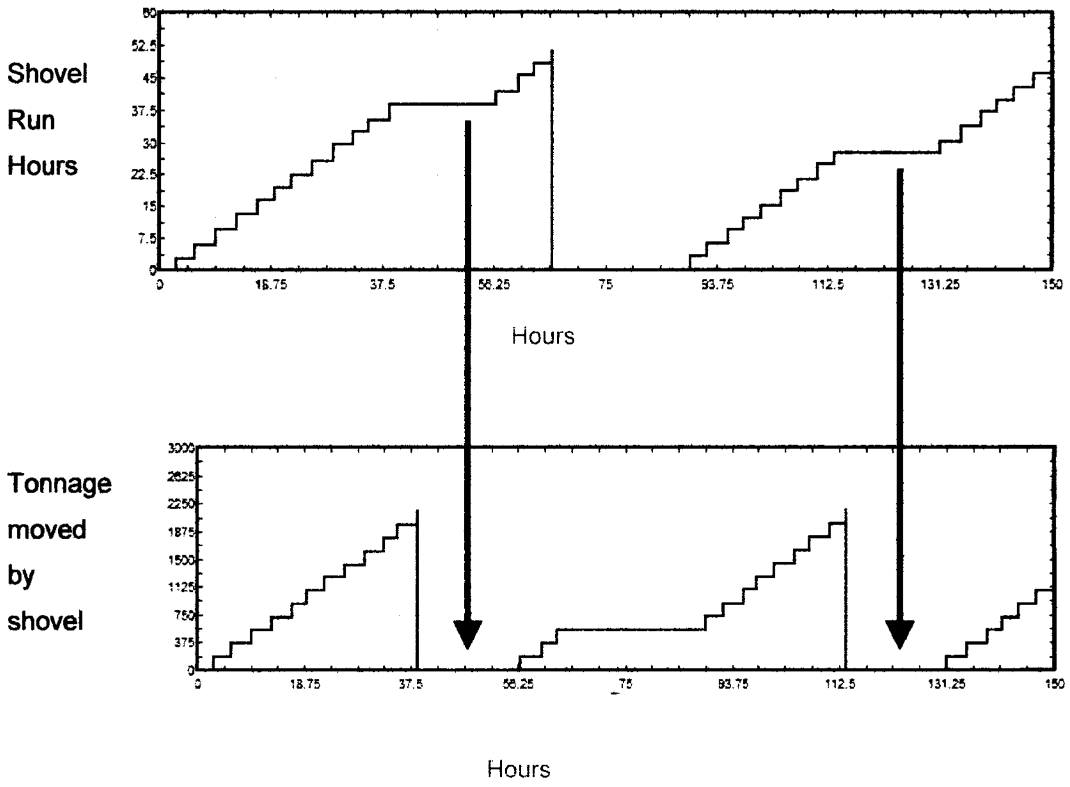


Figure 34 - Run Hours from shovel

At time 39 hours while the shovel is down for maintenance, the accumulated tonnage is on stand-by.

At 113 hours, the running hours for the shovel are not accumulated or reset because at that specific point in time the shovel was moving after reaching the required tonnage to do so. At that point in time the tonnage is reset while the run hours are constant, which implies that the shovel is on stand-by.

When the shovel is not working because it is moving or actually down, the contents of the hopper go down as expected, as shown in Figure 35 inside the circle. At this point in time the shovel is actually down for maintenance. Inside the square, the shovel is actually relocating and therefore not producing.

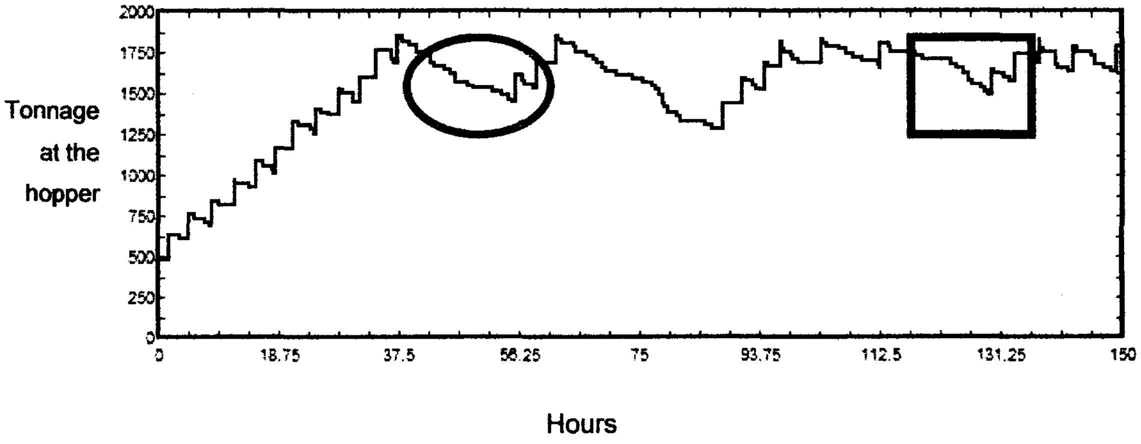


Figure 35 - Hopper contents over time

Both the hopper and surge reservoirs create production constraints in the system given by their physical limitations. This model can be a good tool to define and optimize the capacity of each reservoir given all the other delays in the system.

This is classic behavior of production restrictions in a dynamic system and it shows how the system is affected by production constraints. As such, this example indicates that the model is simulating the system behavior correctly.

From the hopper onwards, the production profile changes mostly because it becomes continuous. Therefore, any delays on the shovel do not affect this downstream process significantly in the model.

The arrangement of the three conveyors from the face actually delays production. Figure 36 displays data that establishes the number of entities that went through each conveyor, which implies that each entity was delayed by a specific amount of time. The conveyor that delays the most entities is the mobile transfer conveyor, which in the run shown below was used 74% of the simulated run time.

Row	Activity	# of Arrivals	# of Departures	Utilization (%)
7	Mobile Transfer	3388	3386	73.9
8	Shiftable Face	3386	3384	62.7
9	Transfer	3384	3383	28.2

Figure 36 - Data validating the use and delay of each conveyor

Also, the mobile crusher coming down for maintenance affects production. Figure 37 shows the plot for unscheduled downtime for the mobile crusher. In the plot, a value of one means that the crusher is down, a value of zero means it is working.

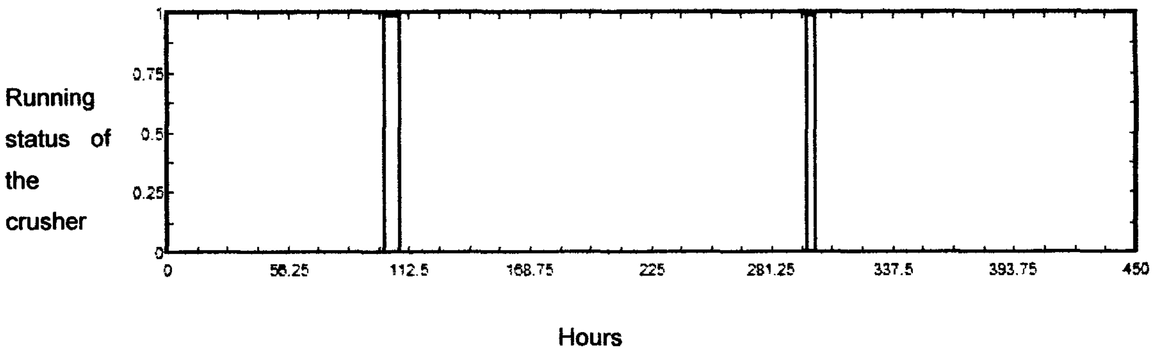


Figure 37 - Crusher unscheduled downtime

Moving into the surge, the production pattern changes once again to become continuous following a new interval. This new time frame is given by the combination of the flow coming from the conveyors and another dummy variable created for the purpose of moving the dry flow through the surge on a continuous fashion. This implies that from the surge onwards, flow is moving on shorter intervals of time, each of which produces a new event into the system. Figure 38 shows the behavior of the surge, which is almost independent of the actions performed by the shovel. The material at the surge accumulates until there is enough room on the storage to fluctuate within the system. In this model, there are no real bottlenecks from the surge perspective.

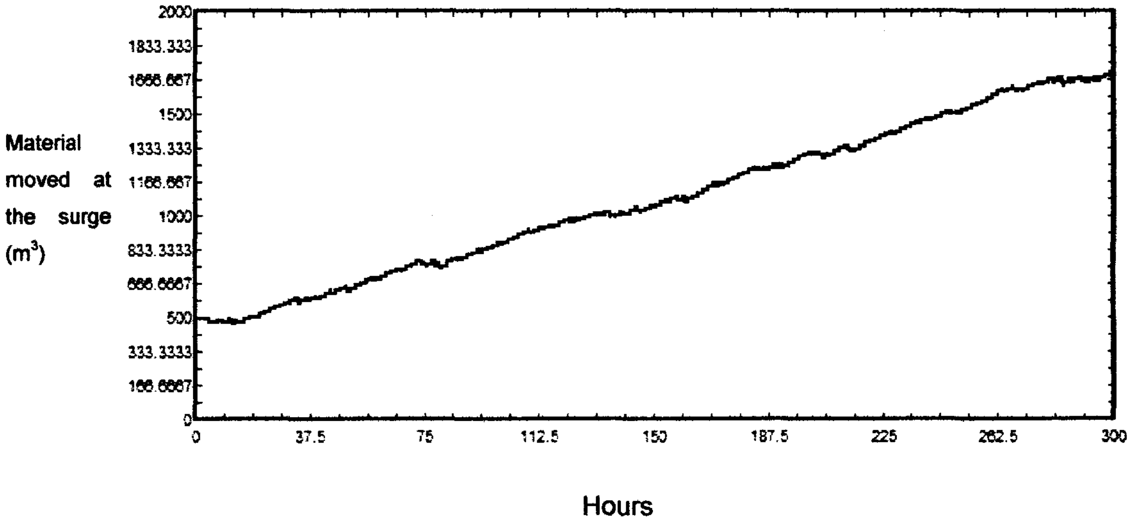


Figure 38 - Surge contents over time

At the Add Water block, the number of events increases again, because water is coming from two different sources and the final slurry gets developed by adding each event arrival. Also, when the water pump is down, the dry flow stops accordingly until the pump is ready to work again.

Slurry flow through the hydrotransport pipeline has the physical constraints of pipe size and pump design pressure, which add to the expected production restrictions.

A continuous product flow, such as the hydrotransport line, may be represented in network form by considering the continuous flow as made up of blocks or batches that sequentially flow through the pipeline in plug flow (no axial mixing).

In this formulation using Extend OR, pipeline flow is analogous to conveyor transport; however, there is an important characteristic of pipeline flow that distinguishes it from conveyor flow. When input to a conveyor ceases, the output plugflow continues until the conveyor is empty. Furthermore, input to a conveyor does not cause an immediate output from it. Thus, output from a conveyor can be obtained with or without input even if the conveyor is half full. With pipeline flow, however, not only must the pipeline be full, but there must also be an input to the pipeline before output is obtained. Units of material entering a pipeline push units ahead of them, and output is realized only when the pipeline is full. Once input ceases, no output flows when both water and oil sands inputs stop.

Finally, all slurry lines ready to be processed converge at the super-pot, which is a reservoir. Fines and grade of the ore define the slurry quality for its process. From hydrotransport experience at Syncrude, there is a list of parameters that affect oil recovery from the oil sands: (1) dilution in the ore quality; (2) the nature of the bitumen due to alterations of the chemistry in the lithofacies of the deposit; (3) the nature and distribution of the fines (< 44 microns) which modifies the surface area potentially available to attract the air for the separation of the oil; and (4) surface activity of those fines with more or less affinity to hydrocarbons. Therefore, the description of the ore block by means of grade and percent fines is not the whole story. However, in this initial model, the recovery function is simplified to account for grade and percent fines only. Also, pH from the added caustic to the slurry and temperature of the slurry define how well the ore can be extracted. These last two conditions of the slurry help to classify the processability of the ore. The super-pot block provides statistics of ore quality based on ore conditions and slurry conditioning.

5.1.1 Reliability in the AFS model

Unscheduled downtime is a reality in any operation; therefore, it was included in the AFS model to simulate realistic scenarios. Figure 39 shows the unscheduled downtime for Pump 2 in the hydrotransport module. This figure shows the overlap of unscheduled downtime and run hours in Pump 2. When the pump goes down for unexpected maintenance the run hours flatten up. Run hours are accumulated to account for when the pump needs to go down due to impeller reasons.

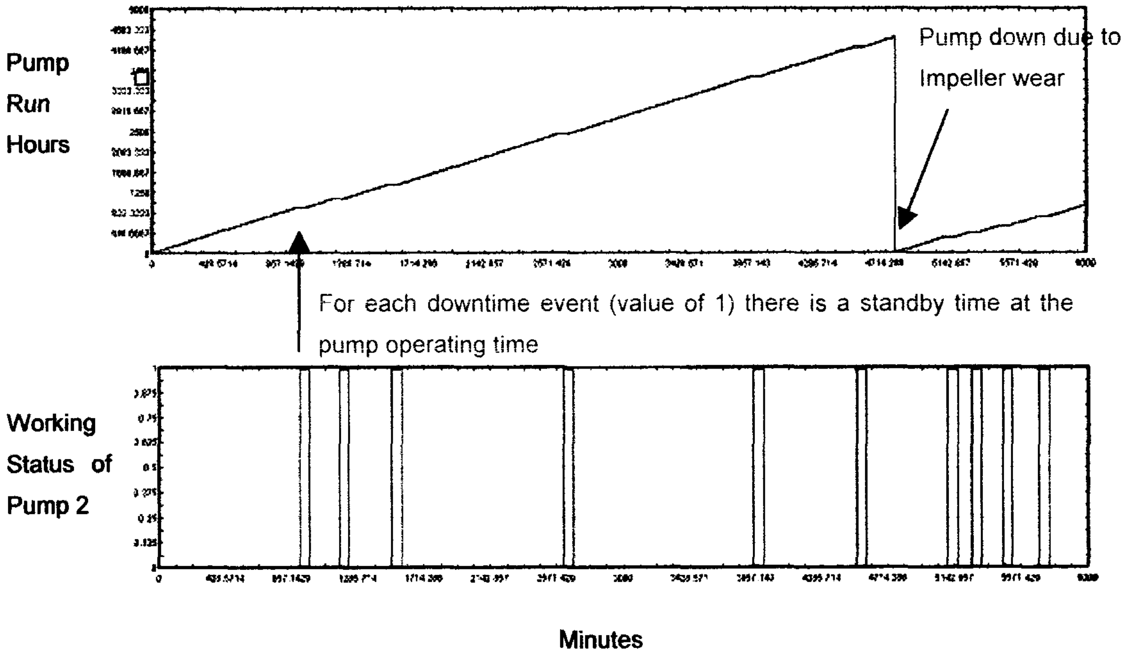


Figure 39 – Pump 2 unscheduled downtime

In this model, 2 pumps are used in series; therefore, unscheduled downtime in only one of the pumps needs to be coordinated with the run hours of the other pump. This means that those unscheduled outages must be accounted for in both pieces of equipment. Both pumps are considered identical with the exception of unscheduled shutdowns; pump 1 has no unscheduled shutdowns while pump 2 has randomly distributed unscheduled downtime. This decision was made in order to simplify the model. When pump 2 is down for unscheduled repairs, pump 1 is neither working nor being repaired. The only repairs for pump 1 are triggered by impeller wear and they follow a specific schedule.

Since both pumps are working in series, both of them should go down when one of them is not working. Figure 40 shows the overlap of both pumps working and both pumps being down.

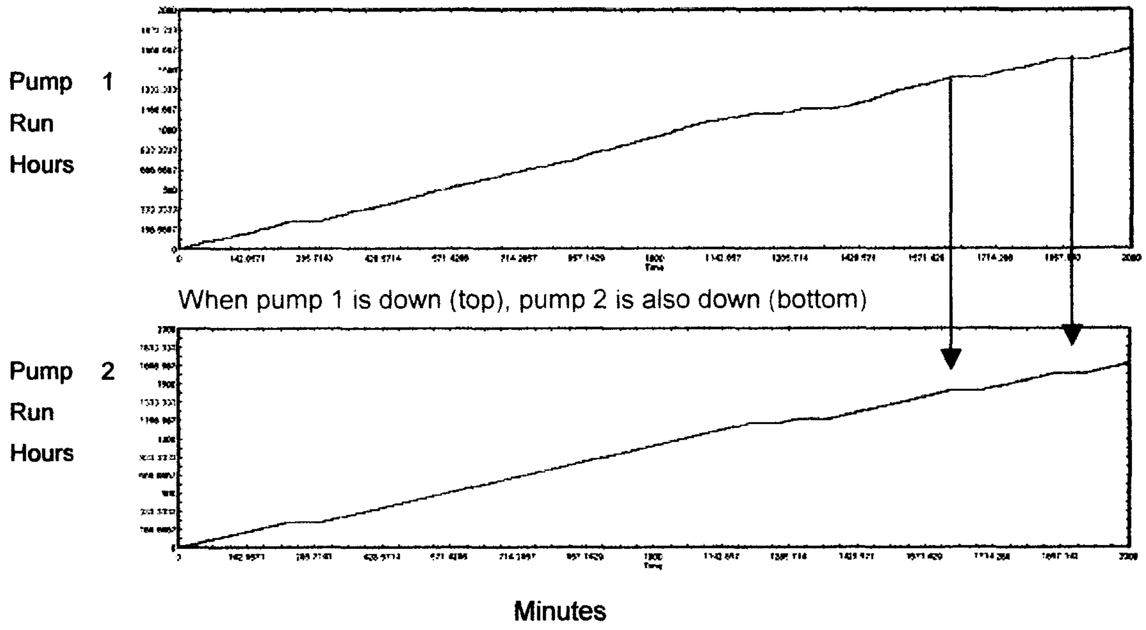
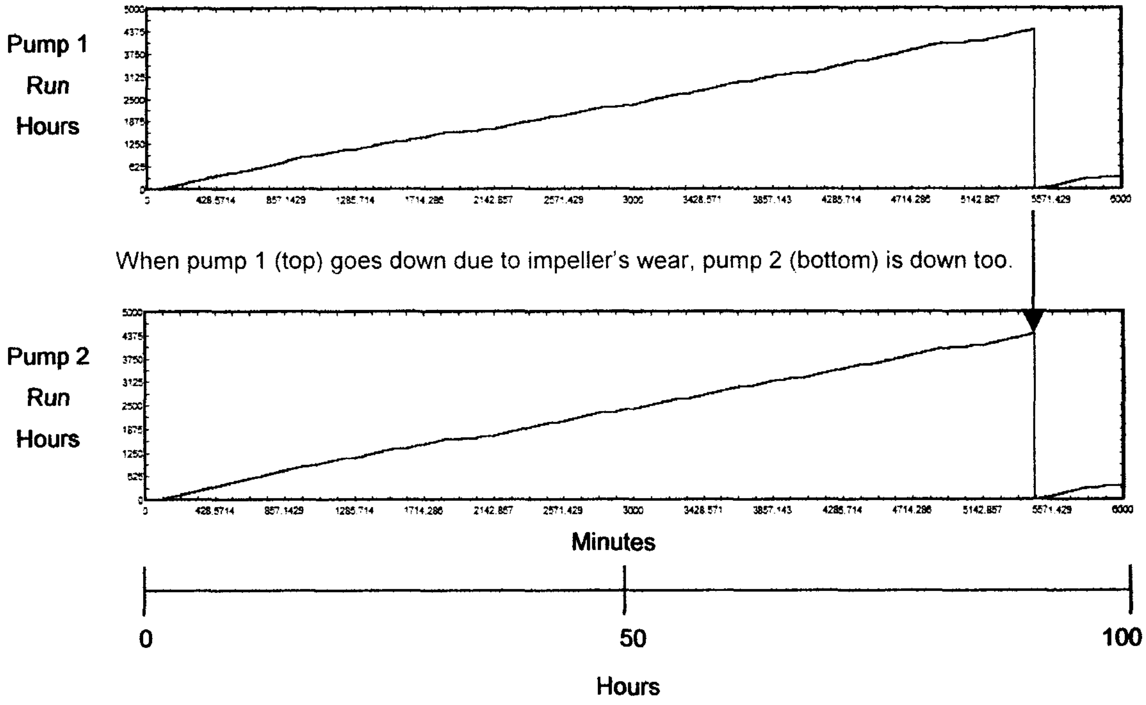


Figure 40 – Maintenance time due to pump impeller

According to the assumptions made, pumps do go down due to wear in the impeller and this is determined by pump life by means of working or run hours. Pump life is calculated every time a load of dry oil sands gets mixed into the slurry. As soon as the cumulative run hours for the pumps surpass the calculated pump life, the pumps go down for service and this downtime is considered to be scheduled downtime. The above-described behavior reflects the fact that stable flow quality and flow conditions will produce a more evenly distributed schedule of downtime. Figure 41 shows downtime for each pump due to impeller wear.



When pump 1 (top) goes down due to impeller's wear, pump 2 (bottom) is down too.

Figure 41 - Scheduled downtime for both pumps

Considering that no impeller is repaired during unscheduled shutdown and that both pumps have the same calculated life, they will go down at the same time.

The reliability of the pipe components affects the system as well. Figure 42 shows those times the system is down due to maintenance interventions on pipe components. As a simplification on the model proposed, pipe components do not experience unscheduled shutdowns.

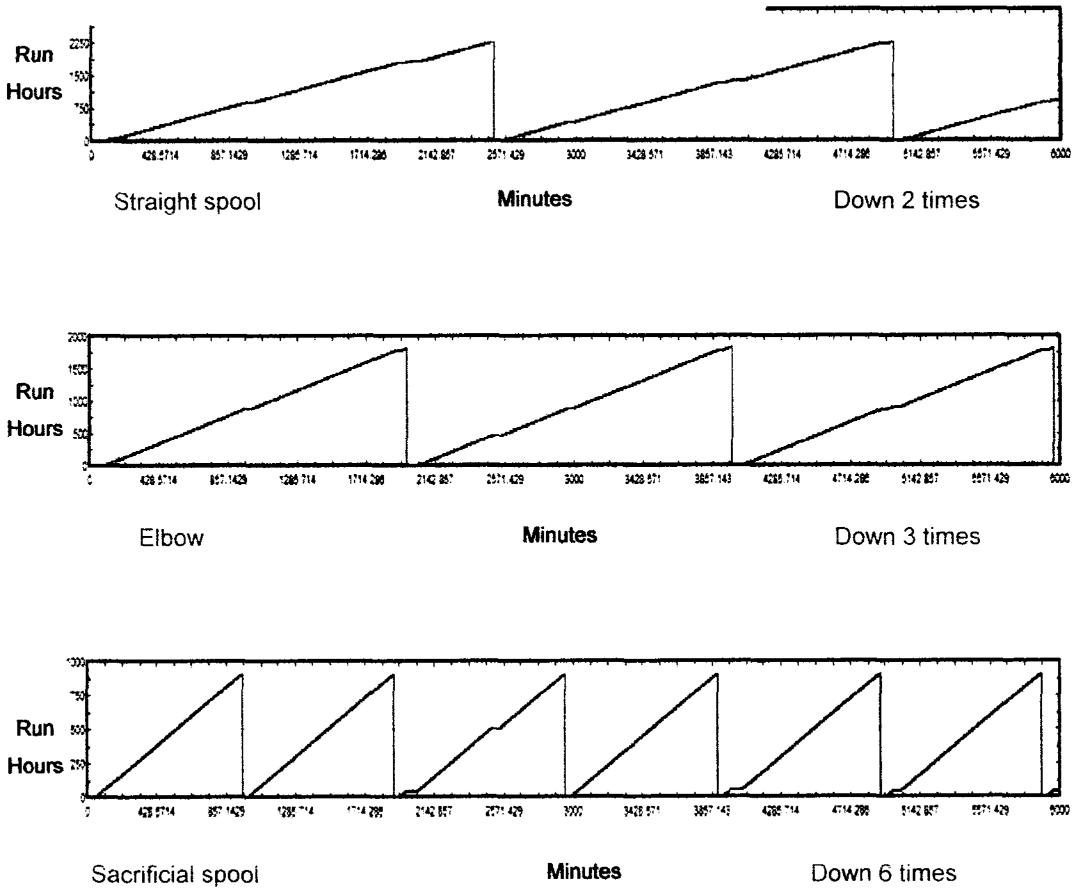


Figure 42 - Scheduled maintenance interventions in pipe components

The straight pipe, due to pipe wear, needs to go down two times, each of which corresponds to a pipe rotation. The elbow goes down three times which means that one new elbow is installed. In the case of the sacrificial spool, the system goes down six times. Since a 3-rotation strategy is also applied to this component, in that time frame, only one new spool is installed.

A closer look at the maintenance interventions shows that when any spool is down for service the entire line is not operating. Figure 43 displays this fact very clearly. When the line goes down for a sacrificial spool rotation, the run hours for the elbow and for the straight spool do not get accumulated.

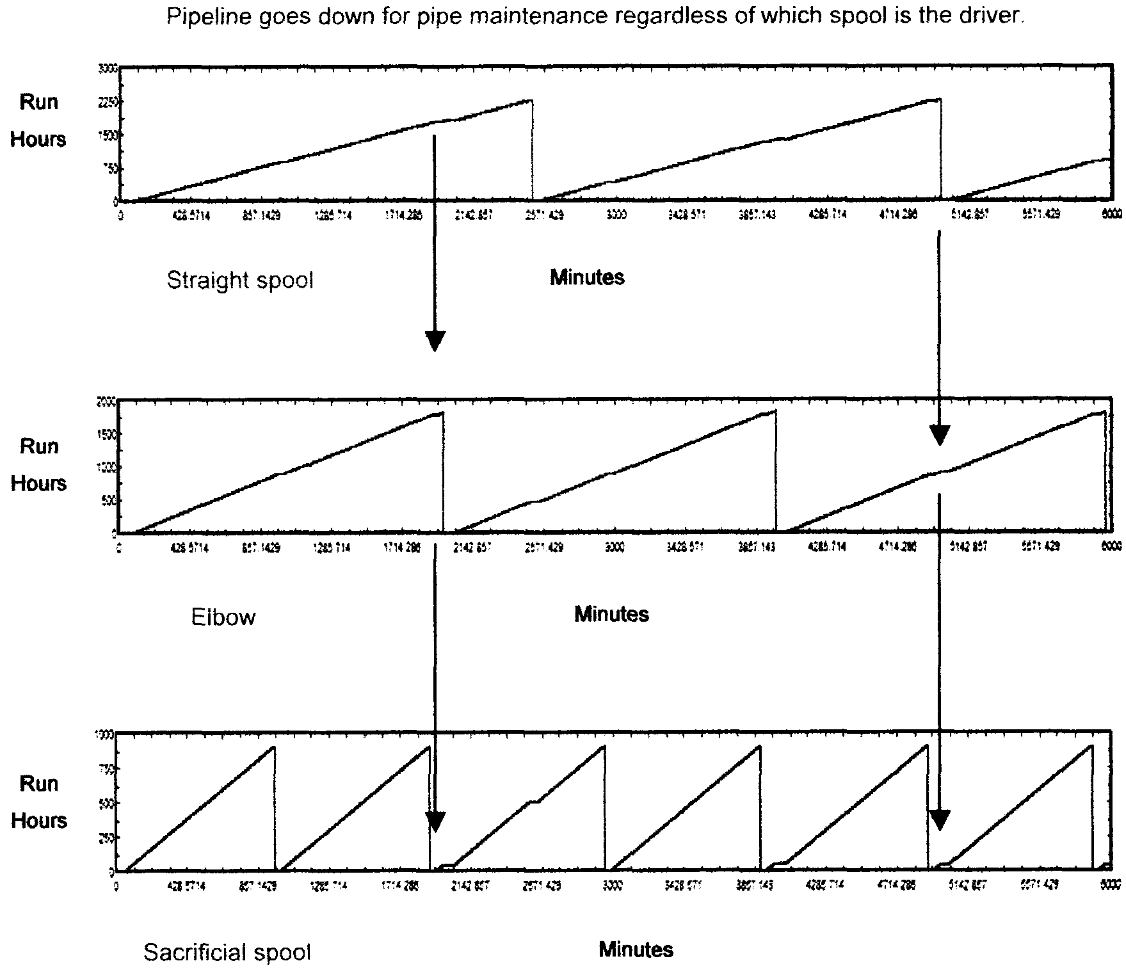


Figure 43 - Line down due to maintenance interventions

The pipeline and the pumps work in unison: if any pump is down, the pipeline stops and vice versa. Figure 44 displays examples of downtime for pumps and pipeline on their own in a given run. The column named duration displays the simulated time at which downtimes started and ended. Figure 45 shows the behavior of pump / pipeline coordination reflected in the Run Hours of pump 1. As an observation, this run does not capture Pump 1 or 2 going down due to impeller wear since the planned maintenance will occur outside of the run time of 2,500 hours.

Element down	Duration (hours)	Order
Pump2 down	632 - 690	1
	1346 - 1403	3
	1833 - 1892	5
	2124 - 2181	7
	2358 - 2413	8
Straight	2364 - 2415	9
Elbow	1815 - 1886	4
Sacrif	896 - 931	2
	1888 - 1922	6

Figure 44 - Pumps and pipeline downtime (both scheduled and unscheduled)

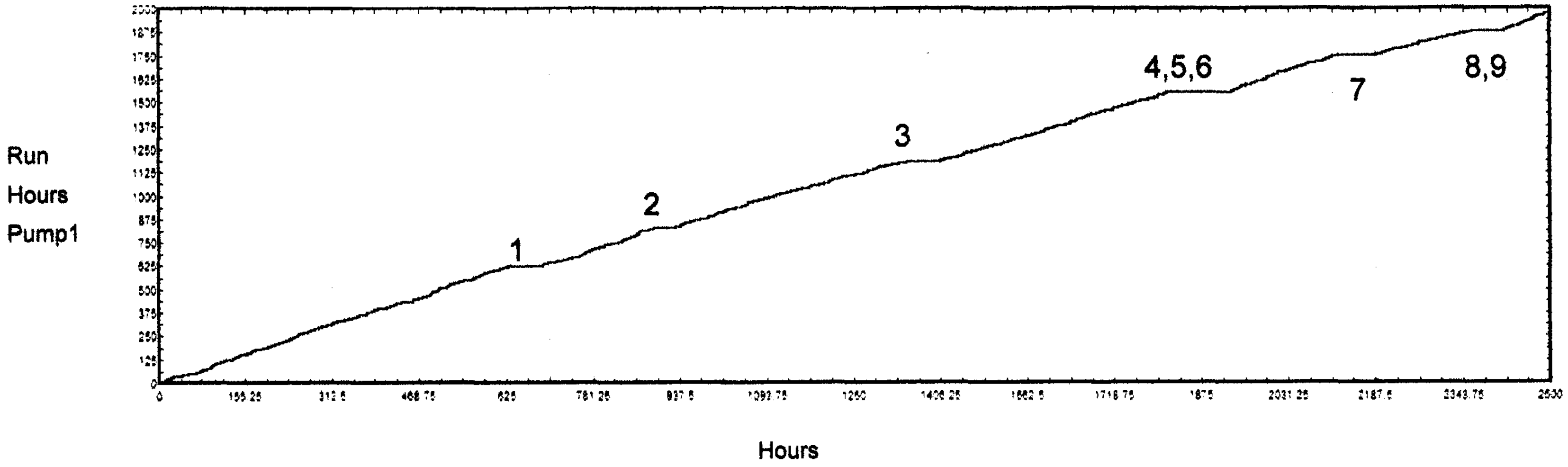


Figure 45 - Run Hours for Pump 1 including all downtime

In order to put the pump/pipeline behavior in perspective, Figure 46 shows a run that captures all type of downtime affecting the pumps, pipelines and ultimately the whole system. Also, in the top left side, the unscheduled downtime for pump 2 is included that accounts for seven down periods. Overall, both pumps have a total of 14 down periods, which include pipeline downtime.

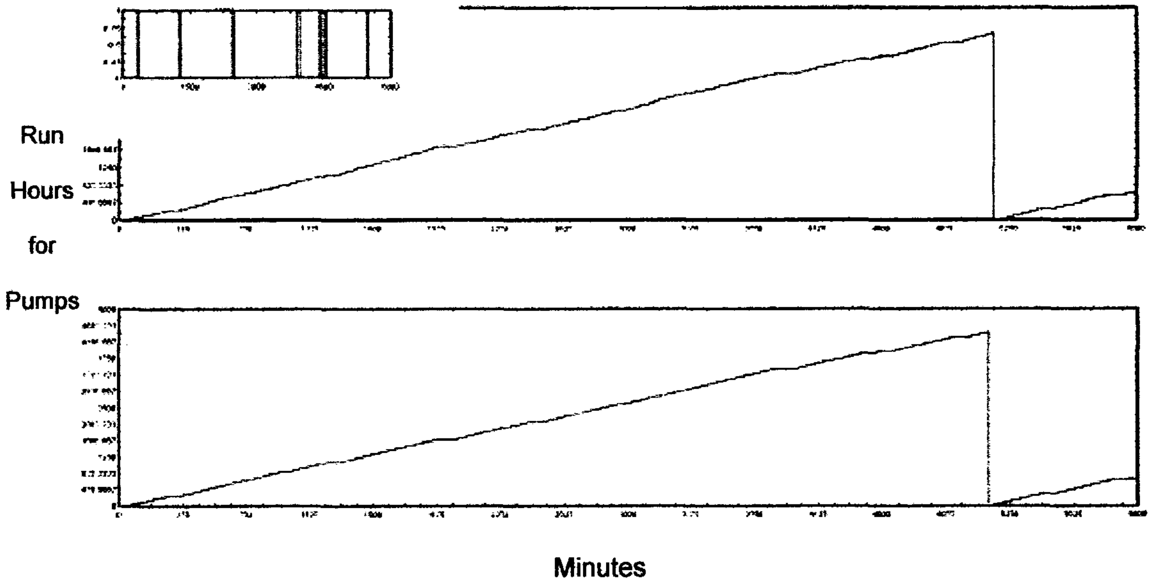


Figure 46 - Total downtime for the system due to pump / pipeline shutdowns

Figure 47 displays the summary of all the activities defined in the model. The highlighted activities depict those entities that are being serviced in each activity. For instance, the shovel is performing a long move at the end of the simulation time (see row 11). Also, some entities are still in the three conveyors (rows 7 to

9) and the crusher (row 6) while the hopper is still crushing some ore. The difference between arrivals and departures identifies those entities that are still in the process of being serviced by the resource. The utilization column depicts how much each activity was used with respect to the total simulated time, for example, the apron feeder at the crusher was used a total of 98.6%. This table can also give an indication of which activities are the ones taking the most time out of the system and it may provide an indication of bottlenecks. However, it should be considered that the utilization is just a report of how much each activity was used in the total simulated time, if there is a very time consuming activity that occurred only once, the utilization may be high.

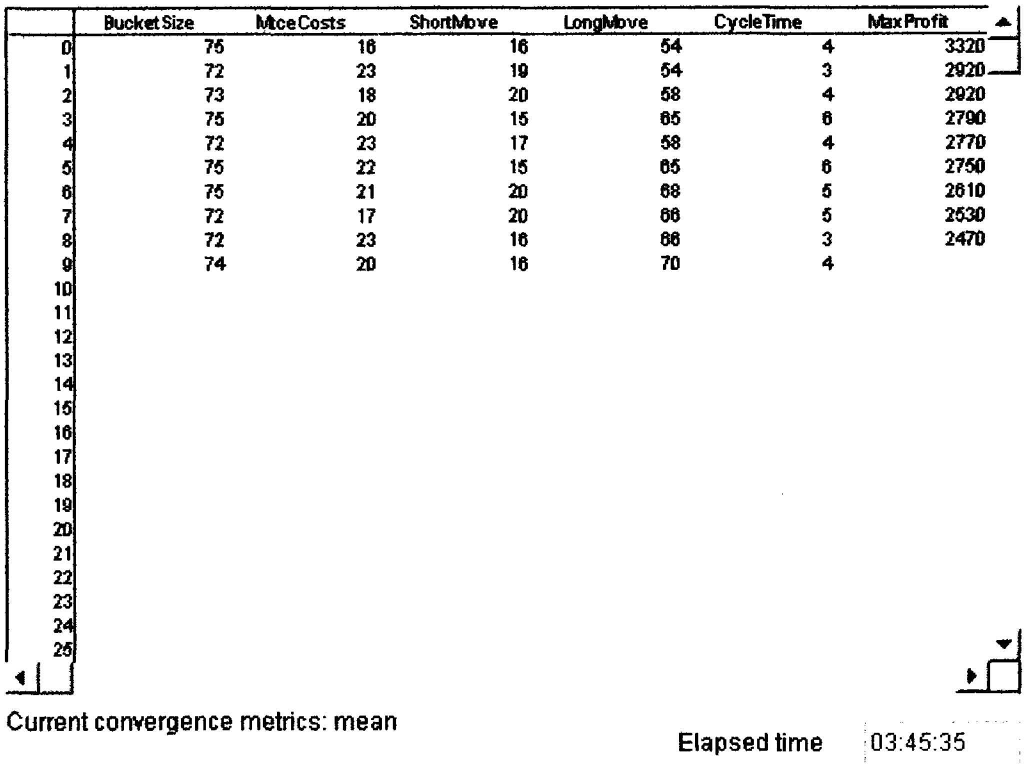
Row	Activity	# of Arrivals	# of Departures	Utilization (%)
1	Swings	824	824	6.1
2	Loads	824	824	7
3	Dumps	824	824	13.4
4	Returns	824	824	17
5	**Apron Feeder C**	**3439**	**3436**	**98.6**
6	**Crusher**	**3436**	**3388**	**57.9**
7	**Mobile Transfer**	**3388**	**3386**	**73.9**
8	**Shiftable Face**	**3386**	**3384**	**62.7**
9	**Transfer**	**3384**	**3383**	**28.2**
10	**Apron Feeder S**	**5054**	**5053**	**5.7**
11	**Long move**	**31**	**30**	**0.01**
12	Crusher S	5053	5053	25.3
13	**Water pump**	**3949**	**3946**	**13.1**
14	**Mixer**	**9848**	**9847**	**82**
15	**Pump 2**	**5716**	**5715**	**81.6**
16	Shovel Mtce	50	50	16.7
17	Short move	98	98	0.02
18	Pump 1 down	1	1	0.3
19	**Pump 1**	**5666**	**5665**	**81.7**
20	Pump 2 down	1	1	0.3
21	**Straight**	5503	5502	91
22	Elbow down	3	3	3.5
23	**Elbow**	**3586**	**3585**	**90.7**
24	Sacrif down	6	6	3.5
25	Straight down	3	3	2.5
26	**Sacrificial**	10829	10828	90.5

Figure 47 - Summary of activities performed in the simulation

5.2 Optimization in the AFS model

As an example of how this model can provide optimized solutions for a specific module, an optimizer block was added to the shovel module. Only the decision variables defined in the shovel module are utilized.

The objective function defined in the optimization example is linear and it includes the maximization of profit given the net income from producing cubic meters of ore while subtracting shovel maintenance costs (delay in minutes due to maintenance) and the costs of moving the shovel (delays for long and short moves) as well as the costs related to cycle time on a minute basis. The list and explanation of decision variables presented in the shovel module should be re-visited in order to understand the results presented through the optimizer example. Figure 48 shows the results from the optimizer, it looks like the best combination is given by a bucket size of 75 m^3 of ore and a cycle time around 4 minutes. If the operation can keep maintenance and move delays as close as the ones showing in Figure 48 (first row), the profit will be maximized. This is just an example of the kind of information that this model can provide. It is outside the scope of this thesis to validate any of the results obtained through this optimization example in detail. To get these results, the optimizer was running for approximately 4 hours.



	BucketSize	MceCosts	ShortMove	LongMove	CycleTime	MaxProfit
0	75	16	16	54	4	3320
1	72	23	19	54	3	2920
2	73	18	20	58	4	2920
3	75	20	15	65	6	2790
4	72	23	17	58	4	2770
5	75	22	15	65	6	2750
6	75	21	20	68	5	2610
7	72	17	20	66	5	2530
8	72	23	16	66	3	2470
9	74	20	16	70	4	
10						
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Current convergence metrics: mean

Elapsed time 03:45:35

Figure 48 - Optimizer example

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The model described in this work shows the interactions on a simple AFS model from a production as well as a reliability perspective with quasi-static steady-state interactions only. Simple case studies clearly show how constraints of each type affect the system. The main objective of this model development is to incorporate the reality of operating conditions into the modeling of the AFS system. This model has not been validated in any way since no AFS system has been yet implemented in the industry. Engineering judgment was used to select values for parameters in the model.

The proposed AFS model provides a tool for analysis of operational scenarios by using an integrated approach to include relationships between production and reliability, with the goal of maximizing equipment life while minimizing downtime. The model is simple to modify and can handle complex scenarios.

By using accurate probabilistic functions for the many delays in the system, bottlenecks and design improvements can be identified. The fact that no AFS system is currently in operation limits the model because operational parameters were assumed from existing equipment. These assumptions do not include compounding effects that may be caused by equipment operating on an integrated system. By the end of 2006, Syncrude will start running a pilot project for a reduced AFS system. The pilot project is called InBit (in-pit bitumen) project. This project will run for approximately one year. Such a system would be a rich source of data to provide specifics for delays to be used in this model.

The improvements that might be made in the AFS model are described below. There is no specific recommendation on what should be attempted first, it will depend on the objectives and goals of the project in question.

- Including unscheduled downtime for Pump 1 and minimizing downtime with a strategy in which when any pump goes down the whole hydrotransport system gets affected

- Using flow architecture, which simulates continuous material flow in a model environment that handles simulation time in a discrete fashion. Time is handled just as it is in a standard discrete event paradigm, not as a finite number of equal steps. This methodology is beneficial to reduce the number of aggregates and steps in the current model. By doing so, more detail can be added to the model without affecting overall performance

- Optimizing the model by re-using blocks and defining parametric variables for instances of a given class

- Defining and including other pipeline components, for example, venturis, wyes, reducers / enlargers and even hybrid components (a spool after an elbow that is longer than 40 ft)

- Defining a realistic optimization case for the whole model in order to make well-informed decisions, incorporating real probability functions based on operating data and experience, conducting sensitivity analyses, and developing an appropriate objective function

- Using real-time data to generate delays, for example, pump vibration analysis to set pump outages

- Identifying an improved characterization of how process variables and design criteria affect component reliability with time

- Including process dynamics to simulate a non-steady state system

- Developing a deeper understanding of the interaction between modules, how feedbacks interact with each other in order to help identify bottlenecks, which can be done by a combination of dynamic modeling and sensitivity analysis

- Including parallel sub-systems into the model, for example, another shovel dumping into the same hopper, or multiple trains entering the super-pot

- Including other operating conditions and failure modes not currently defined in the model

- Including different types of ore to run in the model, with their effects on process performance and reliability

- Developing reliability block diagrams for the AFS series system to depict the relationship between the functioning of the system and the functioning of its components

- Accounting for partial failure of components

- Understanding the effects of adding or removing one conveyor on production

- Including more parameters for oil recovery into the model, for example, distribution of fines in ore body

- Developing libraries of custom blocks in the simulation package used in this work (Extend OR) that include mathematical descriptions of the physical relationships in the system

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8 APPENDIX

The AFS model is defined below according to the hierarchy defined in Extend shown in Figure 16.

The top of the hierarchy is given by the high level definition of the model as shown in Figure A1.

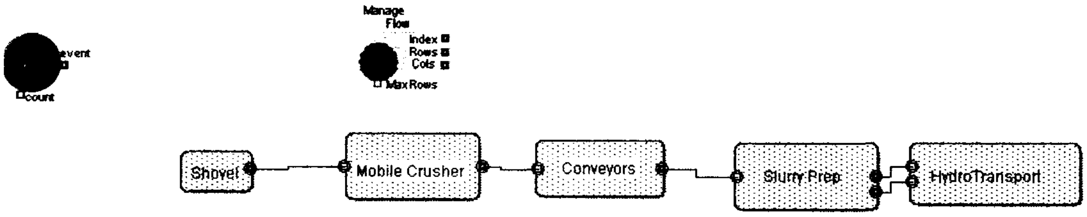

Figure A1 - Top level of the AFS model

The shovel module is displayed in Figures A2a, A2b and A2c given the fact that it is a very involved module.

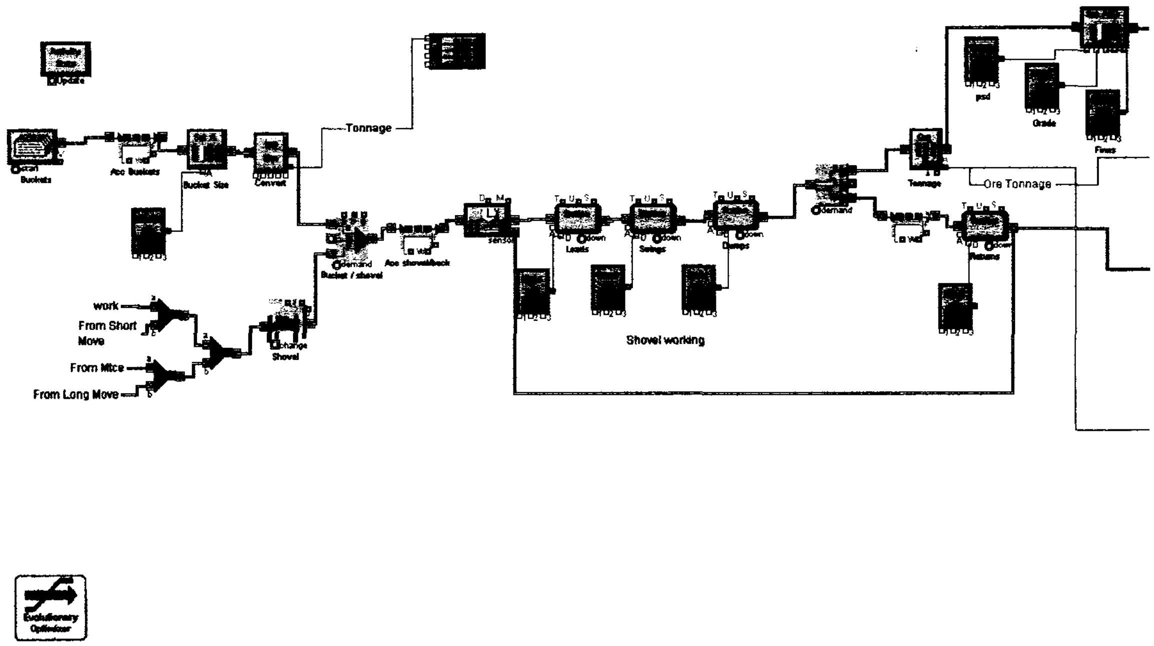

Figure A2a – First part of shovel block

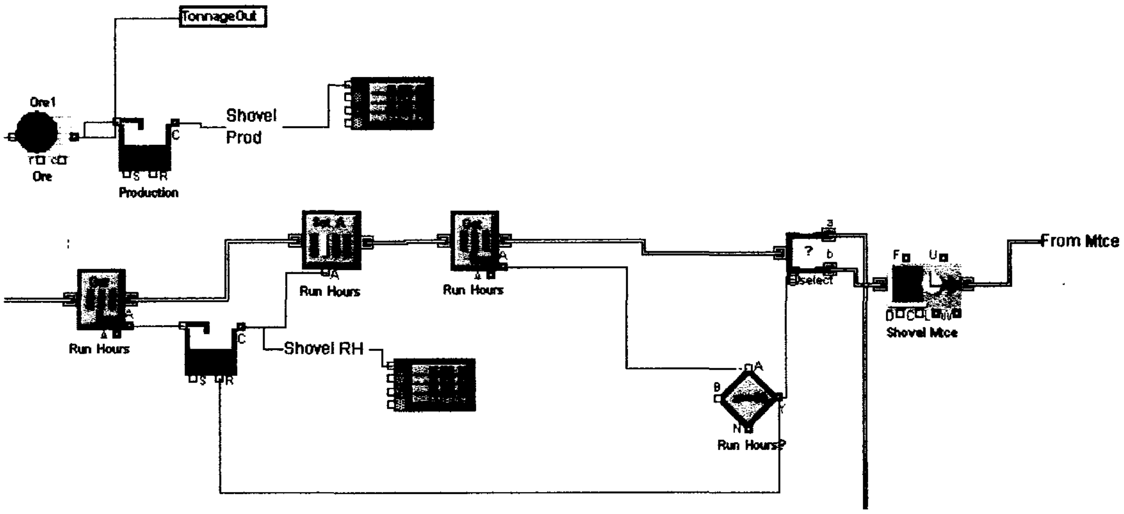

Figure A2b – Second part of the shovel module

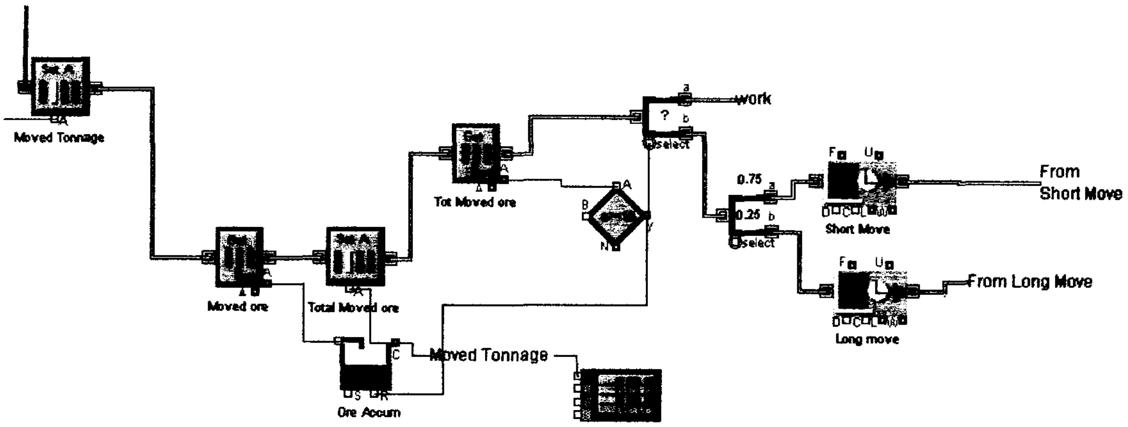

Figure A2c – Third part of the shovel module

The mobile crusher module is depicted in Figure A3.

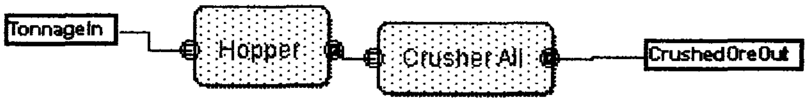

Figure A3 – Mobile crusher

The hopper block is displayed in Figure A4.

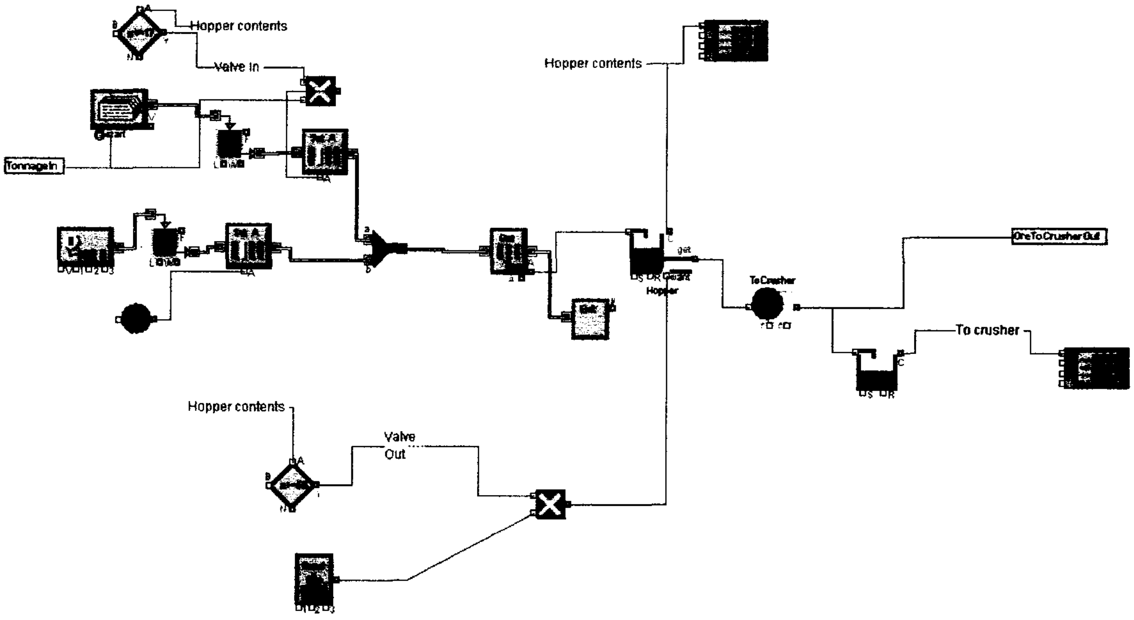

Figure A4 - Hopper block

The crusher block is shown in Figure A5, where the apron feeder is defined as a conveyor block.

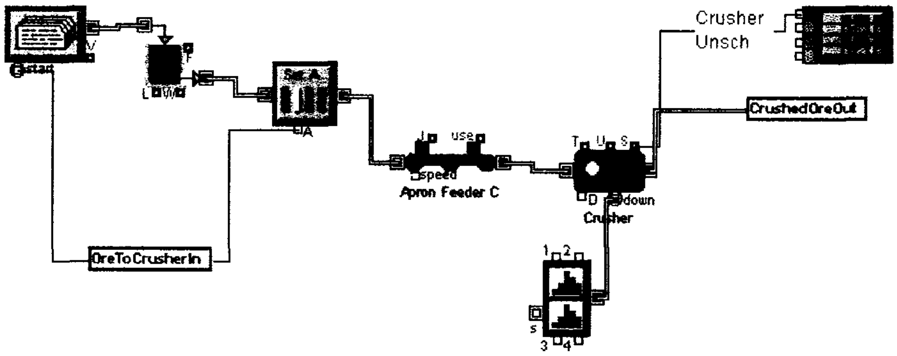

Figure A5 - Crusher block

The conveyors block is shown in Figure A6. This block contains the 3 conveyors as defined in Figure 21.

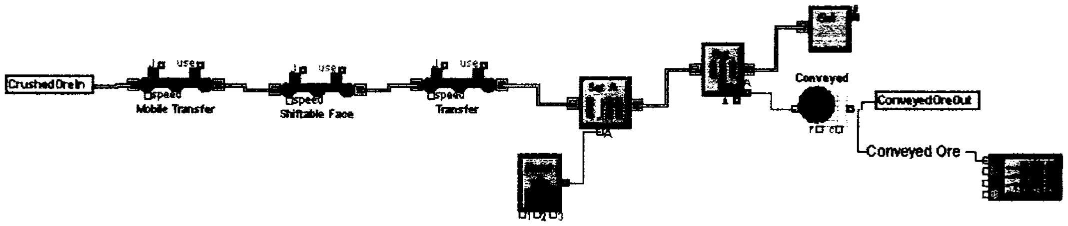

Figure A6 - Conveyors block

The slurry preparation block is depicted in Figure A7.

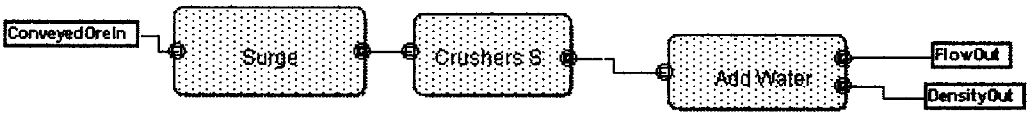

Figure A7 - Slurry preparation block

Figure A8 shows the surge block.

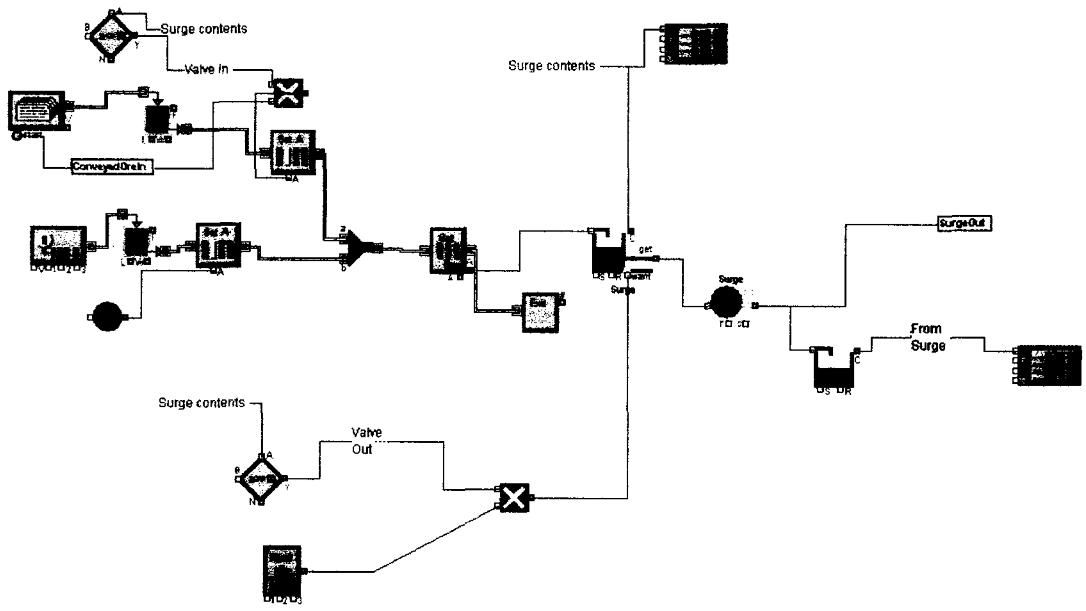

Figure A8 – Surge block

The crusher at the slurry preparation tower is displayed in Figure A9.

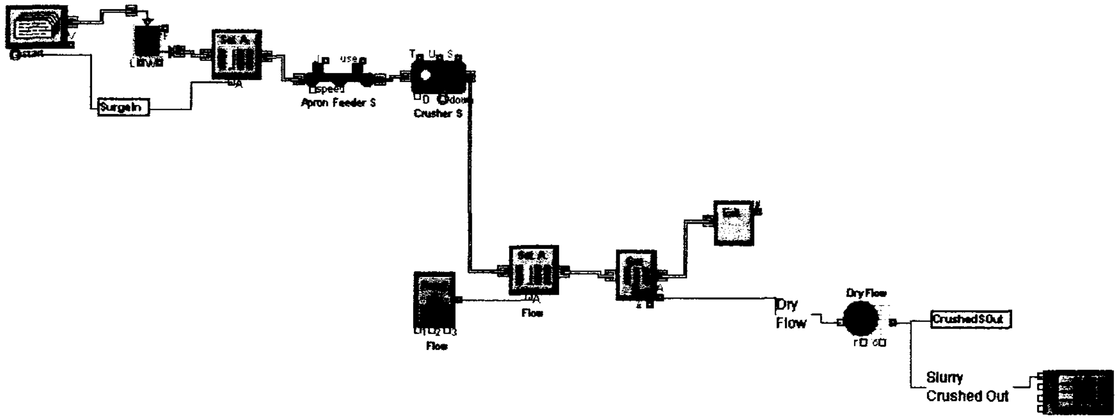

Figure A9 - Slurry crusher block

The addition of water to the slurry is detailed in Figures A10a and A10b.

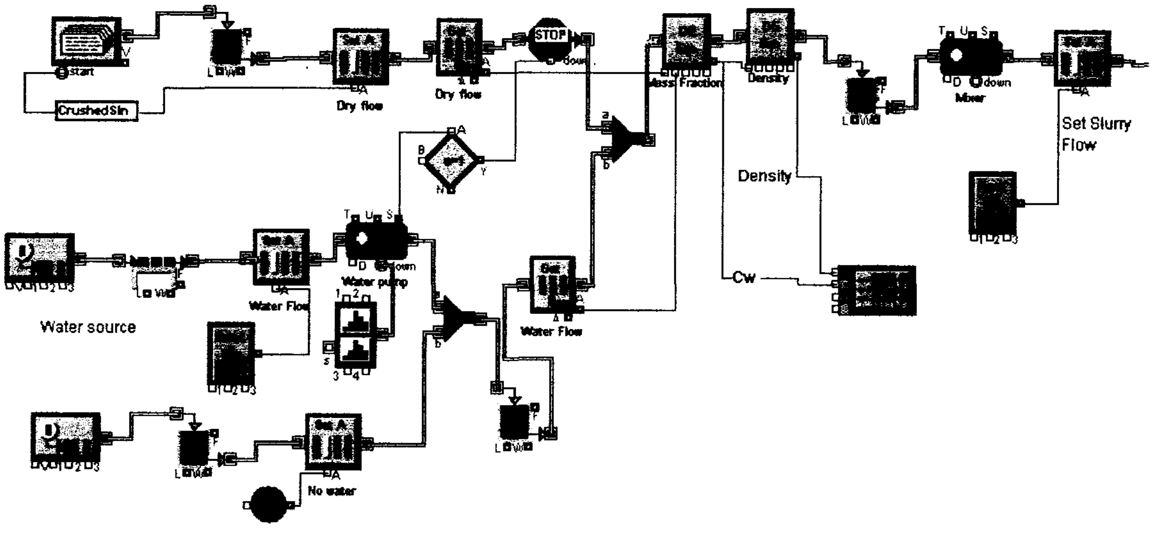

Figure A10a – First part of the water addition block

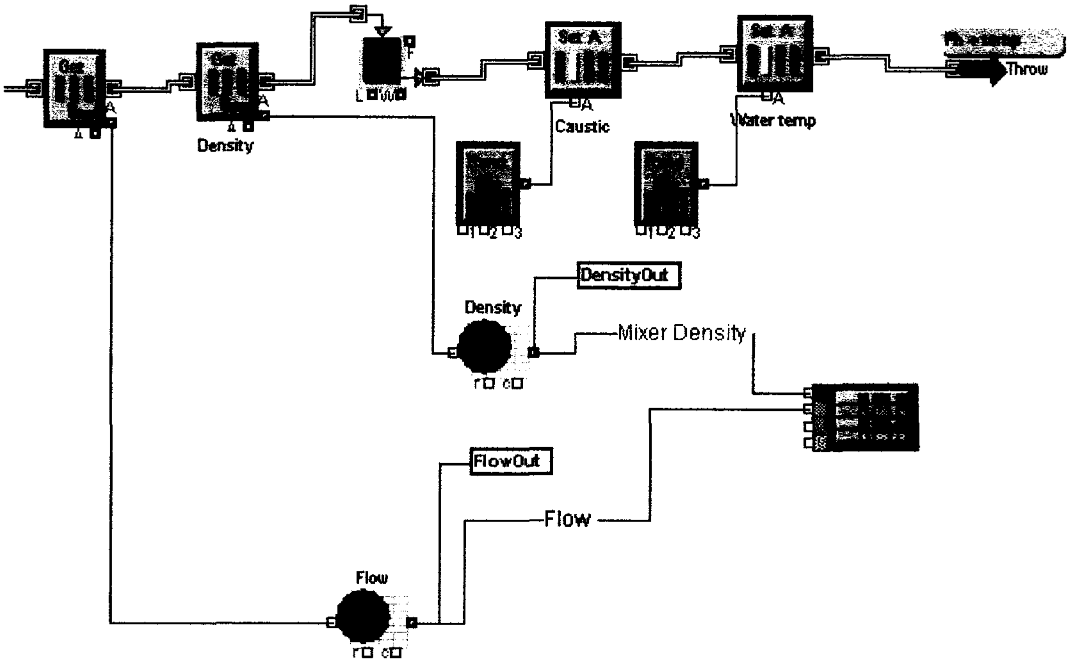

Figure A10b – Second part of the water addition block

The hydrotransport module is depicted in Figure A11.

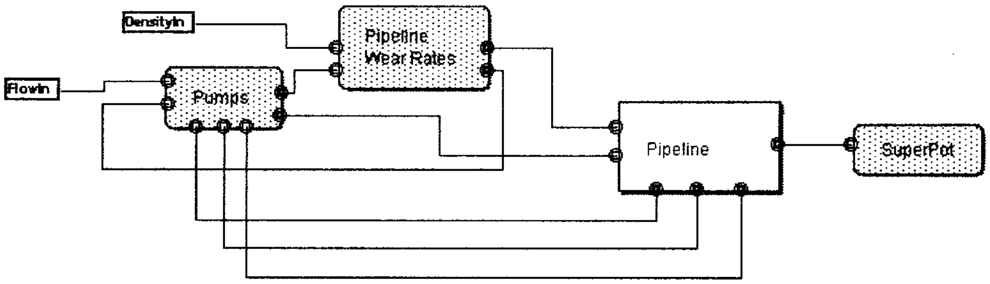

Figure A11 – Hydrotransport module

Figure A12 displays the Pumps module.

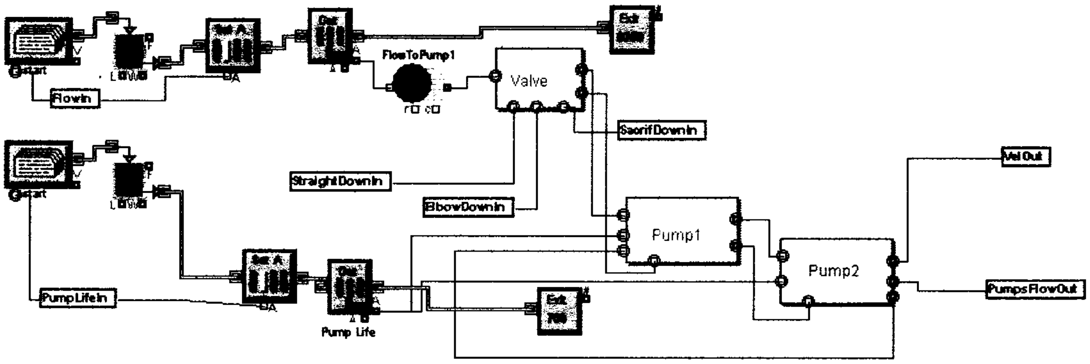

Figure A12 – Pumps module

The valve block was created with the purpose of making sure that when the pipeline is down, the pumps go down as well. Figure A13 shows the valve block.

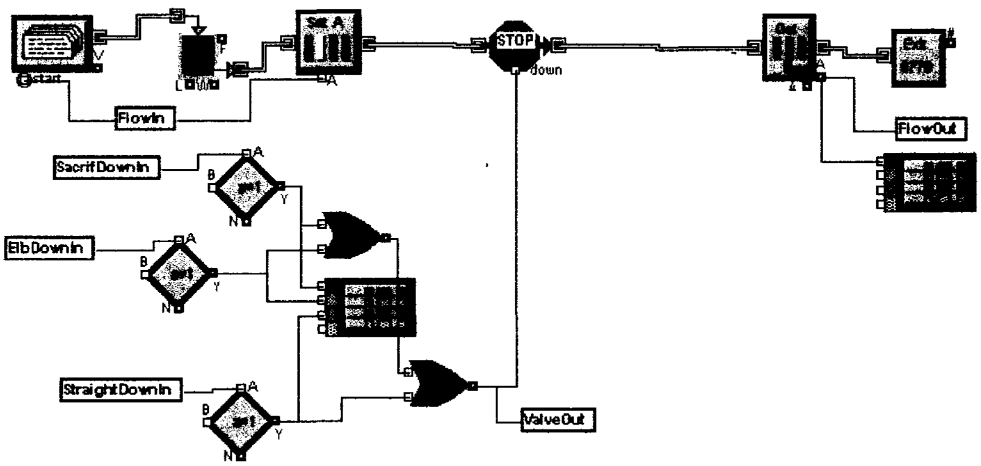

Figure A13 – Valve block

Figure A14 displays the Pump 1 block.

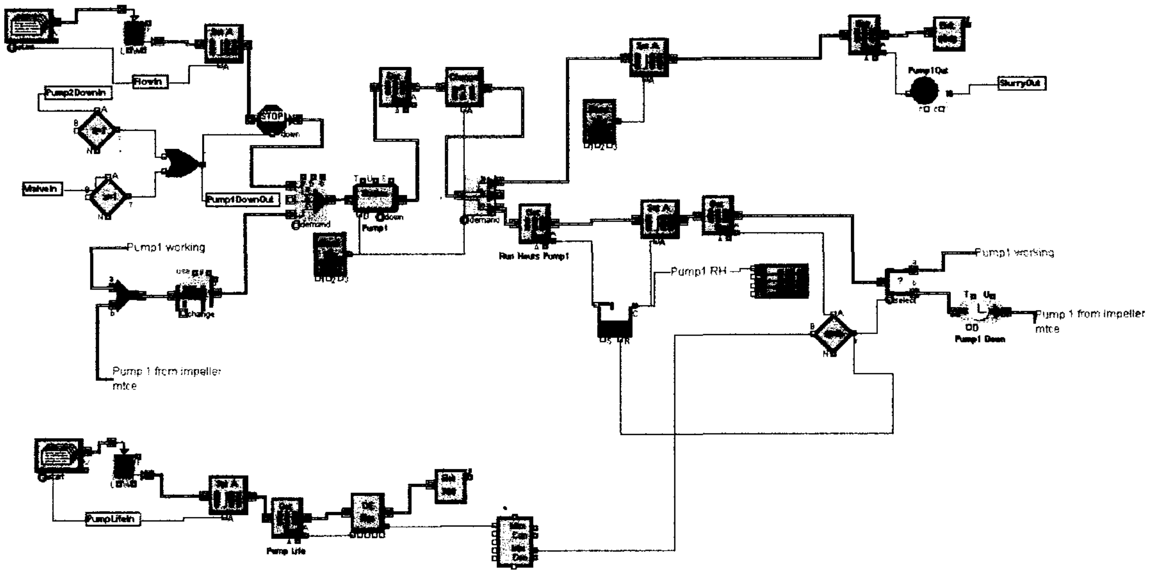

Figure A14 - Pump 1 block

The Pump 2 block is quite similar to Pump 1 with the added difference of unscheduled maintenance for the pump. Figures A15a and A15b display the Pump 2 block.

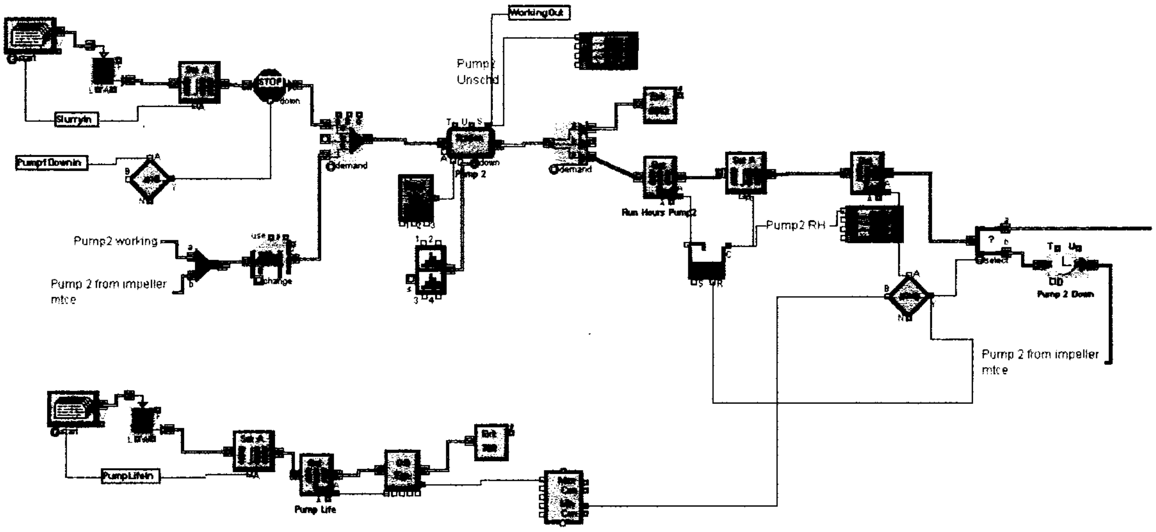

Figure A15a – First part of Pump 2 block

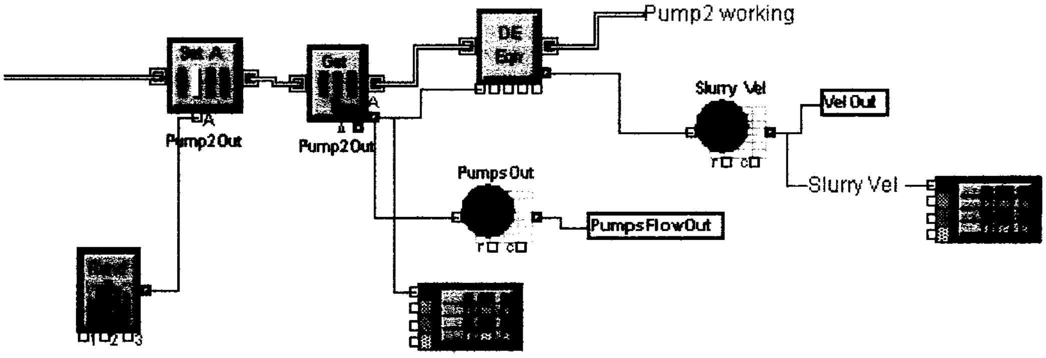

Figure A15b – Second part of Pump 2 block

Figure A16 shows the Pipeline wear rates block where the wear rates for pumps and pipe are calculated.

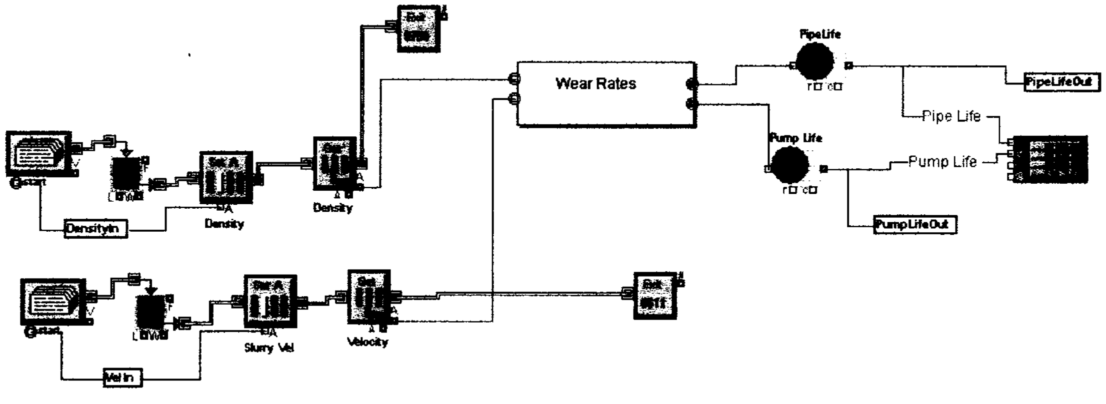

Figure A16 – Pipeline Wear Rates block definition

Figure A17 depicts the wear rate block where the actual wear rates are calculated.

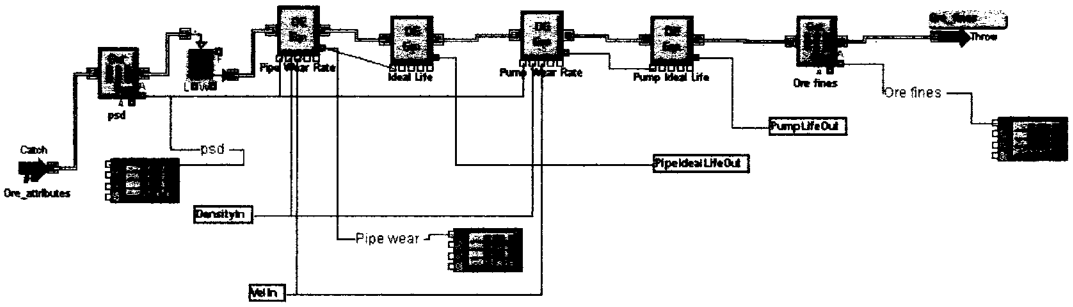

Figure A17 – Wear rates block

Figure A18 displays the pipeline components as defined in the pipeline block.

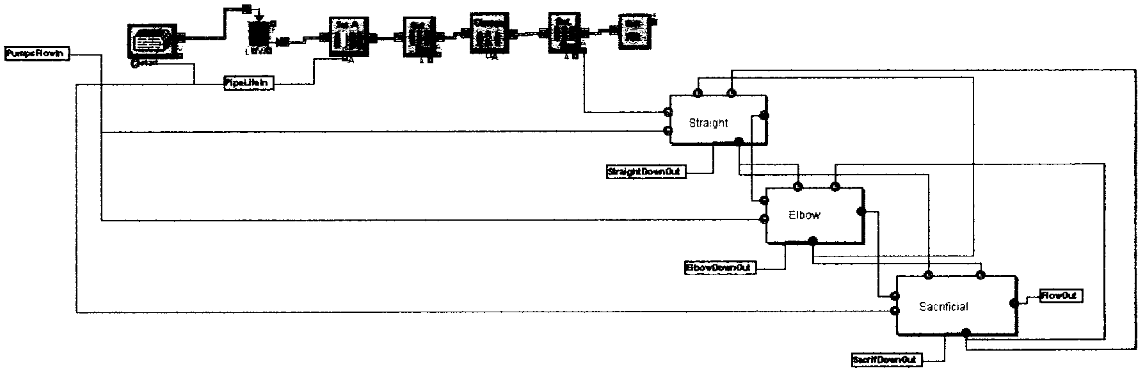

Figure A18 – Pipeline components block

Figure A19 shows the block defined for the straight pipe.

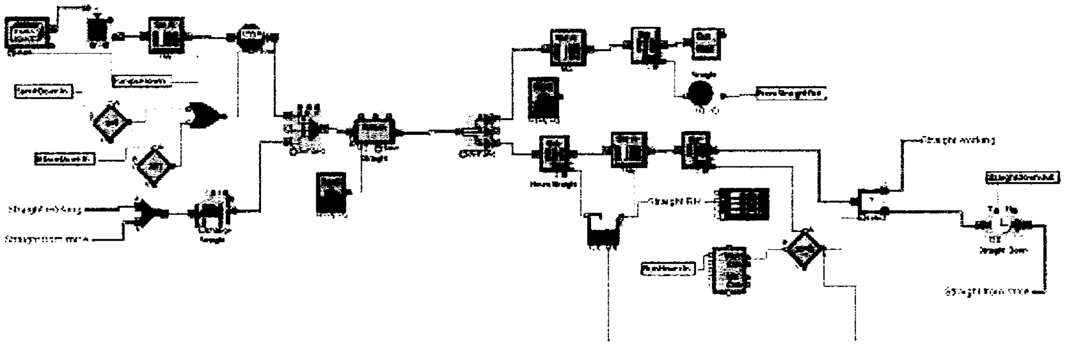

Figure A19 – Straight pipe block

Figure A20 depicts the block defined for the elbow component that is very similar to the straight pipe one.

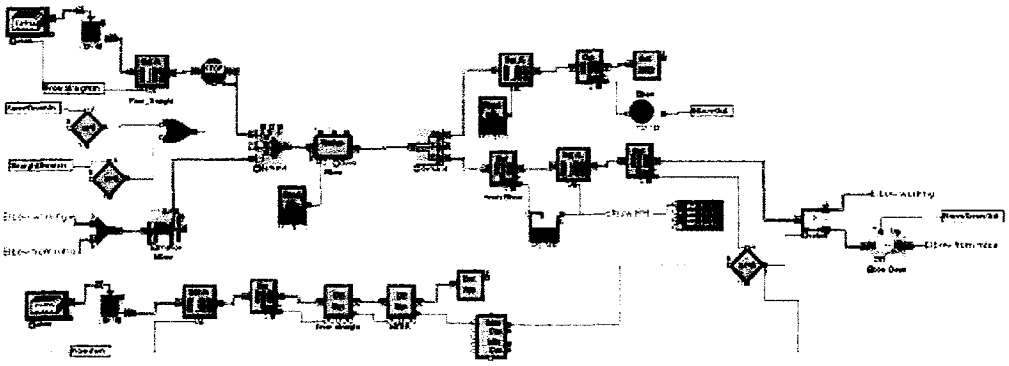

Figure A20 – Elbow block

Figure A21 shows the sacrificial or drop out spool block.

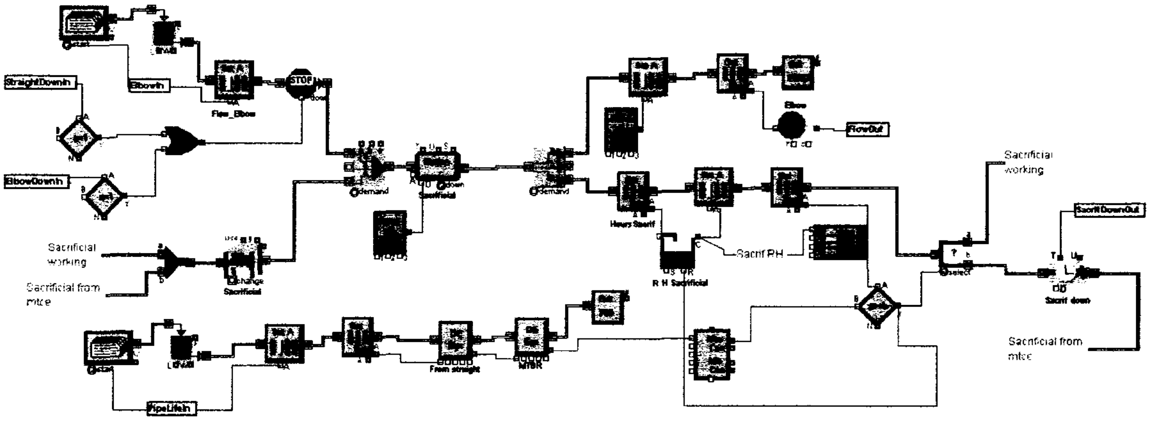

Figure A21 – Sacrificial spool block

Figure A22 shows the last block of the model that defines the super pot reservoir.

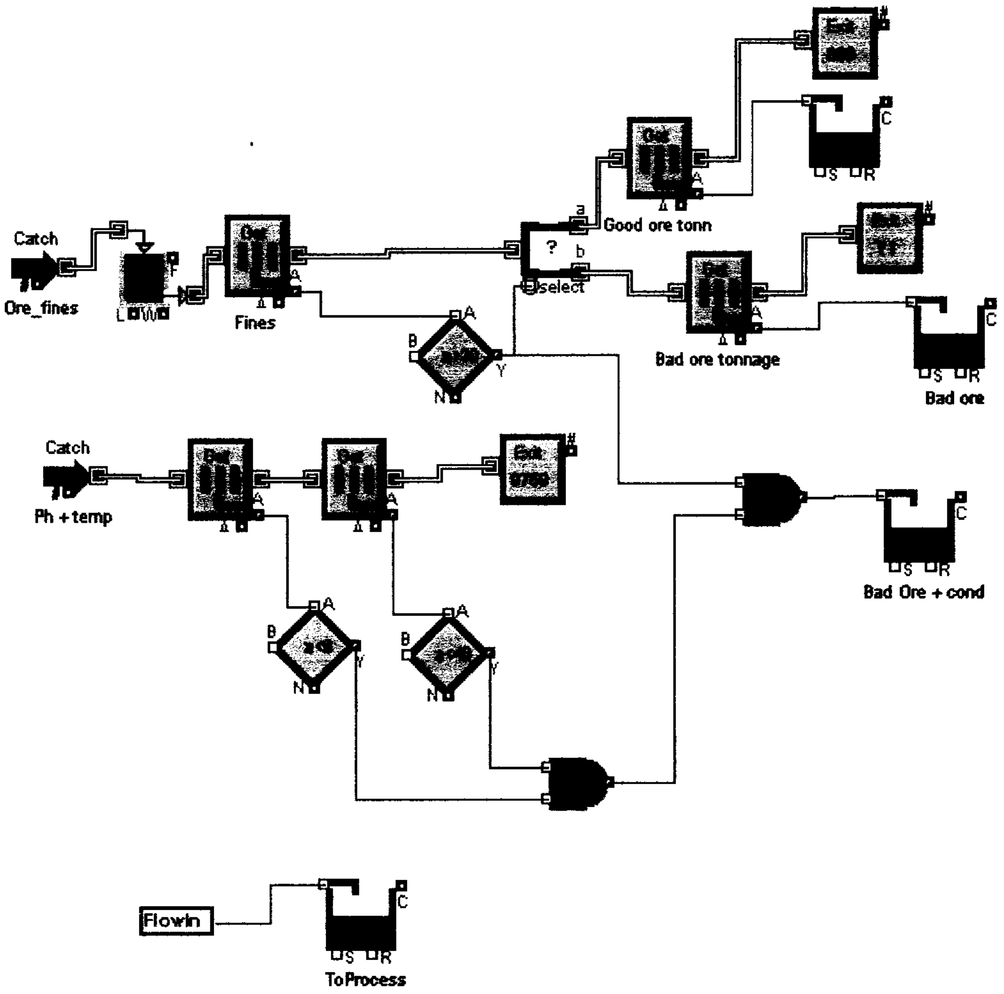

Figure A22 – Super pot block