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Coal Quality Management Model for a Dome Storage (DS-CQMM)

Manuel Alejandro Badani Prado

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Coal Quality Management Model for a Dome Storage (DS-CQMM)

Manuel Alejandro Badani Prado

**Thesis submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
At West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Mining Engineering**

**Vladislav Kecojevic, Ph.D., Chair
Brijes Mishra, Ph.D.
Aaron Noble, Ph.D.**

Department of Mining Engineering

**Morgantown, West Virginia
2015**

**Keywords: Coal Quality; Coal Analyzer; Mathematical Modelling; Dome Storage;
Stacker and Reclaimer; Data Collection; Information Systems**

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ABSTRACT

Coal Quality Management Model for a Dome Storage (DS-CQMM)

Manuel Alejandro Badani Prado

Coal quality (ash, sulfur, moisture and BTU) is one of the key aspects for both coal mines and power plants. Mines invest time as well as economic and technological resources in order to manage coal quality for final use in power plants. In order to deliver uniform coal quality to the power plant, there is a need for a real-time monitoring of coal quality from the mine to the coal stockpiles. The specific problem represents the process of stacking the coal inside the enclosed facility such as a dome. The process of stacking coal inside a dome generates the unique geometry of the stockpile due to the physical constraints caused by the circular shape and walls of dome, and height and length of stacker. The reclaiming process also creates a particular shape of the stockpile. The specific challenge to the mine is to know spatial distribution of coal quality parameters, volume and tonnage in such formed stockpile.

The objective of this research was to develop a custom-made and integrated Coal Quality Management Model for a Dome Storage (DS-CQMM). The DS-CQMM merges existing technology in surface mines, such as coal analyzers, along with automation technologies, information technologies (IT), mathematical models, and different programming languages.

The DS-CQMM is organized into four major sections: Delay Time Application, Stacker Application, Reclaimer Application, and Live Stockpile Application. A sub-process called Volume Calculation is embedded in Stacker Application, while an additional feature called Forecast Tool is included in the Reclaimer Application. The Delay Time Application calculates the time that a batch of coal takes to reach the boom of the stacker from the coal analyzer through the belt conveyor system. The Stacker Application retrieves the information provided by the Delay Time Application and Distributed Control System (DCS) database using a mathematical model. This model is specifically designed for this purpose in order to assign a unique location to coal that is being stacked into the mathematically-discretized dome storage. The volume of the stacked coal is calculated by using the mathematical model and dome discretization. Finally, tonnage is determined and assigned along with coal quality tags. Once the coal is stacked into the dome, the Reclaimer Application displays the ranges of every quality tag within the stockpile. For more accurate representation, coal quality is shown in numerical values in the Forecast Tool using different tables. The Forecast Tool has the capability of calculating the average of each quality tag and the total summation of the tonnage of the coal that will be reclaimed by selecting the desired cells and showing the values in a display window. After reclaiming the coal, the Reclaimer Application retrieves required data from the DCS database and builds the shape of the remaining stockpile. The Reclaimer Application shows the distribution of the coal quality of the remaining stockpile. The Live Stockpile Application is developed for a special part of the dome that was originally designed to serve as an emergency reclaimer in case of failure or maintenance of the mobile reclaimer. The Live Stockpile Application has two parts: stacking and reclaiming. Using the same concept and mathematical model of the Stacker Application, the stacking part of the Live Stockpile Application is developed, while new concepts and mathematical models are developed for the reclaiming part. Both parts show the same graphical outputs as the Stacker and Reclaiming Applications.

The DS-CQMM model was developed for a surface coal mine in the southern United States.

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APPROVAL OF THE EXAMINING COMMITTEE

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List of Symbols

Adaptive Neuro-Fuzzy Inference System	<i>ANFIS</i>
Air Amendments Act	<i>AAA</i>
British Thermal Unit	<i>BTU</i>
Charged-Coupled Device	<i>CCD</i>
Coal Quality Impact Model	<i>CQIM</i>
Conversion Factor	<i>CF</i>
Decision Support System	<i>DSS</i>
Distributed Control System	<i>DCS</i>
Dome Storage - Coal Quality Management Model	<i>DS-CQMM</i>
Dual Gamma-Energy Transmission	<i>DUET</i>
Emission Allowance	<i>EA</i>
Graphical User Interface	<i>GUI</i>
Information Technologies	<i>IT</i>
Integrated Gasification Combined Cycle	<i>IGCC</i>
Light Detection and Ranging	<i>LIDAR</i>
Lignite Delivery Facility	<i>LDF</i>
Megawatt	<i>MW</i>
Programming Logic Controllers	<i>PLC</i>
Prompt Gamma Neutron Activation Analysis	<i>PGNAA</i>
Quality Target	<i>QT</i>
Ultraviolet	<i>UV</i>
Unmanned Aerial Vehicle	<i>UAV</i>

Variable Frequency Drives

VFD

Virginia Department of Transportation

VDOT

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Chapter 1

Introduction

1.1 Background

Knowledge of coal quality properties (ash, sulfur, moisture, and BTU) is very important for mines and power plants. Modern mines invest time and economic and technological resources in order to successfully manage coal quality for final use in power plants. Since the coal market is characterized by the need for a uniform product of particular specifications (Keleher et al. 1998), it is critical that the delivered product meet the quality requirements imposed by contracts. Therefore, coal quality management is a fundamental concern.

In order to deliver a uniform product, mines usually use a process called coal blending. Coal blending represents homogenization of mixtures of coal in such a way that the properties of the final blend satisfy particular specifications. Coal blending is also called coal mixing (Arnold and Smith 1994). Mines not only blend coal to meet the customer's requirements, but also to extend the life of their high quality reserves (Reeves 1995).

Coal blending can be performed at the mine site, on stockpiles, and in bins, bunkers, and silos (Arnold and Smith 1994). There are a number of techniques that enhance the blending process, such as different ways of storage (circular stockpiles, longitudinal stockpiles), different procedures for stacking, and different processes of reclaiming. Wolpers (2014) indicates that stockpile homogenization systems equalize variations of chemical and physical properties of raw materials and transform low-quality grades into a uniform mixture of higher material quality.

Therefore, there is a need to know coal quality before stacking coal at the stockpiles so that potential problems can be blended out (France 1999). Schott (2004) also stated that input properties of coal are a main factor for performance of homogenization of bulk materials in mammoth silos.

Coal quality needs to be known since it has a direct impact on the performance of a power plant. Hajicek et al. (1992) noticed that the performance of power plant units changed while burning five different types of coal. A constant quality of coal helps keep the boiler operation in an optimal regime in terms of efficiency and minimum exhalation release (ENELEX 2014); therefore, coal is blended to maintain an emission specification and specially for maintaining a consistent quality (Arnold and Smith 1994). Theoretical studies show that boiler efficiency is affected mainly by the changes in coal quality (Oman et al. 2001). Considering that the boiler and auxiliary equipment design in power plants is fixed, coal is usually selected to match the specifications required for proper performance (Skorupska 1992). Arnold and Smith (1994) indicated that power plants were built to accommodate a “design” fuel. According to Reeves (1995), coal producers and utilities depend on automated coal blending systems to reduce cost and meet environmental regulations.

The Clean Air Act revisions of November 1990 regulate the reduction of air emissions from major sources (US Environmental Protection Agency 2014). “Major Sources” are defined as a stationary source or group of sources that emit or have the potential to emit at least 10 tons per year of a hazardous air pollutant or at least 25 tons per year of a combination of hazardous air pollutants (US Environmental Protection Agency 2014).

Coal blending for enhancing coal quality has been studied by a number of researchers. For instance, Tenorio and Dessureault (2011) developed an evaluation model to assess the impact of

a decision support system (DSS) integrated in a control room in order to control the coal blending process. They used a discrete event simulator software to simulate the whole production process, and to access performance and current materials handling settings. Simulation software is extremely useful for testing a simulated system when optimal operating points are disturbed by outside factors (such as coal quality variations) and to test the system in any hypothetical situation. According to Carvalho et al. (2012), results obtained by mathematical modelling tools, optimization techniques such as linear programming, and risk analysis, can provide financial gains in the planning process. Linear programming relates to the maximization or minimization of a linear objective function in many variables subject to linear equality and inequality constraints (Dantzig and Thapa 1997). To solve complex systems (of more than 2,000 constraints) and find the optimum value of the variables involved in the objective function requires special software. De Carvalho Junior et al. (2012) used linear programming to find the best production strategy to meet the demand of the market. They asserted that coal can be produced with a minimum cost and a higher profit. One of the restrictions is coal quality. Jerez (1991) used linear programming to enhance production planning, transportation, and shipments at different coal mines. Blankenship (1995) analyzed the technological tools used to find optimum solutions in fueling planning, including predictive models such as “Coal Quality Impact Model” (CQIM). Linear programming was used for optimizing the Clean Air Amendments Act (CAAA) compliance plan, taking into account each station’s fuel constraints, fuel cost, expected electricity demand, and current Emission Allowance (EA) cost to return CAAA compliance at minimum cost.

Blankenship (1995) used on-line coal quality data for fuel analysis in order to obtain better coal blending. The fundamental components of on-line coal quality studies are coal analyzers, and they are employed in monitoring, blending, or sorting applications (Laurila 1995).

The benefits of using coal analyzers are numerous. For example, more consistent quality can be attained, fewer penalties from out-of-specification shipments can be achieved, and the ability to sort different coal qualities can be provided. The benefits at power plants are fewer outages and more electric power generated (Woodward 2006).

There are four types of coal analyzers available: elemental analyzers, ash meters (ash only), moisture meters (moisture only), and slurry analyzers (Arnold and Smith 1994; Woodward 2006). The most common type is the ash meter (Woodward 2006). A number of research studies have been conducted on ash analyzers. For instance, Galetakis and Vasiliou (2006) proposed a new approach for calibration dual gamma-energy transmission (DUET) ash analyzer, developing an adaptive neuro-fuzzy inference system (ANFIS). Yu et al. (2003) conducted research in which a neural network was used to model the relationship between the scintillation counts of an analyzer, and the measured ash for enhancing on-line analysis of coal. According to Yu et al. (2003), the performance obtained by this approach was significantly better than without the use of neural networks.

For more accurate and comprehensive study of coal quality, the most reliable yet also most expensive analyzers are the elemental analyzers. These analyzers are divided in two subtypes: full flow (mounted around a conveyor belt); and sample stream (which analyzes a primary save or a secondary reject stream). The most common technology for this analyzer type is Prompt Gamma Neutron Activation Analysis (PGNAA) (Woodward 2006). The PGNAA works as follows: Coal is bombarded with thermal neutrons from a nuclear source, and many of the

neutrons are captured by elemental atoms. The atom then becomes momentarily unstable and emits a spectrum of high-energy gamma rays. The specific energies of emitted gamma rays are unique for each element of the periodic table, which are detected by a crystal. As the gamma rays enter into the detector, depositing their energy as high-speed electrons creating ionization, photo-multiplier tubes detect the electrons as UV light pulses, and turn them into electrical pulses that are amplified and converted into digital signals collected within a period of time. Finally, these signals are processed and the weight percent of each element is determined by mathematical operations (Foster and Heger 2014). France (1999) asserts that the installation of PGNA is “undoubtedly an expensive exercise,” but there are several benefits, such as improving feedback to mining operations, the ability to stack coal into the correct areas of the stockpile using real-time information, and the capability to automate the process of coal quality data, turning it into a stockpile management system.

Prompt Gamma Neutron Activation Analysis (PGNA) is considered to give the best on-line analysis precision for reporting coal parameters, such as ash, moisture, sulfur, and calorific value, by determining the concentration of its primary elements (Sanders and Smith 1998, as cited in France 1999).

One of the techniques that enhances the blending process is the method of stacking coal. A dome-shaped structure is one of the facilities available for coal storage and blending. Some mines use storage facilities in order to preserve material from weather elements. Dome storage has been widely used by the mining industry around the world. In some cases it is also used for preventing the release of dust into the environment. The Taiwan Power Company, located in Hsinta/Kaohsiung, has four coal domes, each with approximately 187,400 tons of storage capacity, that can supply four existing units for 50 days of operation. To handle inbound and

outbound coal flow, a radial stacker/reclaimer and conveyor system is installed. The stacker capacity is 4,410 tons per hour and the reclaimer capacity is 2,205 tons per hour (GIBISIN Engineers Ltda. 2014). Another example of coal dome use is located in a mine in the state of Iowa (in the United States). It has approximately 66,140 tons of storage capacity (Dome Technology 2014).

Domes are also used for storing materials other than coal. One of the examples is found in the southwest of the Bolivian Andes, at the “San Cristobal” mine, which is at 13,100 ft. elevation above sea level. Silver, zinc, and lead ores are extracted from the mine using the open pit method. The raw material is then hauled to a crusher by haul trucks, and the rocks are there reduced to 6 in. in diameter. Conveyor belts then move this material to a dome where a 140 ft. stockpile is formed. This particular dome holds the raw materials for further processing and prevents dust contamination. Finally, the material is transported from the dome by conveyor belts (Minera San Cristobal 2014). According to Geometrica (2014) this is the largest storage dome on the South American continent.

Domes are not only used for storing extracted materials from mines. In the winter of 1995, the entire East Coast of the United States experienced salt shortage due to inclement weather. The Virginia Department of Transportation (VDOT) ran out of chemicals and had problems with suppliers providing salt for the treacherous roads. In order to avoid the risk of ruining their trucks in bad weather conditions, VODT searched for salt in other states, and bought it at a high price due to the high demand. In order to avoid this problem in the future, they built a regional facility to store salt during the summer when they could buy it at the lowest price (Goldman 1999).

The use of on-line analyzers combined with technological tools and existing infrastructure (such as storage structures) at mines can be of tremendous benefit. An example of integration of on-

line coal analyzers and computer technologies is given by Ganguli et al. (1998). An optimal control algorithm was implemented to split a coal stream into wash and no-wash stocks, reducing the amount of coal that had to be washed, and therefore reducing processing cost, recovery losses, and refuse generation levels. Using on-line analyzers, coal quality was measured in real-time, and the coal stream was physically segregated into stocks of low ash (no-wash stock) and high ash (wash stock) by directing a flop gate in the coal silo, dividing the two stocks. Two approaches were developed: a time series model to capture the stochastic characteristics of the coal quality levels' fluctuations over time; and a moving histogram approach that assumed that recently observed values were representative of the current behavior of the process. Then, a segregation algorithm was developed, along with optimal control techniques for deciding what portion of the coal flow would go to the wash or no-wash stock, maximizing the yield (no-wash stock). The main advantages of this approach were low cost and the absence of additional hardware needed for implementation.

1.2 Problem Statement

Management of coal quality is extremely important for the mining industry. For example, one of the mines in central Mississippi, which provides coal to a 440 MW power plant, experimented with multiple coal quality analyzers in order to find an accurate and reliable solution. The mine and adjacent power plant were challenged with quality deliveries; therefore, a suitable solution was to acquire coal analyzers that would ensure that the product delivered to the power plant did not exceed a certain ash content. Therefore, a dual gamma ash gauge was installed, with an associated microwave moisture meter to monitor coal quality. At first, the results were

encouraging, but soon the operators found that the variation in coal flow rate was causing disparities in ash and moisture results. Additionally, the microwave moisture meters would not work properly when 30% moisture content was exceeded. Due to these problems, the dual gamma ash gauge was removed from service. According to the mine and power plant operators, two lessons were learned from this experience: “Real-time coal quality data is extremely valuable, but incorrect real-time data is worse than no real-time data at all.” The mine then addressed the problem by installing PGNAA analyzers on the conveyor belt system. The analyzers were used to monitor coal flow to the silos and boilers in such a way that if low quality coal was arriving, control room operators could make adjustments to the blend ratio, depending on the real-time data retrieved from the analyzers (Foster and Halsell 2010). However, since silos were used only for temporary storage, the entire system had limited impact on the blending process and therefore on the final quality of the coal being delivered.

A power plant near Castle Dale, Utah, used a coal analyzer to control the ash fusion temperature of the coal blend (Snider et al. 2005). Low ash fusion temperatures were the primary cause of slagging and unplanned outages. Engineers from the plant studied the relationship between certain coal ash minerals and the softening temperature of the ash, and they developed formulas that estimated the ash-softening temperatures of the coal blend as a function of the ash components. They agreed that PGNAA analyzers could help them determine the components of the six major ash components and the ash-softening temperature. The analyzer monitors blend coal conveyed from the stockpiles to the screening transfer building and then to a second transfer tower, which is connected to the storage barn (Snider et al. 2005). This solution was effective with ash challenges and provided reduced slagging, but lost generation and frequency of forced outages indicated that the rest of the quality tags should be given more attention.

According to Woodward (2008), the number of analyzer purchased by utilities is growing. This shows that the coal mining industry has realized the advantages of using analyzers for quality management purposes. This means that effective and user-friendly software can be developed to make blending processes more effective.

In research conducted by Zhao et al. (2014) on coal quality detection and coal quality management for power plants, a Client/Server system was developed in Visual C++. The system is composed of three modules: (i) recipe/allocation that reads barcodes of sample bags and allocates a laboratory's random code; (ii) data acquisition that retrieves data from detection instruments; and (iii) a results management module that processes and stores data, queries the system's database, and prints reports. This was an innovative approach to a coal quality collection/report data system. Nonetheless, effective coal quality management should go beyond just collecting and reporting data. It would be very useful to have a tool that would allow the operator time to make decisions and take action before stacking or delivering coal.

France (1999) analyzed the utilization of coal analyzers in a coal management system already installed in a coal mine. The coal analyzers automated their data with a two-dimensional image of the stockpiles by accepting the coal quality data into stockpiling modelling software. The software was developed by an external company that has the capability of accumulating and summarizing data stored in on-line databases. The software allows users to visualize and analyze the coal stockpile stacked by the traveling stacker/reclaimer. The model also has the stacker/reclaimer position as input data. The model provides the ability to predict the quality of the coal in case of reclaiming a specific area of the stockpile as well. The stockpile management system provides a visual output that allows graphic analysis of the content of ash and sulfur in the stockpile. This is an example of how on-line coal analyzers can greatly enhance the

automation of coal quality management using computer technologies. Nonetheless, there is no evidence that the coal stockpile is contained into any storage, causing variations of coal quality due to exposure to the elements. Also, to the best knowledge of the author, the visual output shows only two quality parameters (ash and sulfur) of the stacked coal.

The Engineering Consultants Group (2014) developed a sophisticated fuel tracking system named AccuTrack. This solution identifies the properties of coal and tracks it through the plant. It shows in real time the coal quality that is stored inside the bunker. Additionally, it includes a predictive tool that allows the user to know when slagging problems will occur. The model digitalizes coal by block models and parses raw data, assigning characteristics to each block. Finally, numerical reports are shown to the user. This is a very suitable solution for customized systems where coal quality must be known. However, to the best knowledge of the author, there is no evidence of the implementation of this solution in other storage structures such as domes.

Therefore, there is a lack of real-time coal quality management models for dome storage. The specific problem represents the process of stacking the coal inside the enclosed facility such as a dome. The process of stacking coal inside a dome generates the unique geometry of the stockpile due to the physical constraints caused by the circular shape and walls of dome and height and length of stacker. The reclaiming process also creates a particular shape of the stockpile. The specific challenge to the mine is to know spatial distribution of coal quality parameters, volume and tonnage in such formed stockpile.

1.3 Scope of Work

The goal of this research study is to develop a user-friendly interface for a Coal Quality Management Model for a Dome Storage (DS-CQMM) by using existing technologies in a surface coal mine in southern United States, merging automation technologies with information technologies (IT), mathematical models, and software programming. The model consists of the following elements:

- PGNAA coal analyzer that provides coal quality information in real-time, every minute for each batch of coal;
- a conveyor belt system that carries the coal to the dome and transfers the coal to the stacker inside the dome;
- coal transfer towers;
- a stacker that stores the coal inside the dome storage which has one degree of freedom in the rotational (azimuthal) angle;
- a dome storage that is the base for the quality model;
- a reclaimer that will reclaim coal from the dome that has two degrees of freedom: one in the rotational angle, and the other one in the elevation angle;
- different sensors such as ultrasonic sensors for measuring the level of the coal stockpile, encoders for determining the angular position of the stacker and the angular position and elevation of the Reclaimer.

The research objectives are as follows:

- create multiple user-friendly applications based on Windows OS for the process of stacking and reclaiming coal flow into a dome storage;
- establish the connection between the applications, the coal analyzer, and the Distributed Control System (DCS) room databases in order to retrieve and store necessary data for building a DS-CQMM model;
- develop an algorithm for retrieving data from the DCS room database containing different conveyor belts' velocities, and calculate the time remaining for a given batch of coal coming from the crusher and belt conveyors to the boom of the stacker inside the dome;
- formulate a three-dimensional mathematical model for developing a stacking algorithm that will assign shape and relative position of the coal stockpile inside the dome;
- create an algorithm for calculating the coal volume that is being stacked into the dome and assign quality properties for presenting values in tons for user interface;
- formulate a mathematical model for developing a reclaiming algorithm that will show the operator the different ranges of values of different quality tags of the remaining coal inside the dome. In addition, it needs to show the remaining shape of the coal stockpile after reclaiming;
- build a tool that implements a set of tables with numerical values of coal quality and tonnage for forecasting future reclaiming processes;
- develop multiple simulators for each created application in order to test and troubleshoot the algorithms and the entire Model.

These applications and tools will be helpful for managing coal quality for two main purposes:

1. Reaction Time. Storing coal inside the dome is an advantage for reclaiming purposes. If the mine needs a specific tonnage with a specific quality in a relatively short time frame, then a dome with an appropriate quality management system is enormously helpful.
2. Blending process. If we know the quality of the coal stored inside the dome and, most importantly, where it is stored and how many tons are available, then the blending coal retrieved from the dome and incoming from the mine will be known.

Chapter 2

Methodology

2.1 Proposed Technical Approach

The objective of this research was to develop a Coal Quality Management Model for Dome Storage (DS-CQMM) in surface coal mining. Development of the DS-CQMM included a variety of methods applied in information technology, mathematical modeling, and computer programming.

The proposed technical approach for the development of the DS-CQMM is based on the technological process designed at a surface coal mine operated by one of the largest United States coal companies. Figure 1 shows the basic concept of the system and the flow of the coal from the dumping point to the dome. The system consists of a hopper, crusher, coal analyzer, conveyor belt system, transfer towers, dome storage, stacker, reclaimer, and emergency reclaimer.

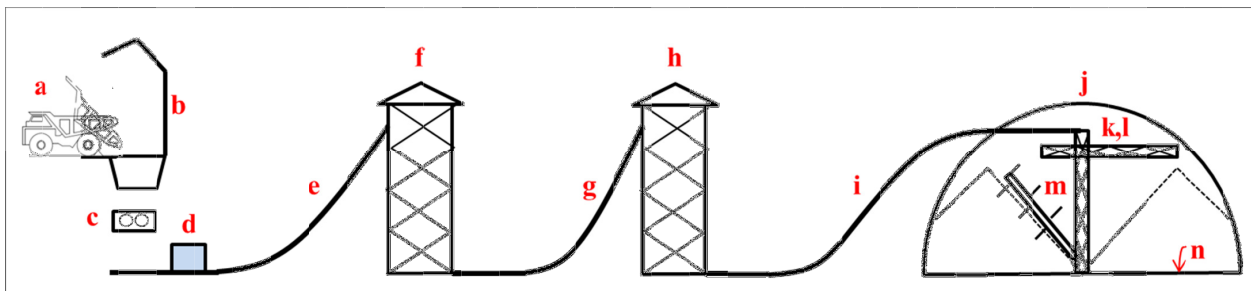


Figure 1. System's description: (a) truck, (b) hopper, (c) crusher, (d) coal analyzer, (e) belt conveyor 1, (f) transfer tower 1, (g) belt conveyor 2, (h) transfer tower 2, (i) belt conveyor 3, (j) dome, (k) stacker, (l) stacker's belt conveyor, (m) reclaimer, (n) emergency reclaimer

Truck (a) dumps the coal through the hopper (b) into the crusher (c). Crushed coal is transported by the belt conveyor 1 (e) to the transfer tower 1 (f) and belt conveyor 2 (g) and then to transfer tower 2 (h), which is designed to direct coal to either emergency stockpile, power plant silos, or dome (j). The process at the transfer towers is conducted by the actuation of fast acting proportional flop gates located on the towers. Coal quality and timestamps are recorded by the coal analyzer (d), which is located above the belt conveyor 1 (e). The coal flow directed to the dome (j) by the belt conveyor 3 (i) is delivered to the stacker (k). The boom of the stacker (k) rotates and steers the coal to its final location through a built-in belt conveyor (l). Finally, the coal is retrieved by the reclaimer (m) and transported outside the dome to the silos located at the power plant. In addition to the reclaimer (m), an emergency reclaimer (n) is installed at floor level in order to reclaim coal in case of the reclaimer's (m) failure or maintenance.

2.2 The Concept of DS-CQMM

Figure 2 shows the concept of the DS-CQMM that is developed through this research. This model is organized into four major sections: (i) Delay Time Application; (ii) Stacker Application; (iii) Reclaimer Application; and (iv) Live Stockpile Application. A sub-process called Volume Calculation is embedded in the Stacker Application, while an additional feature called Forecast Tool is included in the Reclaimer Application. All sections are related to each other in such a way that the data must be sequentially generated so that the DS-CQMM works properly in a specific coal mine.

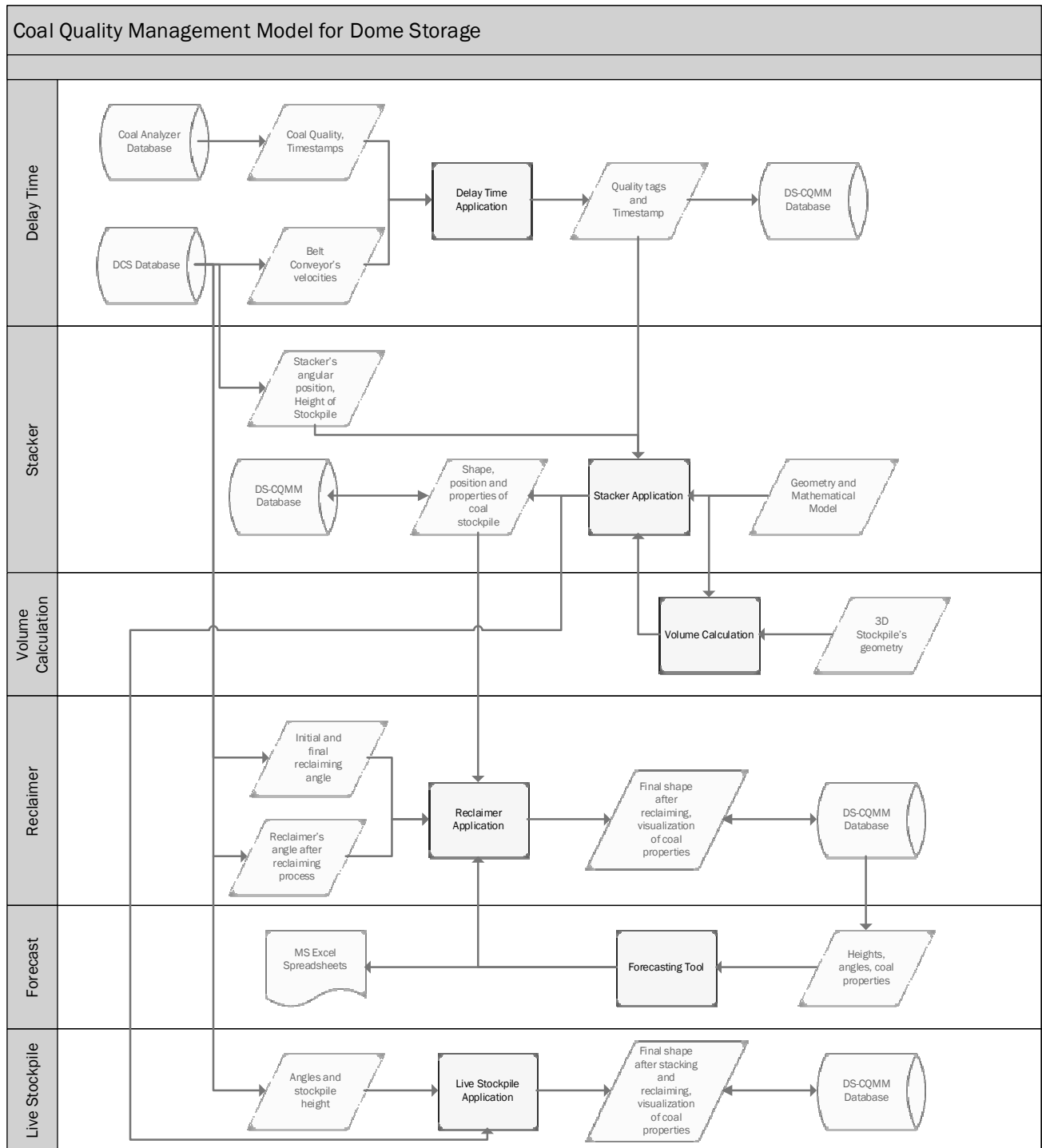


Figure 2. The Concept for Coal Quality Management Model for Dome Storage (DS-CQMM)

2.3 Database Structure

One of the most important components of the DS-CQMM is database synchronization. All Applications are designed to retrieve, parse, and store values from and into the three different Databases and their tables. These databases include: “Coal Analyzer” database, “DCS” database, and “DS-CQMM” database. Figure 3 shows the structure of these databases and their tables that are needed for a proper performance of the DS-CQMM.

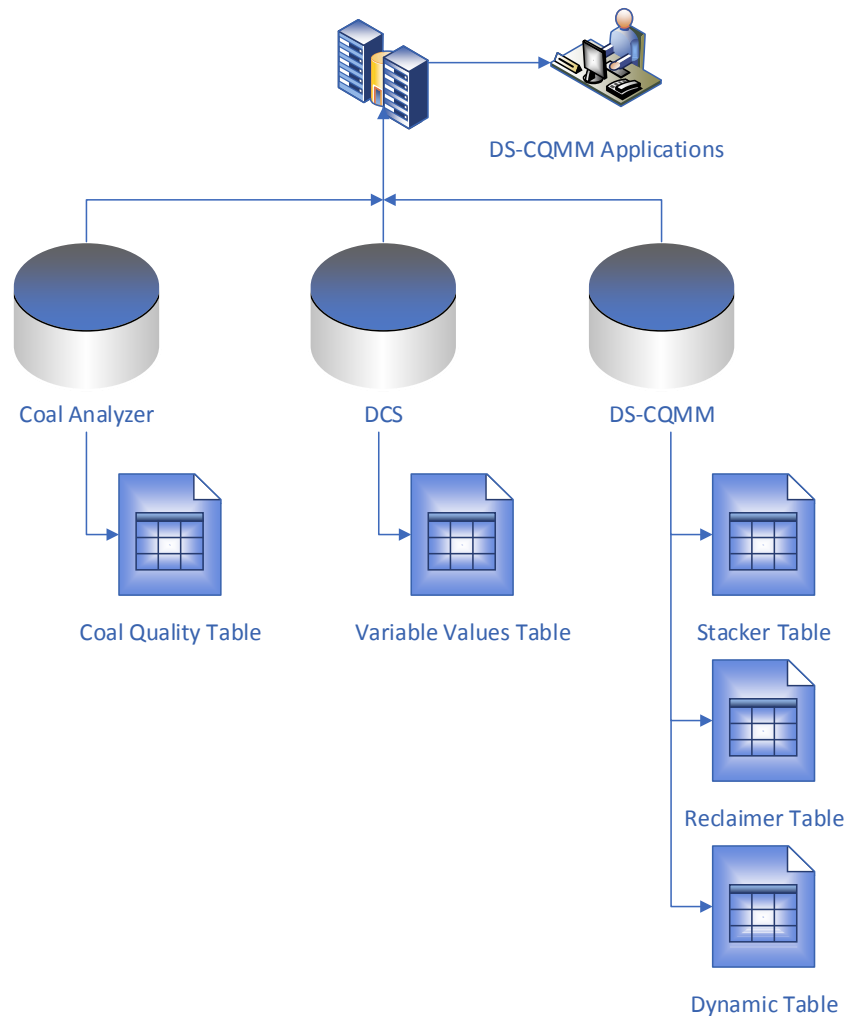


Figure 3. Database structure

2.3.1 Coal Analyzer Database

Data collection on coal quality is conducted by the Coal Analyzer, i.e., the Prompt Gamma Neutron Activation Analyzer (PGNAA). Data is stored once per minute into a *MySQL* database named “Coal Analyzer” database. The Applications retrieve the coal quality values from the “Coal Quality” table. The table structure and the data type of each column are shown in Table 1.

Table 1. Coal Quality table from Coal Analyzer database	
Column Name	Data Type
ID	Int
Timestamp	Date
Tonnage	Double
Moisture	Double
Ash	Double
Sulfur	Double
BTU	Double
SO2	Double

The data is queried once per minute by the Delay Time Application, Stacker Application, and Live Stockpile Application. The DS-CQMM has “read-only” permissions for this table.

2.3.2 DCS Database

The Distributed Control System (DCS) stores values such as belt conveyors velocities, stacker angular position, reclaimer angular position, etc. into a *Microsoft SQL Server* database named “DCS”. These values are required to be updated more than once per minute. These values are

usually obtained by different sensor measurements and gathered by Programming Logic Controllers (PLC). The columns and their data type are given in Table 2.

Table 2. Variable Values table from DCS database	
Column Name	Data Type
ID	Int
Timestamp	Date
Belt Conveyor 1 velocity	Double
Belt Conveyor 2 velocity	Double
Belt Conveyor 3 velocity	Double
Stacker Belt Conveyor velocity	Double
Stacker angular position	Int
Reclaimer angular position	Int
Reclaimer elevation angle	Int
Stockpile's height	Double
Live Stockpile's height	Double

The data queried from this table is used by Delay Time Application, Stacker Application, Reclaimer Application, and Live Stockpile Application. The DS-CQMM has “read-only” permissions for this table.

2.3.3 DS-CQMM Database

The DS-CQMM works with its own database for storing and retrieving data generated by the Applications. This *Microsoft SQL Server* database is named “DS-CQMM” after Dome Storage –

Coal Quality Management Model. There are three tables in this database: “Stacker,” “Reclaimer,” and “Dynamic.”

The “Stacker” and “Reclaimer” tables are used for historical purposes; the Applications only store (write) values into these tables. Every time a stacking process is performed, the Stacker Application and Live Stockpile Application store values into the “Stacker” table along with an ID and a timestamp generated by the database. The same concept is applied for the reclaiming process: the Reclaimer Application and Live Stockpile Application store (write) values into the “Reclaimer” table, along with an ID and a timestamp.

The “Dynamic” table is used for storing and retrieving the actual content of the dome’s stockpile. The Stacker Application, Reclaimer Application, and Live Stockpile Application store and retrieve data constantly as long as the shape of the stockpile changes. The DS-CQMM stores values into the “Stacker” and the “Dynamic” tables when the coal is stacked into the Dome. On the other hand, while coal is reclaimed from the Dome, its data is stored into the “Reclaimer” table and deleted from the “Dynamic” table in order to hold data of the actual coal inside the Dome. The structure and data type of all three tables are similar, and they are shown in Table 3.

Table 3. Structure of Stacker, Reclaimer and Dynamic tables in DS-CQMM database

Column Name	Data Type
ID	Int
Timestamp	Date
Horizontal Angle (θ_i)	Int
Height (z_i)	Double
Radius (ρ_i)	Double
Tonnage	Double
Ash	Double
BTU	Double
Moisture	Double
Sulfur	Double

Each block of coal stacked or reclaimed inside the dome has its own entry in the DS-CQMM database, which means that the block is associated with its unique position in the dome (ρ_i, θ_i, z_i), its properties (Ash, BTU, Moisture, and Sulfur), and its tonnage.

The Applications retrieve and store data from and into the databases. No data is stored into the Applications' local memory or local hard disks. This helps enhance the portability of the DS-CQMM in such a way that if the Applications need to be reinstalled on the same computer or installed on a different one, that can be performed without losing any data.

2.4 Delay Time Application

Coal has to be transported several thousand feet between the coal analyzer (starting point of the system) and the final point inside the dome. The coal analyzer provides the instantaneous quality of the current batch of coal that is passing under the detector at the beginning of the first belt conveyor. Therefore, it is necessary to know, for each batch, what its quality tags and timestamp are, and when will it reach the boom of the stacker – in order to assign the angular position of the boom and the quality tags.

Mine operators can set and change the velocities of each belt conveyor, and this is achieved by the Variable Frequency Drives (VFD). After setting or changing the velocities, the DCS will retrieve the values from the Programming Logic Controllers (PLC) and store them along with a timestamp into the DCS database.

By accessing the DCS database, belt conveyors' velocities can be queried every second or less to compare them with previous values and observe whether the belt conveyor has changed its velocity or not. Along with this information, querying the Coal Analyzer database, and the absolute time from the DCS database clock, one is able to program a routine that calculates the coal delay time.

For example, if one supposes that there is only one batch of coal being transported from the coal analyzer to dome; its trajectory can be analyzed along the belt conveyor system, the two towers, and finally the boom of the stacker. First, the coal is analyzed by the PGNAAs at the beginning of

the conveyor system. Then, it is carried by the belt conveyor 1 and, depending on its velocity, it takes a certain time to travel along this conveyor. After that, it passes through the transfer tower 1 and it is directed towards belt conveyor 2. This process takes a fixed time. Then, it is carried through belt conveyor 2, transfer tower 2, and belt conveyor 3, repeating the described process.

When the coal reaches the dome, it takes a certain time to be transferred to the stacker from belt conveyor 3. This can be considered as a delay time similar to the transfer tower's delay time. Finally, the stacker's belt conveyor meets the same criteria as the other belt conveyors. Once the batch of coal has reached the boom of the stacker, it is ready to be stacked inside the dome. This process is represented in the state diagram in Figure 4.

There is a singularity in the first state (which is the state that corresponds to belt conveyor 1) that is caused by a critical factor such as the process of retrieving coal quality information. At the beginning of the process, quality tags must be "attached" to the batch of coal during the transportation through the conveyor system. In this way, a query to the Coal Analyzer database is performed and stored into local memory during the eight states. At the end of the last state (i.e., when the coal reaches the boom of the stacker and it is ready to be stacked inside the dome), the process will pass the quality information with the timestamp to the next Application for further analysis and database storage.

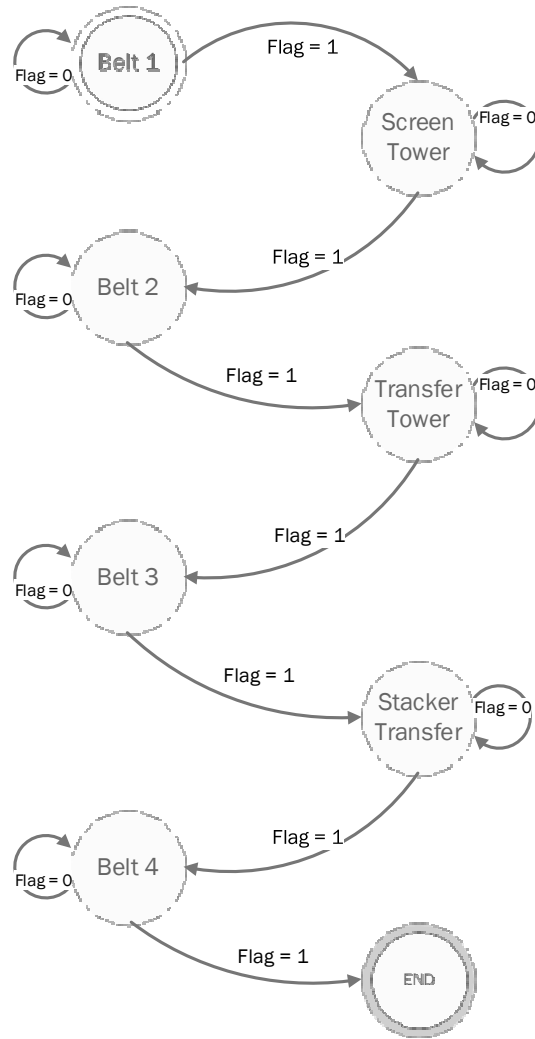


Figure 4. State diagram for delay time calculation

In order to assign quality tags to each batch of coal, they must be “attached” while being transported through the conveyor system and transfer towers. Since this action involves various states, the state diagram shown in Figure 4 is implemented as a state machine that begins on belt conveyor 1 (Start State) and goes to the next state whenever the transition condition is satisfied; otherwise, the system remains in the same state. This condition is shown as “Flag” in Figure 4.

The behavior of the system depends on the coal’s state. If it is being transported by any of the belt conveyors, or if it is being transferred to the next belt by the transfer towers, it has a

different behavior. The difference between these two performances is divided into two sections: belt conveyors states and transfer towers states.

The belt conveyor's state detects any change in the velocities of the belt conveyors in order to recalculate the total delay time that the batch of coal has in that particular belt. In order to satisfy the condition (i.e. $\text{Flag} = 1$), the process checks if the real-time clock has reached the calculated delay time. In that case, the transition takes place and the system moves on to the next state; otherwise the condition remains unsatisfied (i.e. $\text{Flag} = 0$) and the system remains in the same state. In this regard, a function is called every time the timer reaches an interval previously programmed (Δt). This interval should be smaller than 1 second (e.g. 0.5s or 0.1s). The flowchart for this function is shown in Figure 5. The function has the following inputs: actual belt conveyor's velocity (V_k); previous belt conveyor's velocity (V_{k-1}); actual total delay time (D_k); previous total delay time (D_{k-1}); length of the belt conveyor (L_i); summation of previous delay times of previous stages ($\sum_t D_i$); and real-time clock (t).

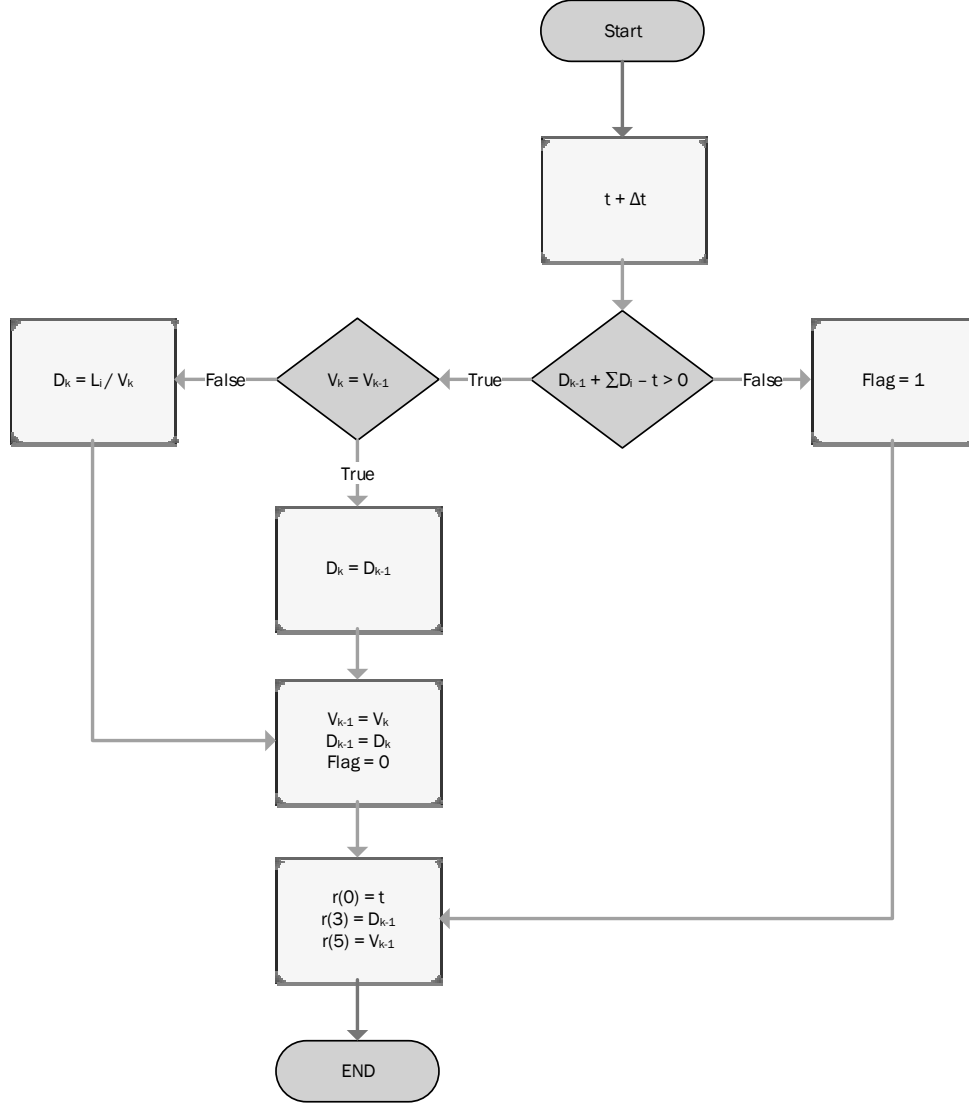


Figure 5. Belt conveyor's delay time calculation flowchart

After initialization, the function checks to determine if the previous delay time calculated for belt conveyor “i” (where i = 1, 2, 3, 4) plus the summation of previous states’ delay times minus current real-time is greater than zero:

$$D_{k-1} + \sum_{t^-} D_i - t > 0$$

This value provides the status of the coal at the current belt conveyor, indicating that if it is greater than zero, then the coal continues its stay on that particular belt; otherwise (i.e. if the

value is equal or smaller than zero), the coal has passed to the next state and the condition for transition is satisfied (i.e. Flag = 1).

Once the delay time has been checked and the coal is still on the belt (i.e. $D_{k-1} + \sum_t D_i - t > 0$) the program checks to see if the belt conveyor's velocity has changed by comparing the velocity retrieved from the DCS database (that was previously obtained from the PLCs) and the previous-instant velocity. In case that the velocity has changed (whether greater or smaller), the program recalculates the new delay time using the following equation:

$$D_k = \frac{L_i}{V_k} \quad (1)$$

where k represents the current instant of time; D_k is the new delay time; L_i is the current belt conveyor's length; and V_k is the new belt conveyor's velocity.

If the velocity has not changed, then the delay time remains the same as the previous instant (i.e. $D_k = D_{k-1}$). Finally, the variables are updated and the condition for transition is not satisfied because the coal is still on the belt (i.e. Flag = 0).

The function's output is an array that provides the input for the function on the next iteration. The array content is: current real-time; status of the transition condition (Flag); actual delay time (that is used as previous delay time in the next period of time); and actual belt conveyor's velocity (that is used as previous velocity in the next period of time).

If the batch of coal is on a transfer tower, then another function is called for calculating the delay time during this transition. A flowchart of this algorithm is shown in Figure 6.

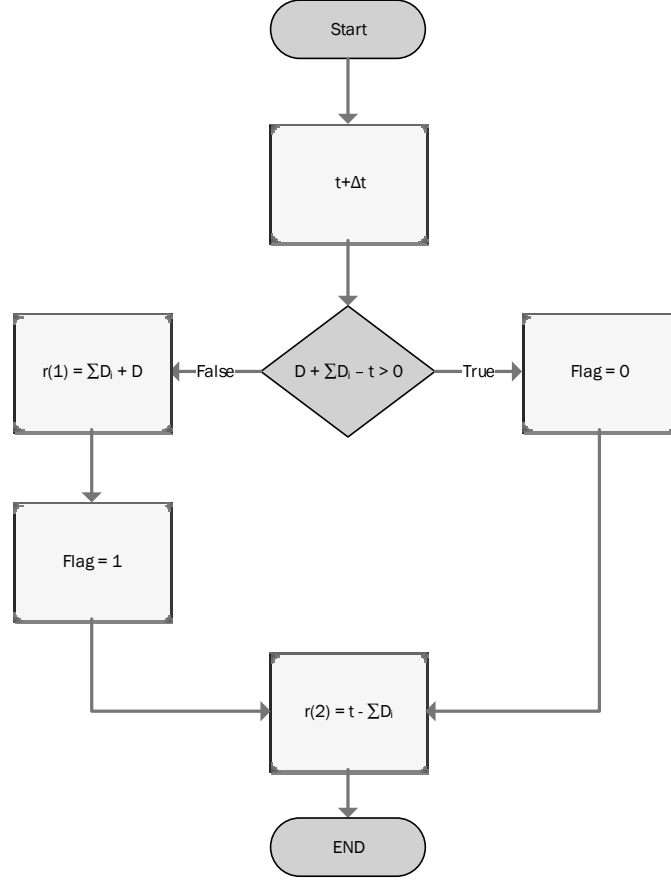


Figure 6. Transfer towers' delay time calculation flowchart.

The function is triggered every time the timer reaches an interval previously programmed (Δt). Then, the process checks to see if the delay time (that will remain constant because the towers do not have time-based variation elements unlike belt conveyors) plus the summation of the delay times of the previous states (belts conveyors or towers) minus the current real-time is greater than zero:

$$D_{k-1} + \sum_{t^-} D_i - t > 0$$

If this value is positive, it means that the coal is still in the tower and the transition condition is not satisfied (i.e. Flag = 0); otherwise, the transition is fired (Flag = 1) and the state passes to the next.

The inputs for this function are: real-time clock (t); summation of previous delay times of previous stages ($\sum_{t-} D_i$); and delay time expected on the tower (D).

When the timer calls the function (i.e. reaches Δt), the process checks whether the delay time expected on the tower is up by evaluating the condition (i.e. $D_{k-1} + \sum_{t-} D_i - t > 0$). If the coal is still on the tower, then this condition is true and the transition condition is not satisfied (Flag = 0). Additionally, the output array contains the current time of the coal on the tower. Otherwise (if the condition is false), then it means that the coal has passed the tower and it is in the next state. This generates an element in the output array that contains the total delay time. The output array content is: current real-time; status of the transition condition (Flag); and total delay time.

2.4.1 Graphical User Interface (GUI) and Simulation of Delay Time Application

Various simulations were performed in order to test and debug the algorithms and functions. The GUI is implemented with the State Machine and emulates a real-time clock. Variations on the belt conveyors' velocities are also implemented as scroll bars in such a way that the whole system can be tested in different situations.

Figure 7 shows the GUI of the Delay Time Application where belt conveyors 1, 2, 3, and 4 (a – d) are shown. Transfer tower 1 and 2 (e, f) are shown along with the stacker's transfer device (g). The calculated delay time is shown for each belt conveyor (h) and the current time of the coal in the belt conveyor (i). The current total delay time is shown by (j). The quality tags “attached” to

each batch of coal are shown in the display window (k). Finally, two buttons are implemented to start running the program (m) and to close database connections and exit the Delay Time Application (n).

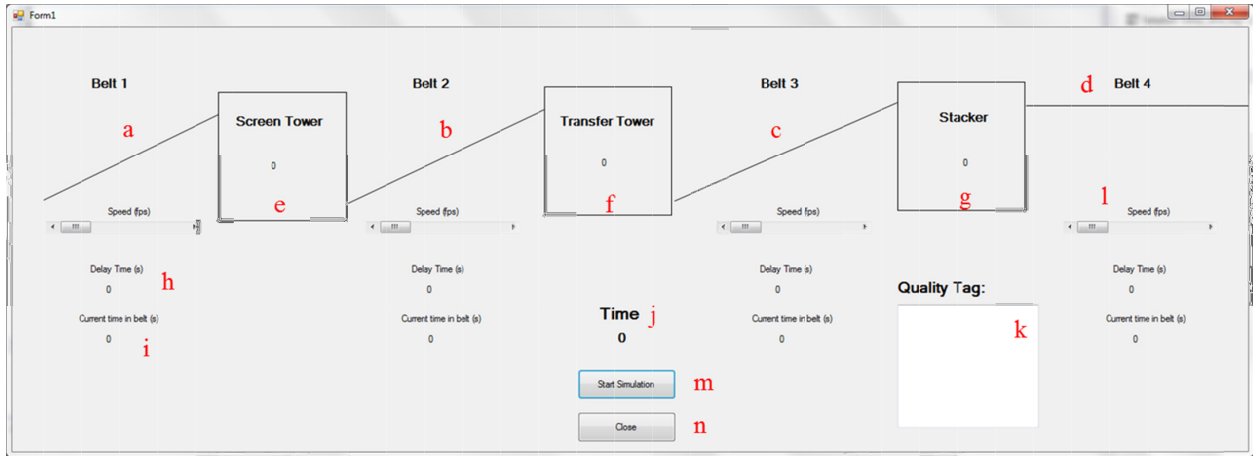


Figure 7. Graphical User Interface of Delay Time Application: (a) belt conveyor 1, (b) belt conveyor 2, (c) belt conveyor 3, (d) belt conveyor 4, (e) transfer tower 1, (f) transfer tower 2, (g) stacker's transfer tower, (h) delay time calculated at the belt conveyor, (i) current time in belt conveyor, (j) total time of the batch of coal in conveyor system and towers, (k) coal quality data associated to the batch of coal, (l) scroll bar for changing belt conveyor's velocity, (m) "Start Simulation" button, (n) "Close" button.

2.5 Stacker Application

Mine operators need to know and visualize actual quantity (volume and tonnage), location, and properties (BTU, moisture, ash, and sulfur) of stacked coal inside the dome.

In order to accomplish this task, the first step is to determine the angular position of the boom of the stacker inside the dome. This enables the assignment of a relative position to the coal along with its particular properties inside the dome. For this purpose, absolute rotary encoders record the angular position of the boom of the stacker into the DCS database through the PLCs. This is

then retrieved by the Stacker Application in order to build the virtual stockpile. Another important piece of information is the height of the stockpile, which is measured by an ultrasonic sensor located at the boom of the stacker. This value is stored into the DCS database.

2.5.1 Mathematical Model of the Stacker Application

The geometry of the dome and coal stockpile is designed by using trigonometry equations. Discretization is conducted by a three-dimensional method. In order to accomplish this, it is necessary to select one of the three most common coordinate systems, as shown in Figure 8.: Cartesian (a), Cylindrical (b), or Spherical (c).

Analyzing the inputs of the DS-CQMM, the following parameters should be considered: rotational angle of the stacker; rotational and elevation angle of the reclaimer; and height of the stockpile.

There are three angles used as inputs; therefore, the coordinate system must have an angular axis. For this reason, the Cartesian System (also known as Rectangular System) is discarded, as its three references (X, Y, Z) are perpendicular between them, making the analysis more difficult.

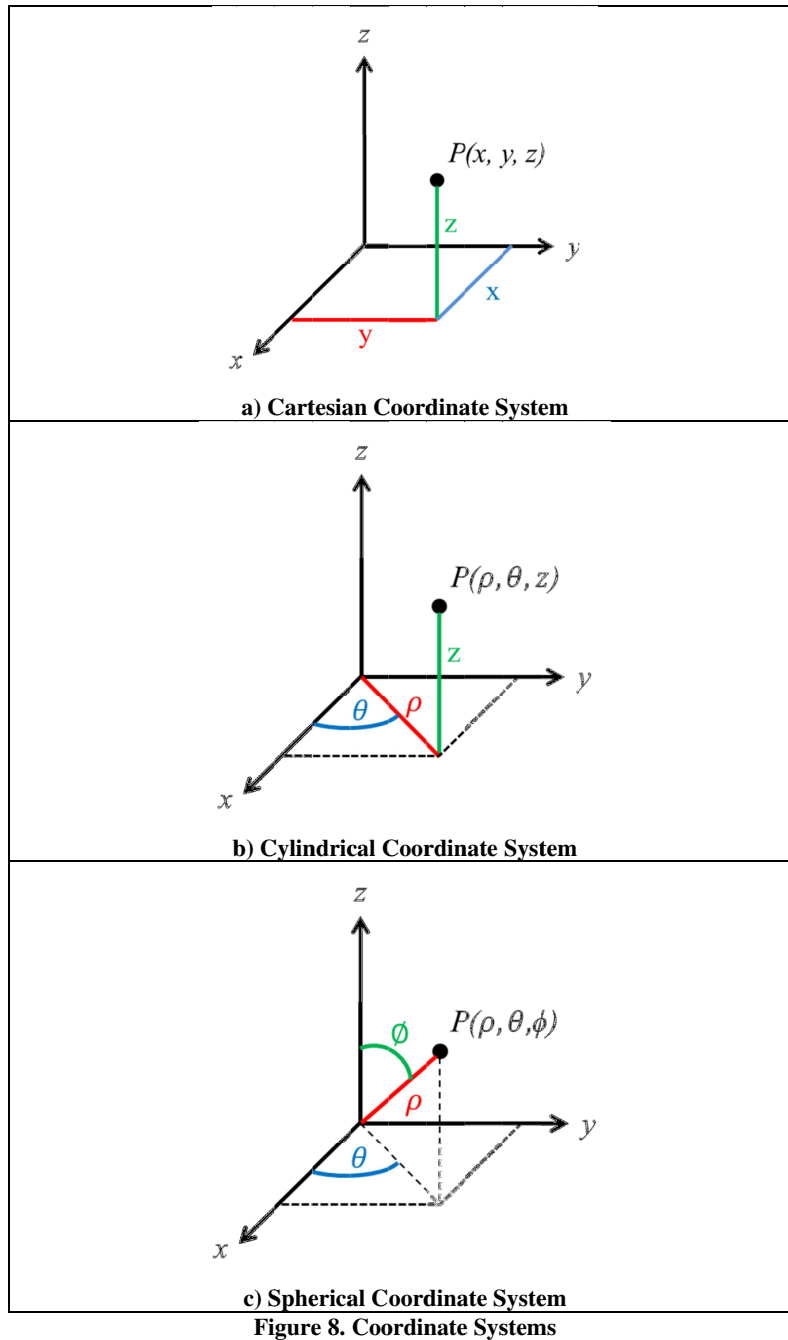


Figure 8. Coordinate Systems

The Spherical Coordinate System is an appropriate option because of the two axes related to angle measurements: polar and azimuthal. However, the Cylindrical Coordinate System is more suitable for this case because both the rotational angle of the stacker and the rotational angle of

the reclaimer can be associated to the polar axis, and the stockpile's height to the longitudinal axis.

A dome has the shape of an upper hemisphere (Figure 9). This *ad hoc* model considers the ground as reference plane and the center of the base circumference as the origin of the Coordinate System. For the purpose of this research, and based on the data from the specific surface coal mine, the following dimensions are adopted: the diameter of the dome is 311 ft. and the maximum height that the coal stockpile can reach is 85 ft.

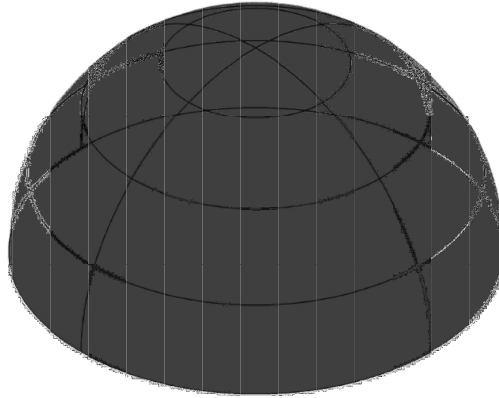


Figure 9. Geometrical shape of dome storage

Discretization of the dome is performed using the Cylindrical System, as follows:

a) Polar axis (θ)

The Dome is divided into 360 equal parts, each one corresponding to 1 degree on the angular coordinate. This is performed in order to retrieve the rotational angle of the boom of the stacker and the rotational angle of the reclaimer from the DCS database with a resolution given by the PLCs of 1 degree. Figure 10 shows the discretization on this axis with 1 division every 10

degrees for clarity's purpose and not 1 division per 1 degree as happens in the original discretization.

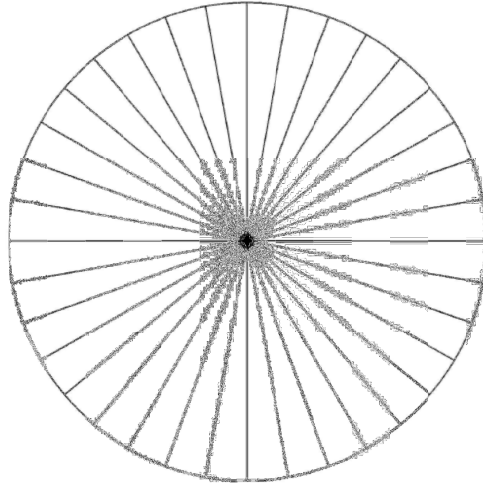


Figure 10. Dome's angular discretization (top view)

b) Radial axis (ρ)

The dome is also divided on the radial coordinate, forming concentric circumferences with 1 ft. of radius-length difference. The discretization on this axis provides the third dimension. Figure 11 illustrates how discretization is performed with a rate of 1 division every 10 ft. (and not 1 division every 1 ft.).

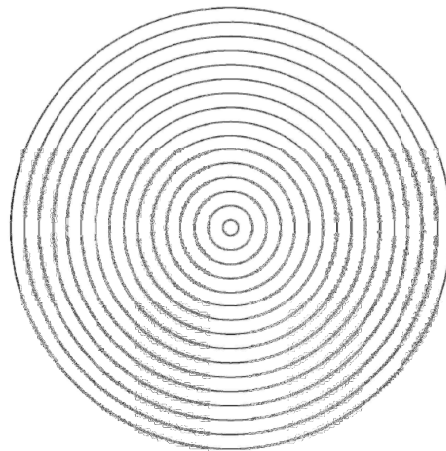


Figure 11. Dome's radial discretization (top view)

c) Longitudinal axis (z)

The dome is divided on the longitudinal axis on 90 equal parts with 1 ft. of distance. Since the maximum height of the coal stockpile is 85 ft., there is no need to extend the division further than 90 ft. Figure 12 shows how this task is performed with a rate of 1 division per 10 ft. (and not 1 division per 1 ft.).

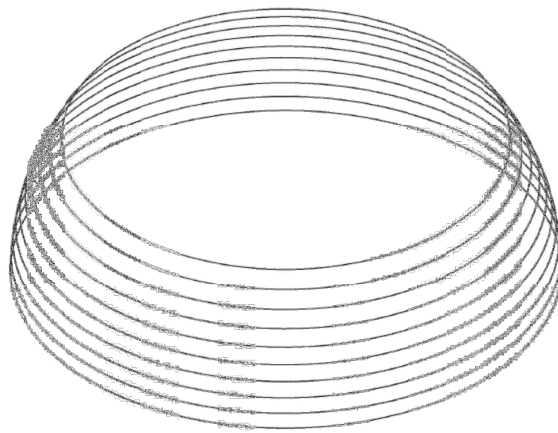


Figure 12. Dome's longitudinal discretization (isometric view)

Graphics in Figure 10 to Figure 12 are intended to illustrate how the discretization is performed for the mathematical model and algorithm implementation, and not to show the exact number of divisions; otherwise, the graphics would be chaotic and provide little or no substantial information. In Figure 13 the dome is divided in four quadrants in order to explain the combination of the three axes. On the fourth quadrant, the discretization is shown separately and repeated in one plane, although the sequence of discretization of each axis is repeated in its perpendicular planes, producing a rotational symmetry about the z axis in every plane where $z = \text{constant}$. The shape of the dome is built by decreasing the length of the radius as the height increases on the z axis, following the hemisphere shape.

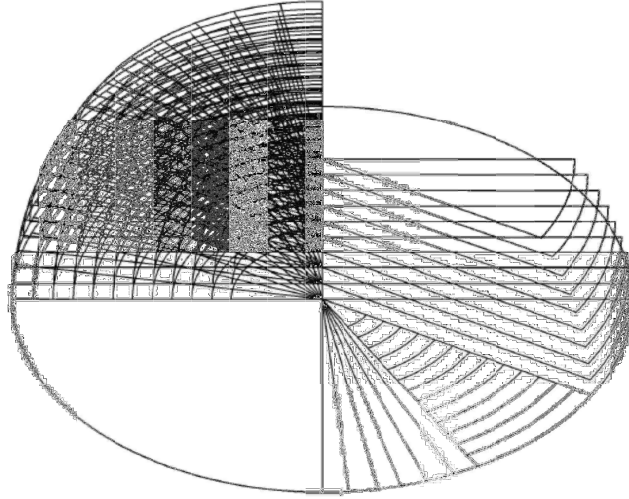


Figure 13. Dome's discretization

With the discretization of the dome, it is possible to build a model for the coal stockpile using mathematical concepts. There are three key inputs for the mathematical model: stockpile's height (z_0); angular position of the stacker (θ_0); and angle of repose of coal (α). As mentioned before, the stockpile's height is measured with an ultrasonic sensor located at the boom of the stacker and retrieved from the DCS database.

The model for the Stacker Application is built based on the following assumptions: (i) the stockpile's shape is approximately a pyramid shape; (ii) the analysis is performed in a plane that "cuts" the pyramid in half; and (iii) the analysis is conducted in a two-dimensional plane. These three assumptions simplify the mathematical modelling and make analysis feasible.

The first assumption is made because of the admissible approximation between the shape of the coal stockpile and the shape of the pyramid observed in perpendicular planes. The stockpile's peak is located at a given (and constant) distance from the center of the dome. Using this

information, the second assumption is made. Since the stockpile's height and stacker's angular position are key inputs of the DS-CQMM, the location of the stockpile's peak seems to be a reasonable main reference for the mathematical model and further Graphical User Interface (GUI). Therefore, the plane where the radius for the stockpile's peak is constant ($\rho = \rho_{peak} = \text{constant}$) is used for developing the model. The third assumption is an extension of the second. Given that the plane of study results in a cylinder shape, it can be “unfolded” and develop the mathematical model in a conventional plane with angle measurements in the abscissae and height measurements in the ordinates.

Additionally, the mathematical model needs a point as an absolute reference (origin). At that point, angles 0° and 360° concur, establishing a rotational symmetry (Figure 14).

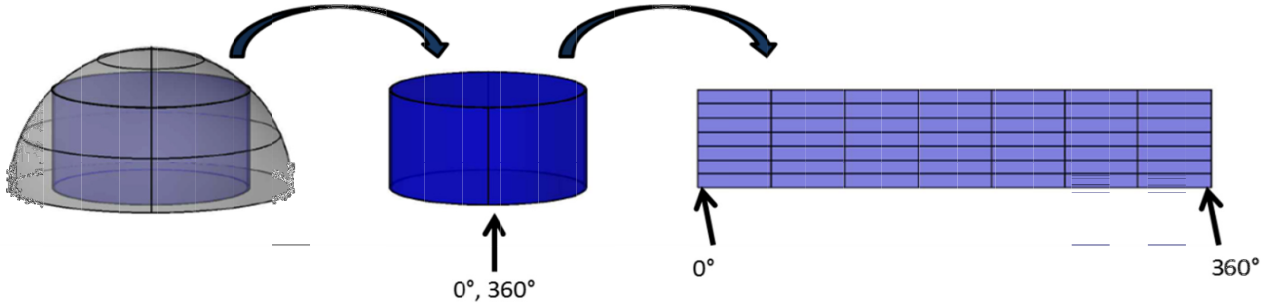


Figure 14. Dome's 2D implementation plane

With the stated assumptions, the mathematical model is created using the provided inputs (z_0 , θ_0 and α). The pyramid is now seen from θz plane and has the shape of a triangle with z_0 height and $\overline{\theta_1\theta_2}$ base as shown in Figure 15. This triangle is the representation of the coal stockpile of z_0 height and angle of repose α stacked at θ_0 . To fully determine the triangle, two unknowns should be determined: θ_1 and θ_2 .

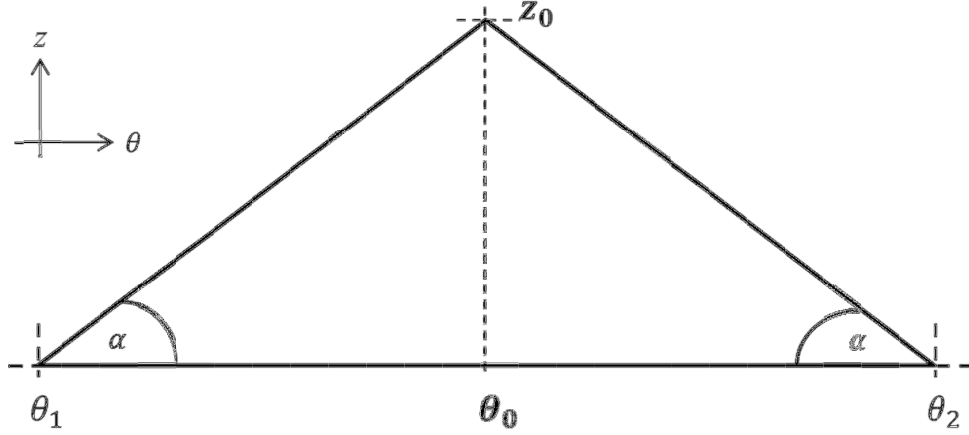


Figure 15. Analysis of triangle on θz plane

These unknowns can be expressed as:

$$\theta_1 = \theta_0 - \frac{z_0}{\tan \alpha} \cdot CF_2 \quad (2)$$

$$\theta_2 = \theta_0 + \frac{z_0}{\tan \alpha} \cdot CF_2 \quad (3)$$

where θ_1 is the starting point of the base; θ_2 is the final point of the base; θ_0 is the angular position of the Stacker; z_0 is the stockpile's height; α is the angle of repose of coal; and CF_2 is a conversion factor.

Equations (2) and (3) find the points that are needed in order to determine the triangle for the model. Since the axes of this particular plane are with different units, the units of the quantities should be converted in order to perform algebraic operations.

The length of an arc is given by:

$$s = \phi \cdot r$$

where s is the arc length; ϕ is the measured angle; and r is the radius of curvature.

One can take $\emptyset = 1^\circ$ and $r = \rho_{peak}$ to obtain a constant value:

$$s_{peak} = 1^\circ \cdot \frac{\pi}{180^\circ} \cdot \rho_{peak}$$

$$CF_1 = \frac{\pi}{180} \cdot \rho_{peak} \quad (4)$$

where ρ_{peak} is the stockpile's peak radius, and CF_1 is a constant with units in $[ft/^\circ]$ (i.e. feet per degree).

Using the CF_1 , one can calculate CF_2 in $[^\circ/ft]$ as

$$CF_2 = \frac{1}{CF_1} \quad (5)$$

2.5.2 Stockpile's Volume Calculation

Since the dome is discretized in three dimensions and the first assumption for the mathematical model let us build the stockpile as a pyramid, it is possible to calculate the volume based on geometrical shapes.

Recall that the divisions are performed on the three axis (ρ, θ, z) at given distances. A closer observation of the resulting unit division of the intersection of these three divisions lets us find the primary unit of volume, which is shown in Figure 16.

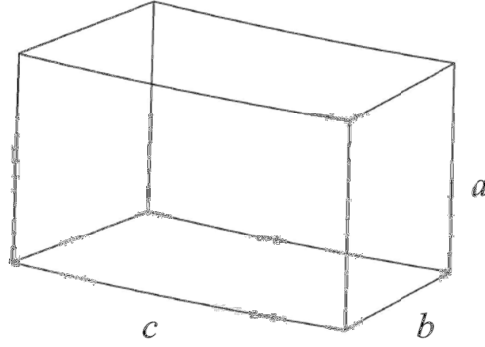


Figure 16. Volume prism

Sides a and b measurements are each 1 ft. in length. Side c has no linear shape because it depends on the position of the prism, being larger if it is located farther from the center of the dome. In other words, side c depends on the radius; therefore, there are two measurements of this side in each prism. For simplicity we take the average of the two measurements for further calculations, and c is calculated as follows:

$$c(\rho) = \frac{\pi}{180^\circ} \cdot \rho \quad (6)$$

where c is the variable side of the prism; and ρ is the radius variable.

The average between the two measurements of c for the same prism is calculated as:

$$\bar{c}(\rho) = \frac{\pi}{180^\circ} \left(\frac{\rho_1 + \rho_2}{2} \right) \quad (7)$$

where ρ_1 is the radius at position 1; ρ_2 is the radius at position 2; c_1 is the variable side of the prism at radius ρ_1 ; c_2 is the variable side of the prism at radius ρ_2 ; and \bar{c} is the average value of the variable side of the prism.

Finally, the volume of the prism is calculated as:

$$V(\rho) = a \cdot b \cdot \bar{c}(\rho) \quad (8)$$

where V is the volume of the prism; a is a fixed-length side of the prism; and b is a fixed-length side of the prism.

This calculation of volume of coal is measured in ft^3 , therefore the tonnage can be calculated as:

$$T = \frac{V \cdot \delta_{coal}}{2000} \quad (9)$$

where T is the tonnage of coal, and δ_{coal} is the coal density in lb/ft^3 .

2.5.3 Stacker Application algorithm

The mathematical model of the dome uses the same assumptions and equations stated in previous sections.

Figure 17 shows interactions between the Stacker Application and databases. First, the shape of the actual stockpile is plotted on the screen by querying the DS-CQMM database so the mine operator can know the actual shape of the coal stockpile inside the dome. Simultaneously, the screen shows an update of the remaining time of the next batch of coal along with its quality tags that will arrive to the boom of the stacker. This enables the operator to rotate the boom of the stacker to a specific location of the dome. This is achieved by using the Delay Time Application that queries the Coal Analyzer database.

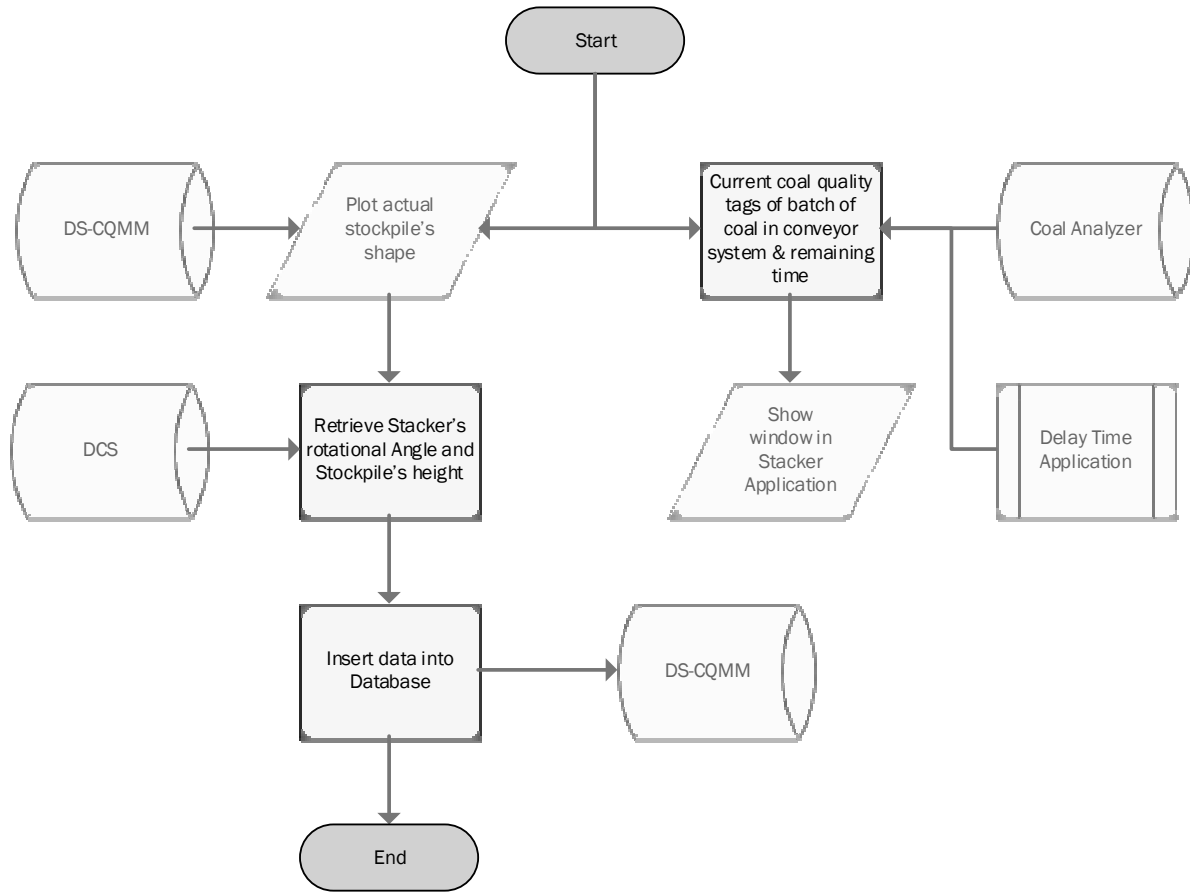


Figure 17. Stacker Algorithm

The Stacker Application retrieves the angle of the boom of the stacker from the DCS database along with the height of the stockpile measured after the stacking process. The rotational angle and the stockpile's height are the key inputs for this algorithm. After retrieving them, the Stacker Application calculates and generates data that is finally stored into the Stacker and Dynamic tables in DS-CQMM database.

The stockpile's shape is plotted point by point in a plane that follows the criteria explained in Figure 14 where a plane (θz) is extracted from the dome at a constant radius. The points plotted on this plane satisfy the unit-consistency established for equations (2) and (3). In order to show just the shape of the stockpile, the model needs the top layer of the stockpile, in other words the

maximum height of stacked coal. This information is retrieved from Dynamic table in DS-CQMM database for every angle of the θ axis incremented by 1° each iteration (Figure 18). Finally, the program plots the points on the screen.

Now that the stockpile's shape is shown to the operator, the Stacker Application is ready to generate the data of the stockpile that will be stored inside the dome. For each batch of coal the program retrieves the angular position of the boom of the stacker and the actual height of the stockpile (θ_0, z_0) from the DCS database, and the quality tags from the Delay Time Application.

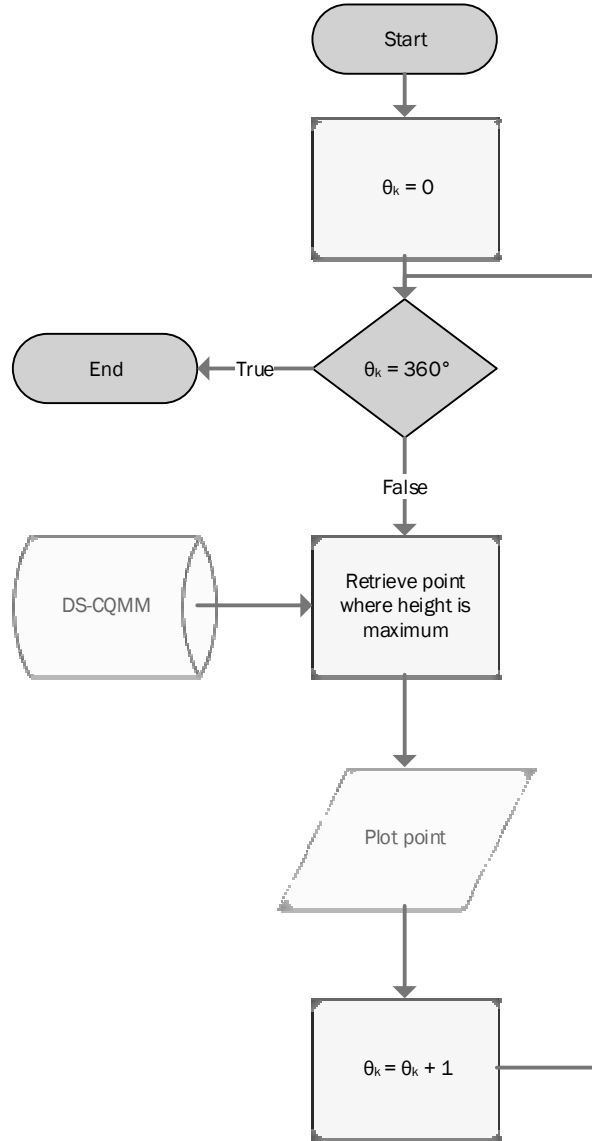


Figure 18. Stockpile's shape plotting flowchart in Stacker Algorithm

Using this information, the algorithm calculates θ_1 and θ_2 with equations (2) and (3); calculates the volume and tonnage for that given batch; and provides the circular continuity of the mathematical model. The circular continuity is accomplished by checking that θ_1 and θ_2 are contained within the circumferential angular range (i.e. $0^\circ \leq \theta_1, \theta_2 \leq 360^\circ$). The algorithm considers three possible scenarios as shown in Figure 19.

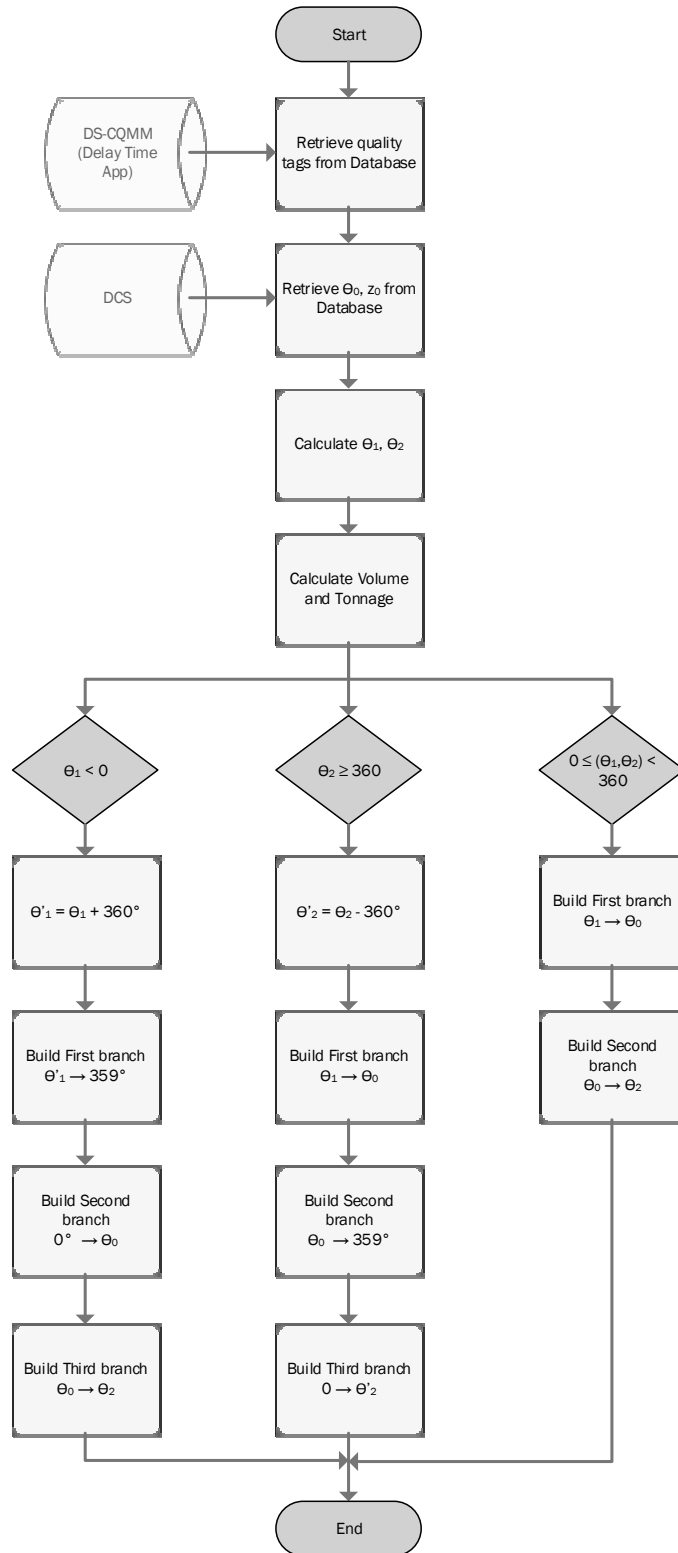


Figure 19. Generation of stockpile's data flowchart in Stacker Application

1. If θ_1 is a negative angle, the algorithm corrects and assigns a new angle contained in the 360° range:

$$\theta'_1 = \theta_1 + 360^\circ \quad (10)$$

where θ'_1 is the corrected angle for θ_1

The first branch of the triangle is built from θ'_1 to 359° ; the second branch is built from 0° to θ_0 ; and the third branch from θ_0 to θ_2 .

2. If θ_2 is greater than 360° , the algorithm corrects and assigns a new angle within the allowed range:

$$\theta'_2 = \theta_2 - 360^\circ \quad (11)$$

where θ'_2 is the corrected angle for θ_2

In this case the first branch of the triangle is built from angle θ_1 to θ_0 ; the second branch is built from θ_0 to 359° ; and the third branch from 0° to θ'_2 .

3. If angles θ_1 and θ_2 are contained within 0° to 360° range, then no correction is needed and therefore only two branches of the triangle are built. The first branch is built from θ_1 to θ_0 ; and the second is built from θ_0 to θ_2 .

The triangle branches are built following the flowchart in Figure 20. The program calculates the height z_k for each angle θ_k contained within θ_1 and θ_2 keeping a triangular shape determined by z_0 . Figure 21 shows an outline of the triangle defined by stockpile's peak height (z_0), angular position of the boom of the stacker (θ_0), and angle of repose of coal (α). Angles θ_1 and θ_2 are shown as well.

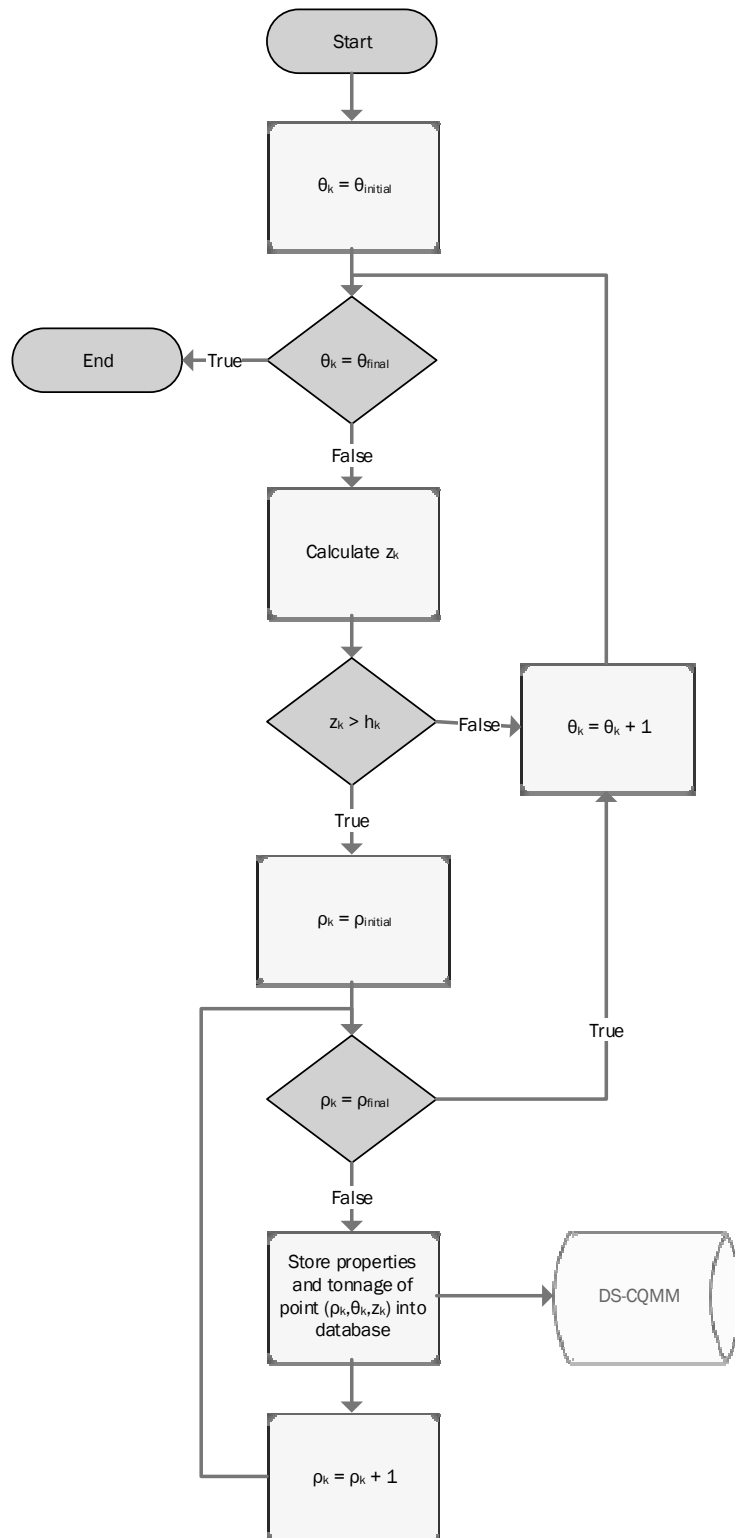


Figure 20. Branch building flowchart on Stacker Application

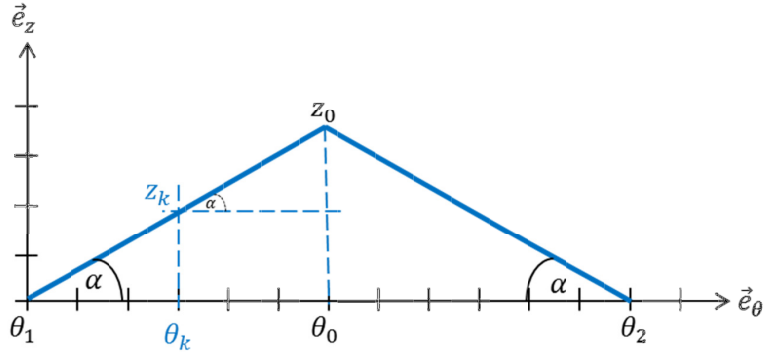


Figure 21. Calculation of height z_k at angle θ_k

For the analysis and further calculation for each angle's height, a change of coordinates is performed. The new coordinate system is parallel to the original system, that is:

$$\vec{e}_\theta || \theta \text{ and } \vec{e}_z || z \quad (12)$$

The difference between both coordinate systems is that the origin is transferred to the starting point of the base of the triangle as shown in Figure 22.

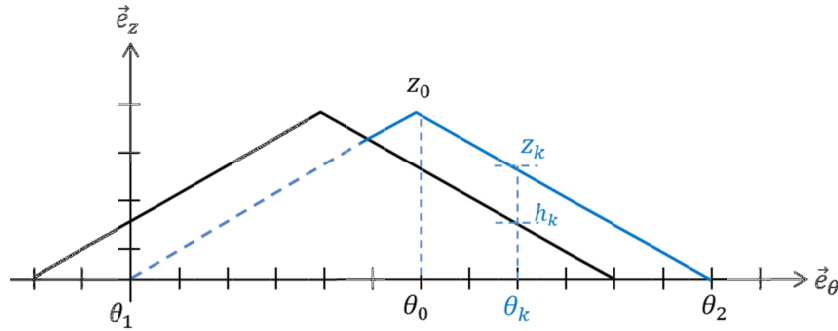


Figure 22. Maximum and existing height for a given angle

As it was pointed out, z_k is the height of a given angle θ_k . The angle θ_k matches with the angular divisions of the dome. By analyzing triangle $\angle O z_0 \theta_0$ the following can be written:

$$\tan \alpha = \frac{z_0}{\theta_0}$$

Applying the *Similar Triangles Theorem*:

$$\frac{z_0}{\theta_0} = \frac{z_0 - z_k}{\theta_0 - \theta_k}$$

which itself is:

$$\tan \alpha = \frac{z_0 - z_k}{\theta_0 - \theta_k} \quad (13)$$

where θ_k is a generic point on θ axis; and z_k is a generic point on z axis.

Solving for z_k :

$$z_k = z_0 - (\theta_0 - \theta_k) \tan \alpha \cdot CF_1 \quad (14)$$

where CF_1 is the conversion factor obtained from (4) that provides unit consistency.

The formula for calculating each point of the rising branch of the triangle is shown in equation (14); but the model needs a general formula that determines the entire triangle. To obtain it, a symmetry axis is taken on $\overline{z_0\theta_0}$ segment of the triangle that allows calculating z_k based only on the variation of $\overline{\theta_k\theta_0}$ module. Therefore, a general formula that calculates z_k for the entire triangle by varying only θ_k is:

$$z_k = z_0 - |\theta_0 - \theta_k| \tan \alpha \cdot CF_1 \quad (15)$$

For each angle contained in the $[\theta_1, \theta_2]$ range, the algorithm verifies if the new height calculated with (15) is higher than the already stored in the Dynamic Table in DS-CQMM database. It is done by retrieving the maximum existing heights (h_k) stored and comparing them.

If z_k is greater than h_k , the Stacker Application assigns the quality tags and tonnage to each point from the existing height stored in the database (h_i) to the height calculated (z_k); otherwise continues to the next iteration as shown in Figure 20.

The justification for checking the heights is that the program cannot assign new properties to a point where coal has been already stored. Otherwise, the stockpile would grow above the existing coal. Figure 22 shows how the new stockpile stacked in angle θ_0 occupies the space determined for triangle with blue continuous line. The dashed line indicates the points where no new coal will be stacked. However, on the other branch the assignment is performed from h_k to z_k .

2.5.4 Volume Calculation Algorithm

Along with the quality tags, the Stacker Application algorithm assigns the corresponding tonnage to each block at angle θ_k within h_k and z_k . Since volume calculation is a three-dimensional problem, a solution given for dome's discretization stated in section 2.5.2 is considered. The Stacker Application algorithm is the base for this algorithm with some differences.

The most substantial contrast is that in this case a three-dimensional calculation is performed; thus an additional axis is needed. That axis corresponds to ρ coordinate.

The process starts by retrieving the DS-CQMM key inputs from DCS database: the angular position of the boom of the stacker (θ_0) and the stockpile's height (z_0). Then, it calculates the two first reference points: θ_{1v} and θ_{2v} . As explained in the Stacker Application section, trigonometric concepts are used for the development of the model and algorithms. Figure 23 shows the use of the plane where the radius is constant and coincides with the peak's radius ($\rho_{peak} = \text{constant}$).

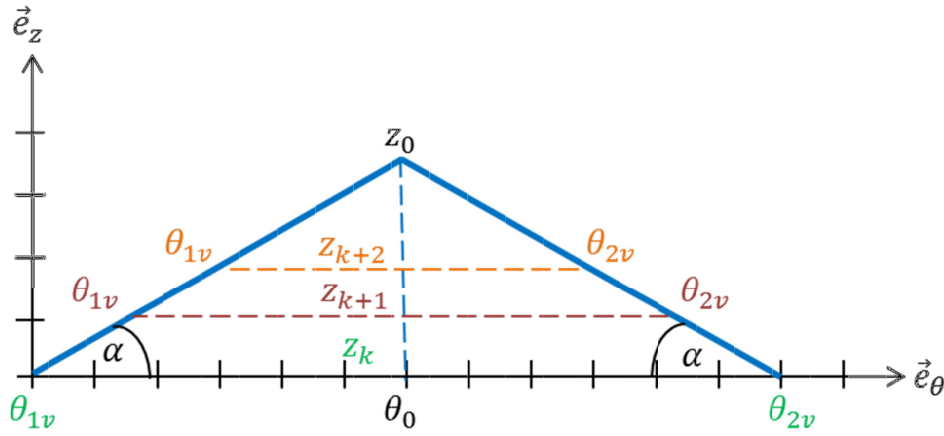


Figure 23. Sequential assignation of angles θ_{1v} and θ_{2v}

Following the same criteria for the deduction of equations (2) and (3), the reference points can be calculated as:

$$\theta_{1v} = \theta_0 - \frac{z_0 - z_k}{\tan \alpha} \cdot CF_2 \quad (16)$$

$$\theta_{2v} = \theta_0 + \frac{z_0 - z_k}{\tan \alpha} \cdot CF_2 \quad (17)$$

where θ_{1v} is the initial point of the base of the pyramid on θ axis; and θ_{2v} is the final point of the base of the pyramid on θ axis.

It is important to note that θ_{1v} and θ_{2v} decrease mutual distances when their height increases, following the shape of a triangle. Sequential assignation of angles θ_{1v} and θ_{2v} is performed for each z_k height.

For the third-dimensional measurements on ρ axis, the diagram shown in Figure 24 is used. The origin of the coordinate system ρz is placed at the center of the dome in order to locate the measurements for the calculation of the actual volume. Let (θ_k, z_k) be any given point on the triangle in Figure 23. For that point, the algorithm calculates the starting ρ_1 and ending ρ_2 point of the third dimension. Analyzing the triangle $\angle \rho_1 \rho_{peak} z_0$ the following can be written:

$$\tan \alpha = \frac{z_0 - z_k}{\rho_{peak} - \rho_1}$$

where ρ_1 is the initial point of the base of the pyramid on ρ axis. Solving for ρ_1 :

$$\rho_1 = \rho_{peak} - \frac{z_0 - z_k}{\tan \alpha} \quad (18)$$

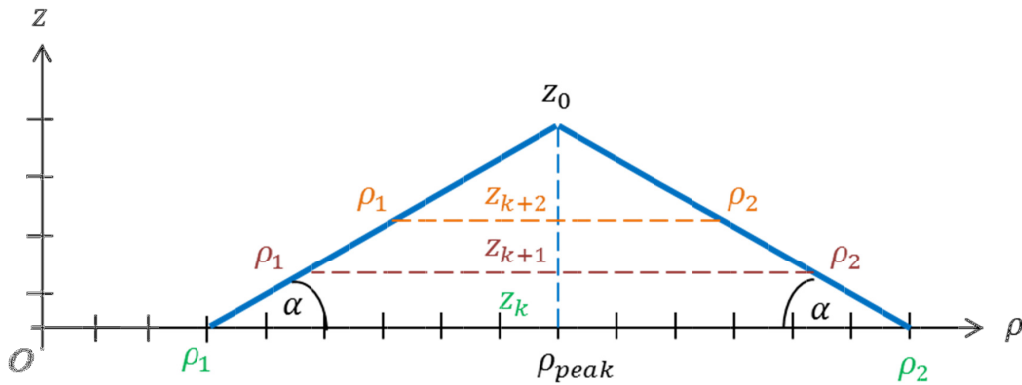


Figure 24. Sequential assignation of ρ_1 and ρ_2

Following the same concept, for triangle $\angle \rho_{peak} \rho_2 z_0$:

$$\tan \alpha = \frac{z_0 - z_k}{\rho_2 - \rho_{peak}}$$

where ρ_2 is the final point of the base of the pyramid on ρ axis. Solving for ρ_2 :

$$\rho_2 = \rho_{peak} + \frac{z_0 - z_k}{\tan \alpha} \quad (19)$$

There is a peculiar situation in the third dimension. The stockpile's peak is not located in the midpoint of the radius axis; therefore, when the stockpile reaches a given height, the triangle is not completed on one of its vertex due to physical restrictions of the dome, specifically ρ_2 vertex. Figure 25 shows the dome's border and the restriction of ρ_2 side.

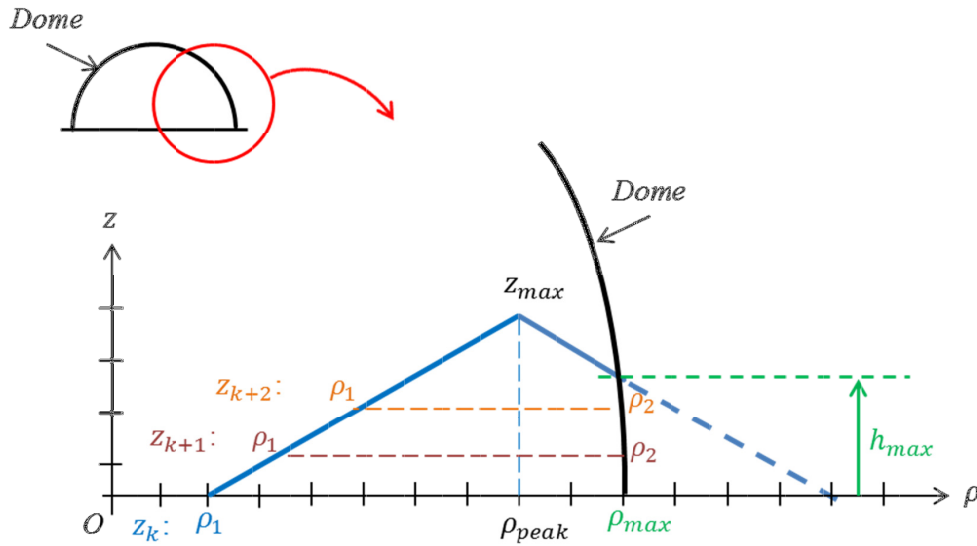


Figure 25. Restriction of ρ_2 point due to dome's wall

The algorithm checks if the current height z_k is smaller than the maximum contact height between the coal stockpile and the dome assigning point ρ_2 :

$$\rho_2 = \rho_{max} \quad (20)$$

where ρ_{max} is the Dome's maximum radius.

Now that the stockpile is completely defined in three dimensions, the program calculates the volume of each block by following the flowchart in Figure 26. After retrieving θ_0 and z_0 from DCS database, θ_{1v} and θ_{2v} are calculated.

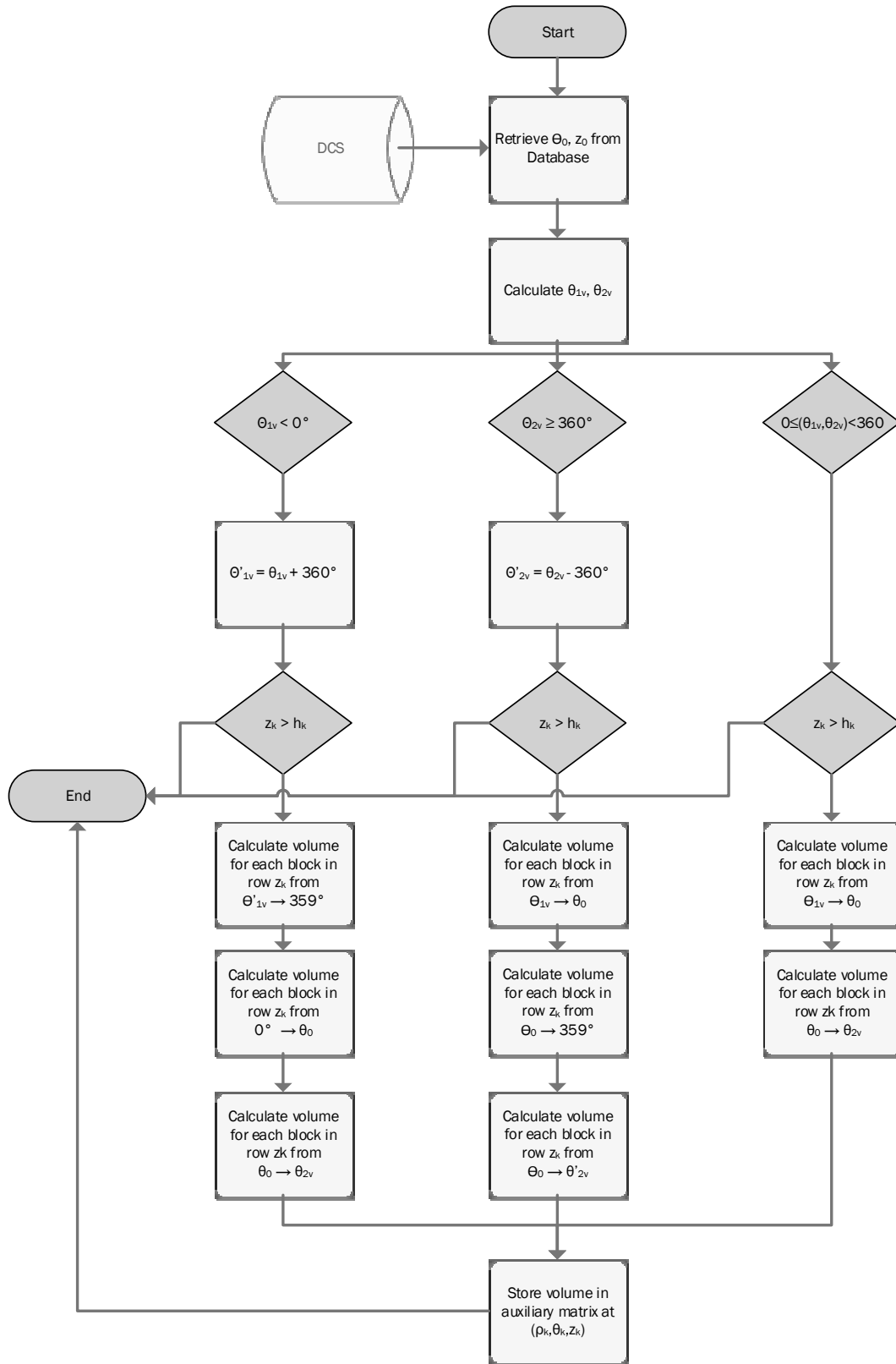


Figure 26. Volume calculation flowchart

As it happens in the Stacker Algorithm, circular continuity is preserved by meeting one of the following three cases:

1. If θ_{1v} is a negative angle, the algorithm corrects and assigns a new angle contained into the 360° of range:

$$\theta'_{1v} = \theta_{1v} + 360^\circ \quad (21)$$

where θ'_{1v} is the corrected angle for θ_{1v} .

The program calculates the volume for each block (prism) corresponding to row z_k at angle θ_k from θ'_{1v} to 359° ; then from 0° to θ_0 ; and finally from θ_0 to θ_{2v} .

2. If θ_{2v} is greater than 360° , the algorithm corrects and assigns a new angle within the allowable range:

$$\theta'_{2v} = \theta_{2v} - 360^\circ \quad (22)$$

where θ'_{2v} is the corrected angle for θ_{2v} .

In this case the volume of each prism is calculated in row z_k from angle θ_{1v} to θ_0 ; then from θ_0 to 359° ; and then for row z_k from angle 0° to θ'_{2v} .

3. If angles θ_{1v} and θ_{2v} are contained within 0° to 360° range then no corrections are needed, so the algorithm calculates the volume for each block of height z_k from θ_{1v} to θ_0 ; and finally from angle θ_0 to θ_{2v} .

Prior to making any calculations for a given point, the algorithm verifies if there are properties assigned to that particular point. If there is information already assigned to that point then the algorithm passes to the next iteration; otherwise, the calculations take place.

The third dimension and volume are calculated following the flowchart in Figure 27. The first radius point (ρ_1) is calculated and the algorithm checks if the actual height (z_k) is greater than the dome wall's height. In that case ρ_2 is calculated, otherwise ρ_2 is assigned with a constant value determined by the dome's radius.

After calculating the volume for each block, the correspondent height, and angle using equation (8), the volume is converted to tonnage using equation (9) and stored in an auxiliary matrix:

$$\text{Volume Matrix (radius } \rho_k, \text{ angle } \theta_k, \text{ height } z_k) = \text{Tonnage}_{\rho_k, \theta_k, z_k}$$

where $\text{Volume_Matrix}(\rho, \theta, z)$ is an auxiliary matrix (array) at point ρ, θ, z ; ρ_k is a given point on ρ axis; and $\text{Tonnage}_{\rho, \theta, z}$ is the tonnage at point ρ, θ, z .

The elements of this matrix are used during the database storing process in the Stacker Algorithm, which stores every single element associated with their position (ρ_k, θ_k, z_k), properties (quality tags such as ash, BTU, moisture, sulfur) and tonnage value into the Stack and Dynamic Tables in DS-CQMM database. Since every radius corresponds only to one height and one angle uniquely, a correct assignation is achieved.

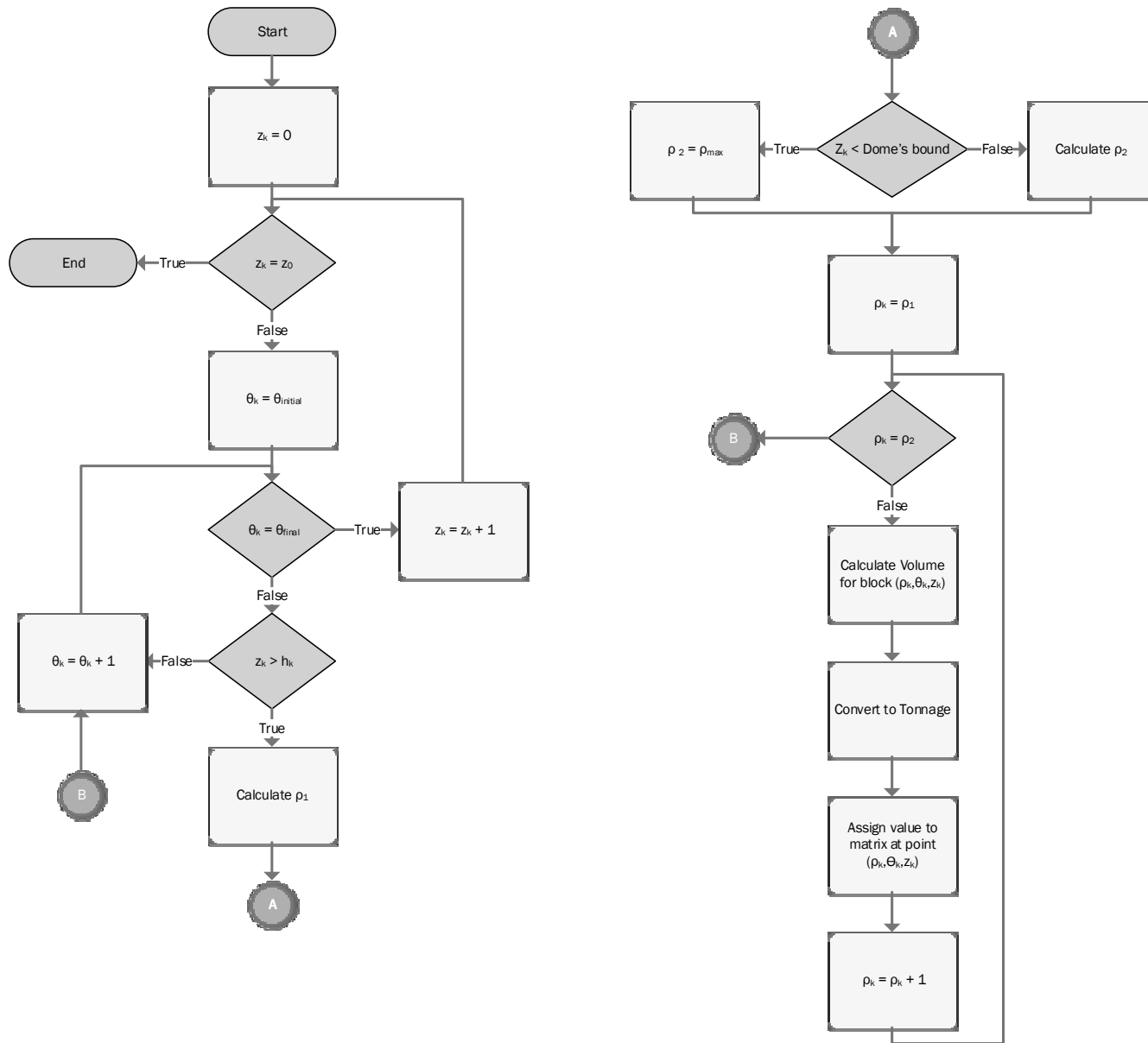


Figure 27. Volume and tonnage calculation for (ρ_k, θ_k, z_k) point

2.5.5 Graphical User Interface (GUI) and simulation of the Stacker Application

Various simulations are performed in order to test and debug the Stacker Application. Figure 28 shows the configuration of the GUI. The screen shows the quality tags of the actual batch of coal that is being transported from the coal analyzer to the dome through the conveyor system along with the remaining time for reaching the boom of the stacker. This enables the operator to know how much time the stacker has for rotating to a desired angle if the transported coal contains low (or high) quality (a). In case the operator needs to visualize the actual shape of the stockpile at any time, a specific button (b) is designed for that purpose. By clicking on this button the resulting shape of the entire coal stockpile inside the dome is shown.

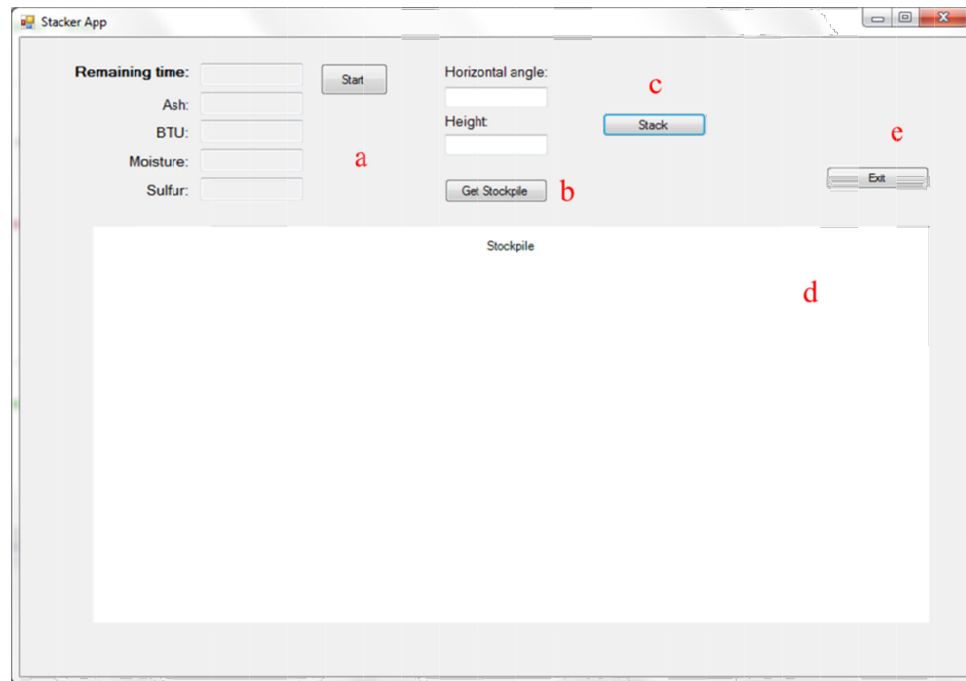


Figure 28. Stacker Application GUI: a) Remaining time before reaching stacker and quality tags for batch of coal, b) “Get Stockpile” button for retrieving actual stockpile’s shape, c) Horizontal angle (θ_0) and Height (z_0) inputs, d) “Exit” button.

There are two input fields for submitting the desired angular position for the Stacker and the final height of the stockpile (c). With the implementation of the DS-CQMM in the mine, these two inputs will be retrieved automatically by querying the DCS database. The building process of the stockpile while it is being stacked and the final shape are shown to the operator in two dimensions (d). Finally, for closing database connections and exiting the Application, the “Exit” button is implemented (e).

2.6 Reclaimer Application

One of the objectives of the DS-CQMM was to develop a user-friendly interface for determining the coal quality distribution inside the dome. Therefore, the Reclaimer Application should have a layout that allows the operator to navigate through the application with minimal training. The Reclaimer Application should also be able to get the correct inputs in order to show the previous and later status of the coal stockpile at the reclaiming process. In addition, numerical values of different coal quality tags should be available in tables for more accurate studies and analysis. Since the dome is used for storing purposes, the operator should be able to observe how much coal can be reclaimed, from which point of the dome, and the average of each quality tag that the reclaimed coal would have. This is achieved with the Forecast Tool, where interactive tables are shown, and by selecting different cells or range of cells, the application shows different values of interest.

The Reclaimer Application needs to show the actual state of the coal stockpile inside the dome using the same interface layout as the Stacker Application; which means that the interface is

implemented in a two-dimensional plane where the radius of the peak of the stockpile is located. Figure 29 shows the overall operation of the Stacker Application. The operator has three options while the shape of the stockpile is being displayed: (i) to see the different coal quality tags distribution of the stockpile differentiated by colors; (ii) to perform reclaiming process; and (iii) to start the Forecast Tool.

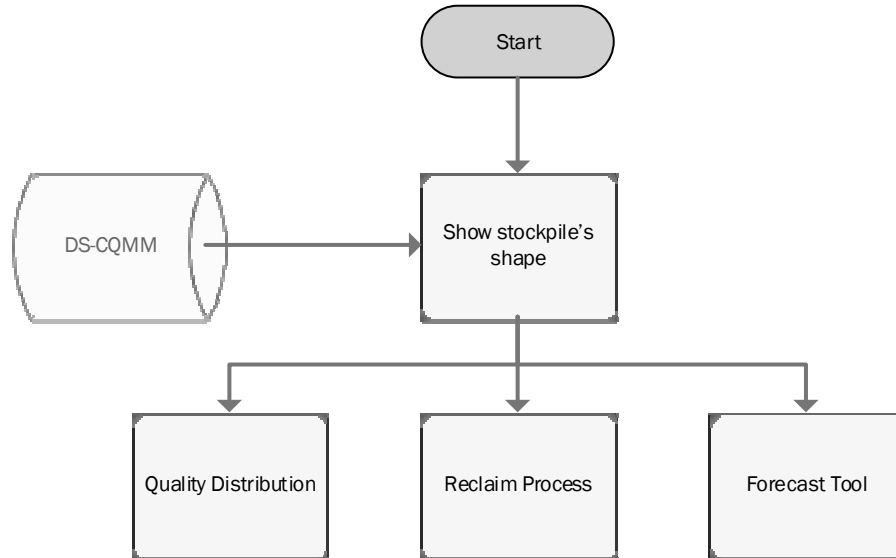


Figure 29. Reclaimer Application overall view

2.6.1 Quality Distribution Algorithm

The operator is able to observe the coal quality distribution inside the dome of the actual stockpile differentiated by colors. These colors are associated with a range of values for each quality tag. In other words, different ranges of coal quality are shown by colors for each coal quality tag following the actual shape of the stockpile.

The program retrieves the values of the different coal quality tags along with their position from the Dynamic table in DS-CQMM database as shown in Figure 30.

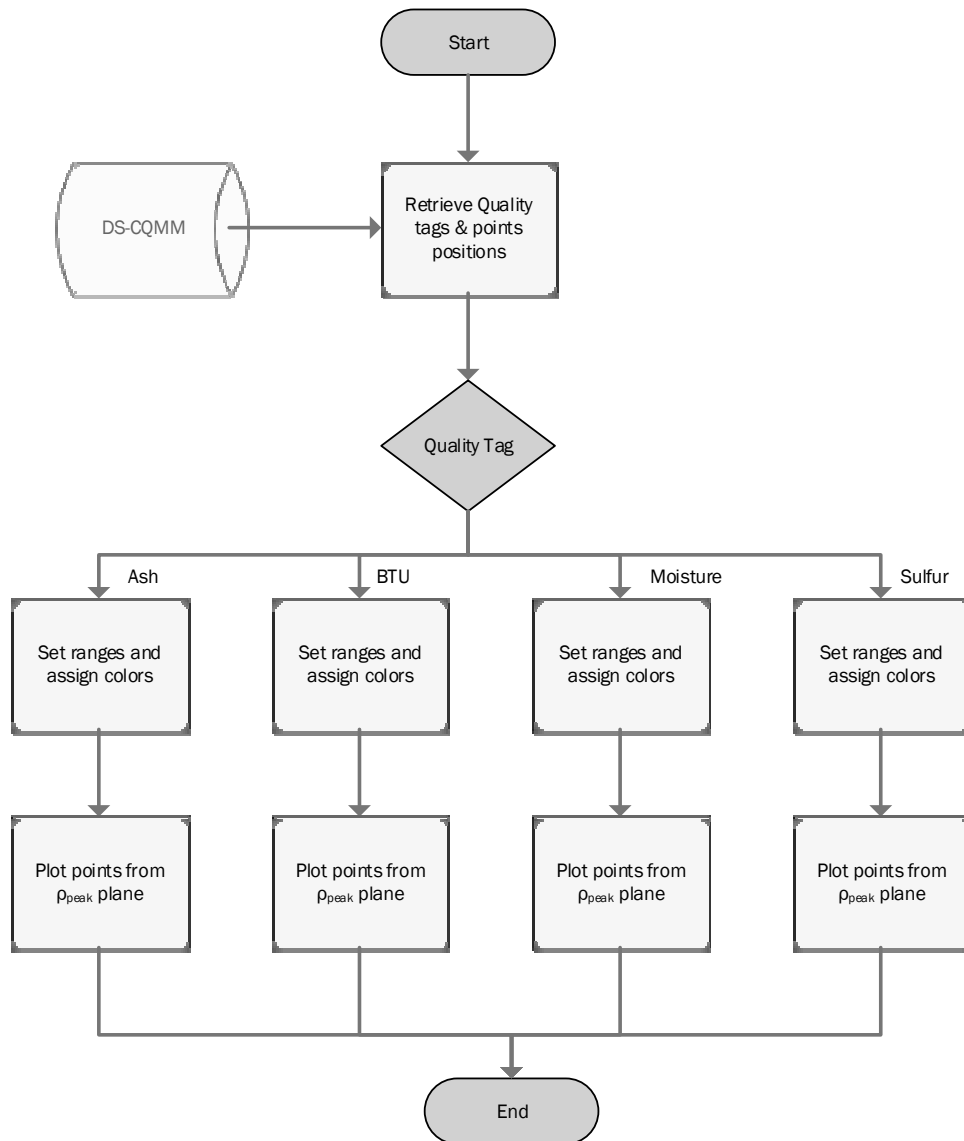


Figure 30. Quality distribution display flowchart

The operator can decide which of the following quality tags distribution will be shown in the display area: ash; BTU; moisture; or sulfur.

The process of plotting the quality distribution is the same for all tags. First, ranges of quality are set for each color. Then, each point's quality value is compared with the ranges and the

algorithm decides which color is assigned to that particular point. Finally, points are plotted into the display area.

It is important to recall that the points plotted correspond to the blocks located in the plane $\rho = \rho_{peak}$ (i.e. stockpile's peak radius). This situation is similar to the Stacker Application where the two-dimensional implementation was performed. However, the database contains the entire data from the stockpile stored for every block: the location (ρ, θ, z) of the block, its quality tags (ash, BTU, moisture, and sulfur), and the tonnage.

2.6.2 Reclaimer Application algorithm

For this particular section of the DS-CQMM, three inputs are needed for the implementation of the algorithm. These three values are: initial angle of reclaiming process: θ_s (Figure 31); final angle of reclaiming process: θ_f (Figure 31); and final angle of the Reclaimer after the reclaiming process: φ (Figure 32).

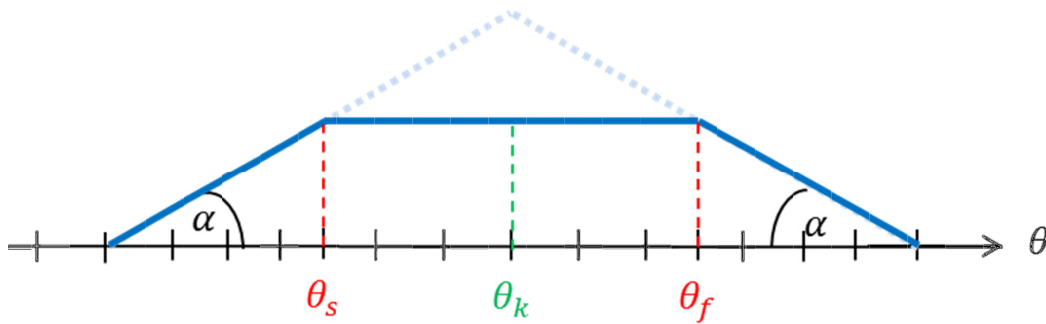


Figure 31. Initial and final angle of reclaiming

The algorithm begins at angle θ_s and finishes at angle θ_f performing the routine increasing one by one the actual angle θ_k (Figure 31). Additionally, the algorithm is developed in the plane ρz ,

as the reclaimer performs its work in that plane. Figure 32 shows the reclaimer performing a reclaiming process. The dashed line shows the original shape of the stockpile before reclaiming. Figure 32 also shows the reclaimer's angle of action (φ).

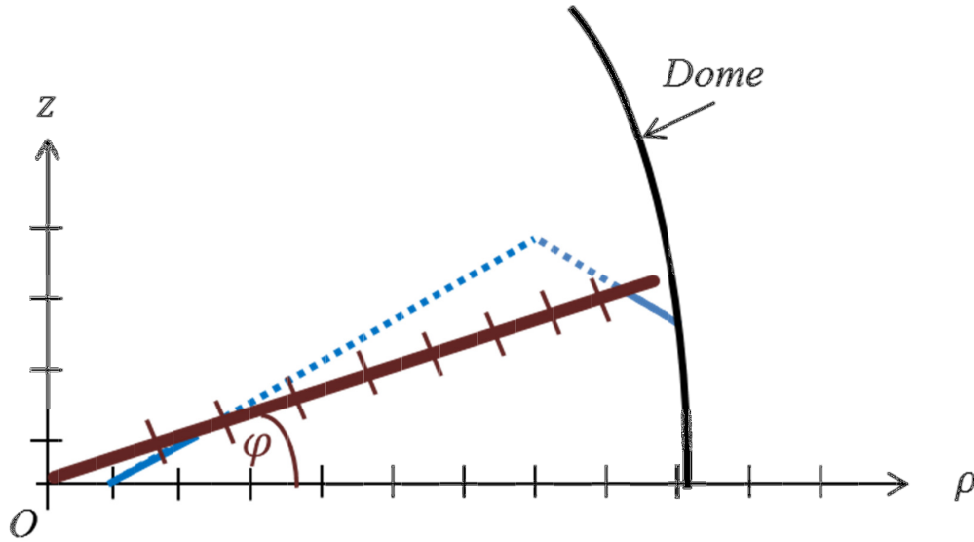


Figure 32. Reclaimer performing work in plane ρz

When the reclaiming process is finished, the last angle φ is taken for building the new shape of the coal stockpile. This shape contains the remaining properties and tonnage of coal inside the dome.

This process is performed at every angle within the reclaiming zone (i.e. between θ_s and θ_f). The algorithm retrieves three inputs for this Application (θ_s , θ_f , φ) from the DCS database. As it happens in the Stacker Application, circular continuity must be preserved. Assuming that the reclaiming process is performed in the increasing direction on the θ axis, there are two cases as shown in Figure 33:

1. Initial angle of reclaiming θ_s is greater than final angle θ_f . In that case, the algorithm reclaims from θ_s to 359° and continues from 0° to θ_f .
2. Initial angle θ_s is smaller than final angle θ_f . In that case, the reclaiming process begins on angle θ_s and ends at angle θ_f (normal performance).

The recurring algorithm is performed at every angle by calculating the height of the remaining stockpile according to the angle of the reclaimer. This height z_k is calculated for every radius ρ_k by using trigonometric concepts, which can be deduced from diagram in Figure 34. From the graphic, one can state that:

$$\tan \varphi = \frac{z_k - z_{or}}{\rho_k - \rho_1}$$

where φ is the reclaimer's angle; and z_{or} is the height at the origin of coordinate system.

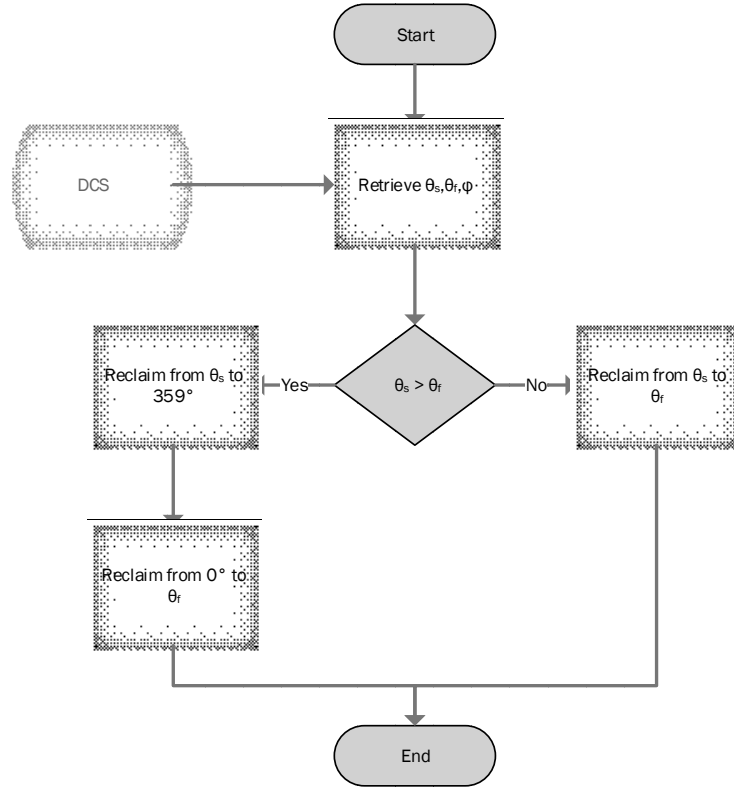


Figure 33. Reclaiming algorithm flowchart

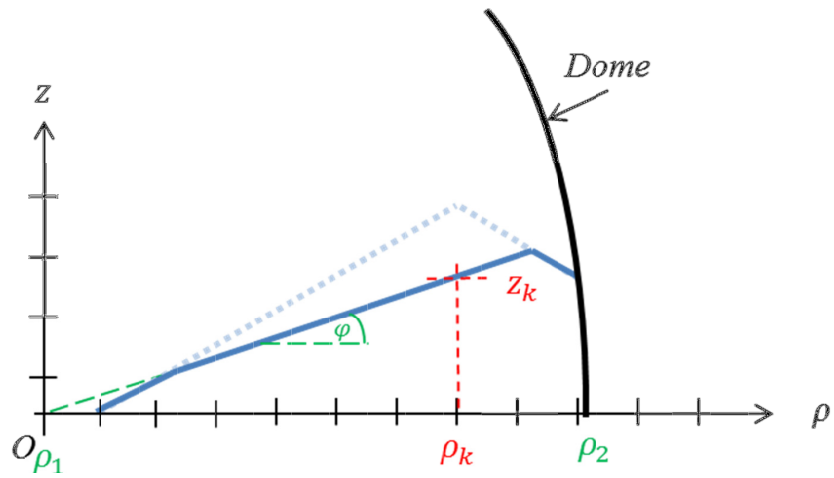


Figure 34. Reclaimed stockpile diagram

If one takes ρ_1 in the origin of coordinates and z_{or} as the ground, then:

$$\tan \varphi = \frac{z_k}{\rho_k}$$

Solving for z_k :

$$z_k = \rho_k \tan \varphi \quad (23)$$

which represents the height for a given value of radius at angle θ_k within range (θ_s, θ_f) .

For historical records, the algorithm stores the reclaimed coal properties and tonnage divided by blocks into Reclaimer and Dynamic tables in the DS-CQMM database as shown in flowchart in Figure 35. Using equation (23) the program deletes the blocks that are located above that line defined by the Reclaimer angle from the Dynamic table in the DS-CQMM database.

It is important to recall that the Dynamic table is used as a bridge table between the Stacker and Reclaimer tables. This table contains the actual state of the dome's stockpile. In that sense, the blocks corresponding to reclaimed coal are deleted from the Dynamic table but not from the Reclaimer table.

The process of calculating the height and deleting the points above is repeated for every radius point ρ_k at every angle θ_k contained into θ_s, θ_f range.

The final shape of the stockpile is shown in the Reclaimer Application display area after the reclaiming process. It corresponds to the plane where the radius is constant ($\rho = \rho_{peak}$) as shown in Figure 36; however, there is coal stacked above that height “behind” that plane. This is not reflected at the Application display area, but remains stored in the DS-CQMM database and is reflected in numerical values at the Forecast Tool.

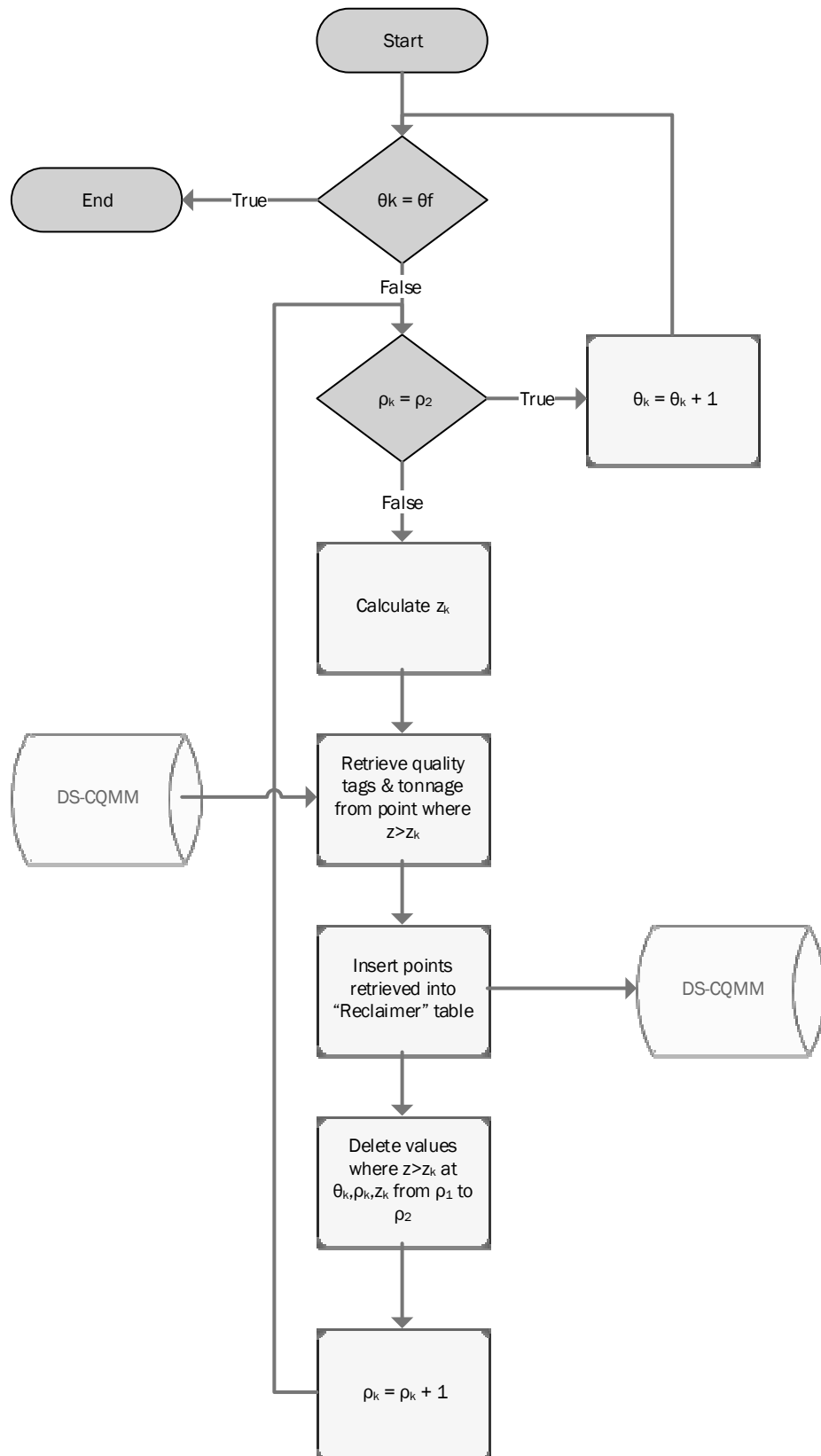


Figure 35. Reclaim process flowchart

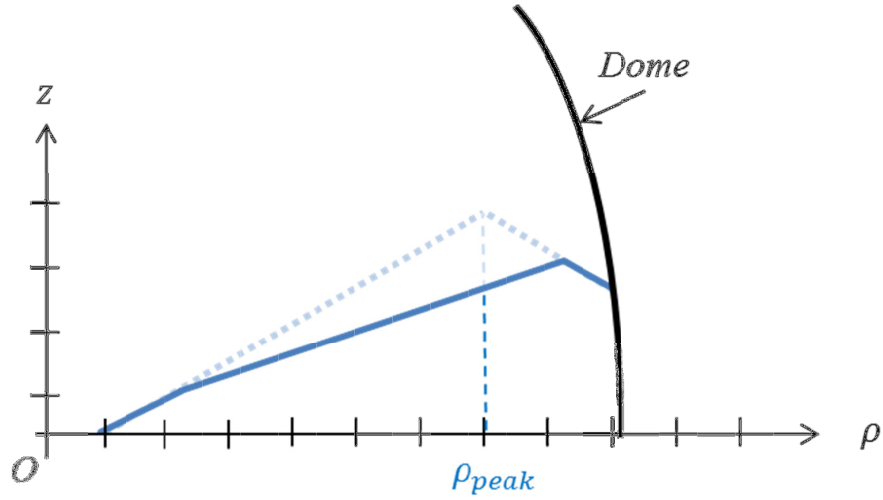


Figure 36. Final shape of coal stockpile after reclaiming process

2.6.3 Forecast Tool

The Reclaimer Application is a useful tool for a graphical determination of coal quality distribution inside the dome. It gives the operator a good approximation of quality values and relative position of the stacked coal. However, it is necessary to obtain numerical values of coal quality data for different purposes such as forecasting, mine planning, blending, etc. The Forecast Tool is developed for giving the operator information about the numerical values within a given range of angle and height for each coal quality tag presented in tables. It also gives the operator a quick reference of average values of all the quality tags by selecting specific cells. Each quality tag and tonnage includes its own table of values that are shown on a display grid. This process is performed as shown in Figure 37.

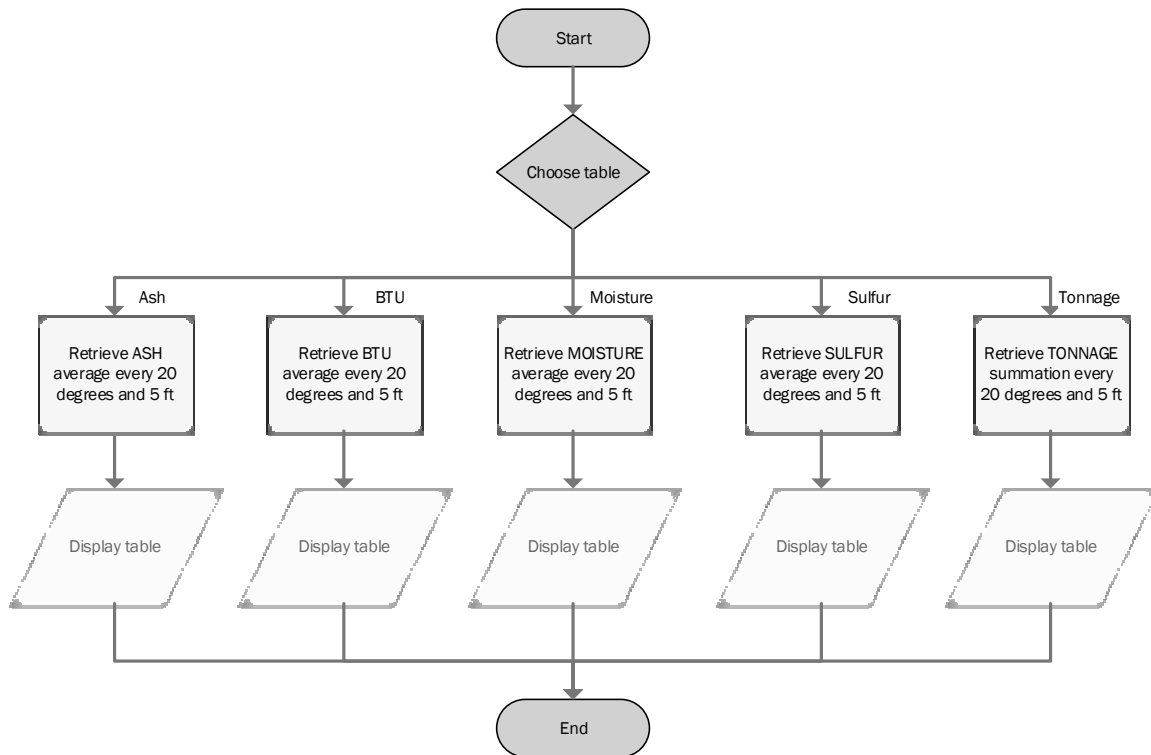


Figure 37. Tables display on Forecast Tool

These tables are divided using the same concept as used for Stacker and Reclaimer Applications, i.e., by angles on the abscissae and heights on the ordinates. The user can select one of the following tables: Ash; BTU; Moisture; Sulfur; or Tonnage. The average values of the selected quality tag are shown in the table within a range of angles and heights.

The Forecast Tool provides a dynamic way to get averages and summation of these values by merely selecting the desired cells. Then the algorithm gets the initial and final value of the angle by getting the initial and final selected column. Once the program obtains these values, it queries the Dynamic table in the DS-CQMM database for retrieving the averages and summation values as shown in Figure 38.

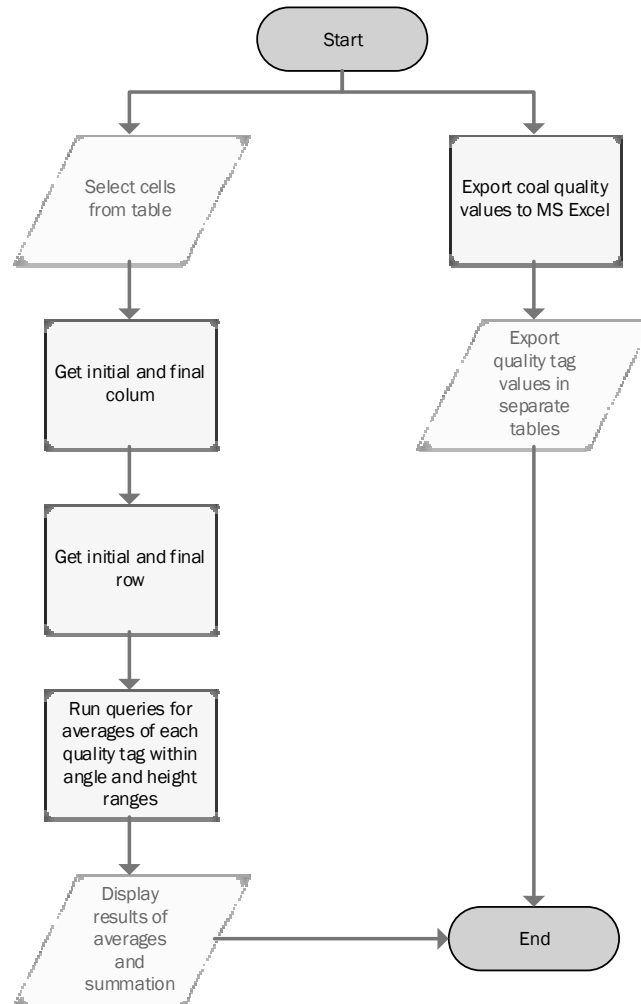


Figure 38. Forecast algorithm

After selecting the table of interest (i.e. any quality tag or tonnage table), the operator can select any range of cells from the table and the Forecast Tool provides the averages and summation of the rest of the quality tag values. This flexible tool provides the operator with the ability to forecast the reclaiming process based on one decision variable and to know the value of the rest of the variables in the system in a dynamic way.

Finally, the Forecast Tool can export the queried values to a Microsoft Excel workbook. The different quality tag tables are exported to separate sheets in MS Excel following the same

divisions of angles and heights. The operator will eventually save the file and work with it as with regular Excel sheet.

2.6.4 Graphical User Interface (GUI) and simulation of Reclaimer Application and Forecast Tool

In order to debug and test the Reclaimer Application and the Forecast Tool, a number of simulations were performed. Keyboard inputs were implemented for emulating the inputs to be queried from the DCS database once the DS-CQMM is validated in the mine.

Figure 39 shows the GUI of the Reclaimer Application. The operator selects between different quality tags buttons (a) in order to show the distribution of coal quality on the display area (g). The actual coal stockpile shape can also be seen (b).

The inputs needed for the correct performance of the Reclaimer Application are: the initial angle θ_s (c), final angle θ_f (d), and final angle of reclaimer φ (e) after reclaiming. A “Reclaim” button (f) is also included in order to run the algorithms.

The Forecast Tool includes a direct link to the Reclaimer Application where the graphical interpretation of coal quality distribution can be seen. By clicking the “Tables” button (h) the Forecast Tool shows the quality distribution in numerical values (b). Finally, the Reclaimer Application and Forecast Tool, along with their database connections, get closed by clicking on the “Exit” button (i).

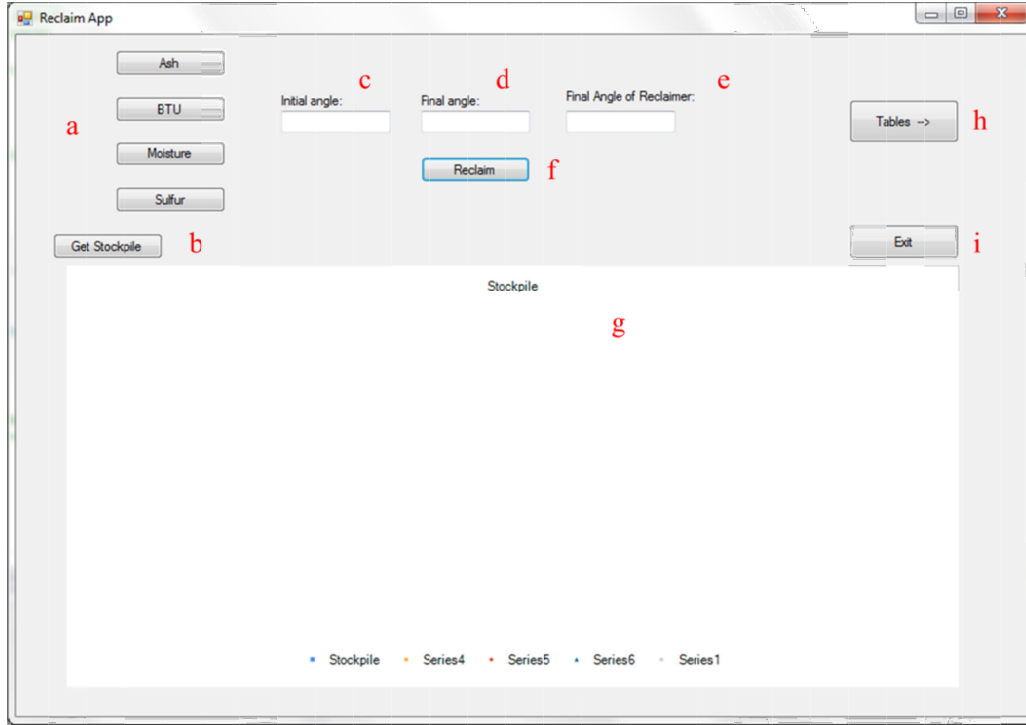


Figure 39. Reclaimer Application GUI: (a) Coal quality buttons, (b) “Get Stockpile” button for retrieving the actual shape of coal stockpile, (c) initial angle of reclaiming process (θ_s), (d) final angle of reclaiming process (θ_f), (e) final angle of reclaimer after the reclaiming process is completed (φ), (f) “Reclaim” button for running algorithms, (g) graphic display area, (h) link button to launch Forecast Tool, (i) “Exit” button

The Forecast Tool has no inputs given that it reads and runs calculations with already-generated data. It queries the Dynamic table in the DS-CQMM database for running averages and summations. On the GUI (Figure 40), the user selects one of the quality tag tables on the scroll down menu (a) to be shown on a display grid (c). Once the table is populated, the user selects the desired cells for running the forecast routine, and the Forecast Tool displays the results of the average values of the rest of the quality tags and total summation of tonnage (b). This process is performed dynamically, which means that the operator can change the selection whenever it is needed and the results will be shown for every different selection.

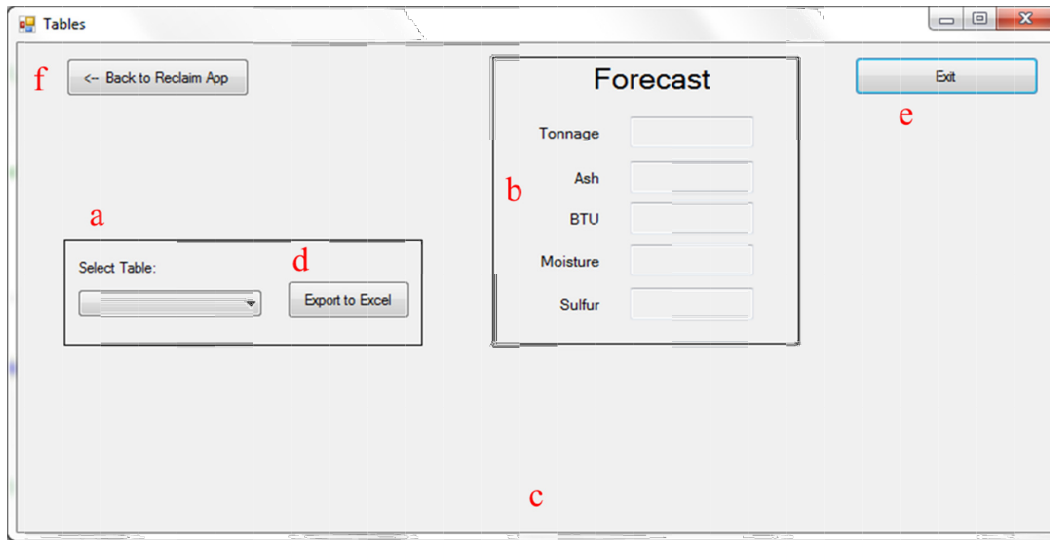


Figure 40. Forecast Tool: (a) Scroll down menu, (b) display window of average values, (c) display grid area, (d) “Export to Excel” button, (e) “Exit” button, (f) link button to Reclaimer Application

The values calculated and shown in different tables are then ready to be exported to a Microsoft Excel worksheet by clicking on “Export to Excel” button (d). The tables are available in Excel separated by quality tags, the same as in the Forecast Tool.

If the operator needs to go back to the Reclaimer Application, the specific button (f) needs to be selected for that purpose. Finally, the Reclaimer Application and the Forecast Tool, along with their respective database connections, can be closed through the “Exit” button (e).

2.7 Live Stockpile Application

The emergency reclaimer is installed at the dome’s ground level. This reclaimer is designed to work when the mobile reclaimer is under maintenance or has a possible failure. It is located at

290° from the origin and the area of the Live Stockpile covers from angle 200° to angle 360° as shown in Figure 41.

The coal will spend less time in this area of the dome than in the rest of the dome. In fact, the Live Stockpile increases and decreases the quantity of coal stored constantly. By locating the stacker at angle 290°, and activating the emergency reclaimer, this stockpile will dynamically change its shape.

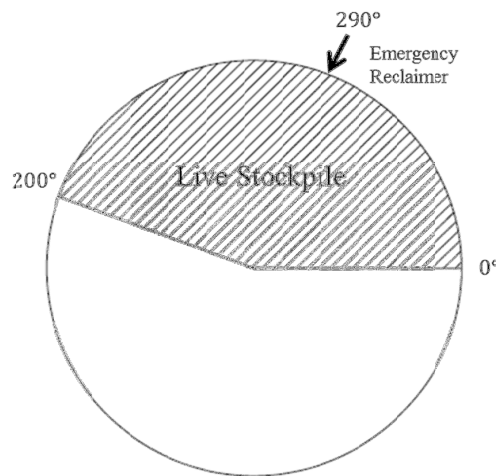


Figure 41. Live Stockpile delimited area

Above the emergency reclaimer, an ultrasonic sensor is installed in order to provide the value of the stockpile's height constantly; in this way the Live Stockpile Application can retrieve that value from the DCS database in order to build the model.

The Live Stockpile Application consists of a stacking part and reclaiming part. The operator decides what action is taken by switching between different available options: stacking, reclaiming or coal quality display (Figure 42).

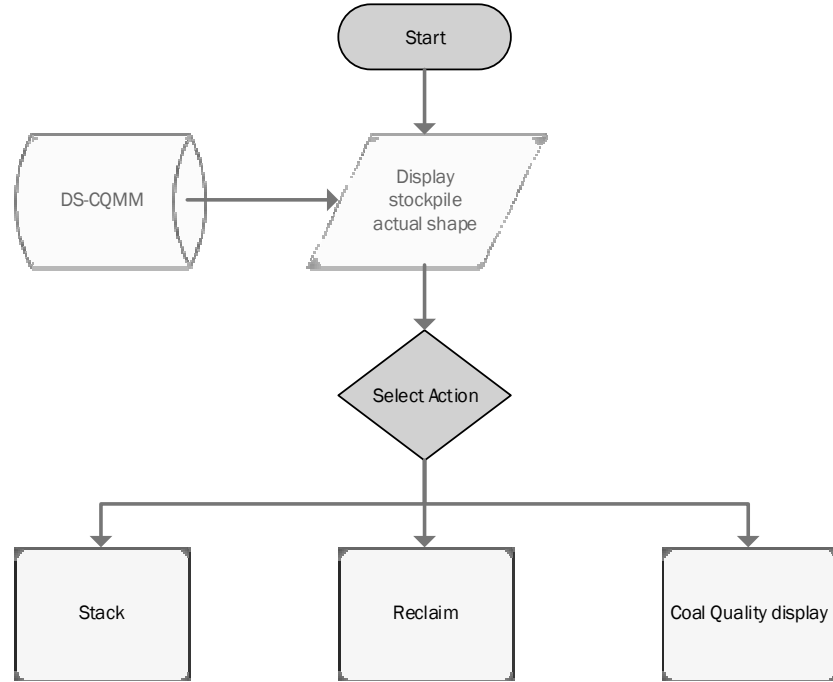


Figure 42. Live Stockpile Application overview

2.7.1 Live Stockpile Coal Quality Distribution Display

The Coal Quality Distribution display is performed the same way as was done in Section 2.6.1 . This process shows the quality tags distributed within the coal stockpile differentiated within quality ranges by different colors. It is performed at the θz plane where the radius is constant and coincides with the radius of the peak of the stockpile (i.e. $\rho = \rho_{peak}$). The difference is that coal quality distribution is shown in this section from angle 200° to angle 360° .

2.7.2 Stacking part for Live Stockpile Application

For implementation of the stacking part on the Live Stockpile Application, the same inputs (i.e. stacker's angular position (θ_0) and stockpile's height (z_0)) and same volume calculation concepts

as Stacker Application are used. The data generated is also stored in Stacker and Dynamic tables in the DS-CQMM database. Additionally, this section includes the same graphical outputs as the Stacker Application.

The display area shows the shape of the actual coal stockpile in a plane θz where the radius is constant and coincides with the radius of the peak of the stockpile (i.e. $\rho = \rho_{peak}$).

The only difference between the Stacker Application and the stacking part of the Live Stockpile Application is that the display area of the shape of the stockpile is now delimited from angle 200° to angle 360° .

2.7.3 Reclaiming part of Live Stockpile Application

Although the concept and development of the stacking part in the Live Stockpile Application is similar to the Stacker Application, the reclaiming concept and development is completely different.

In the Reclaimer Application, the reclaimer performs the reclaiming process on the surface of the stockpile. In other words, it reclaims from top to bottom and from side to side. In this case, the emergency reclaimer is located in a fixed position at the ground level and reclaims from the bottom and from only one point of the stockpile. These are opposite concepts.

The reclaiming process at the Live Stockpile is compared with an hourglass when it is getting empty of sand. The shape of the remaining stockpile will have a hole with a shape of an inverted pyramid.

The width of the emergency reclaimer is also taken into consideration for the purpose of accuracy. Figure 43 shows the shape of the remaining stockpile after the reclaiming process. The dashed line represents the original shape of the coal stockpile.

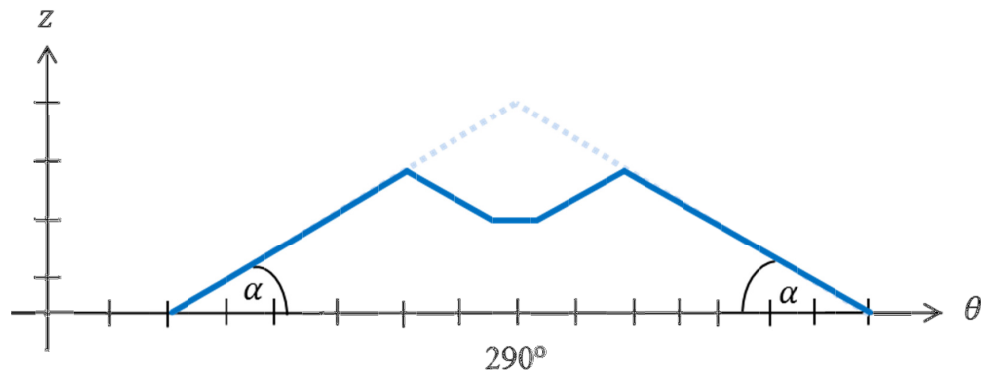


Figure 43. Stockpile after reclaiming process at Live Stockpile area

For implementation of the mathematical model, it is necessary to build an upside down pyramid that works as the reclaimed volume by the Emergency Reclaimer. For that purpose, the mathematical model is implemented on plane θz where the radius is constant and coincides with the stockpile's peak radius ($\rho = \rho_{peak}$) (Figure 44).

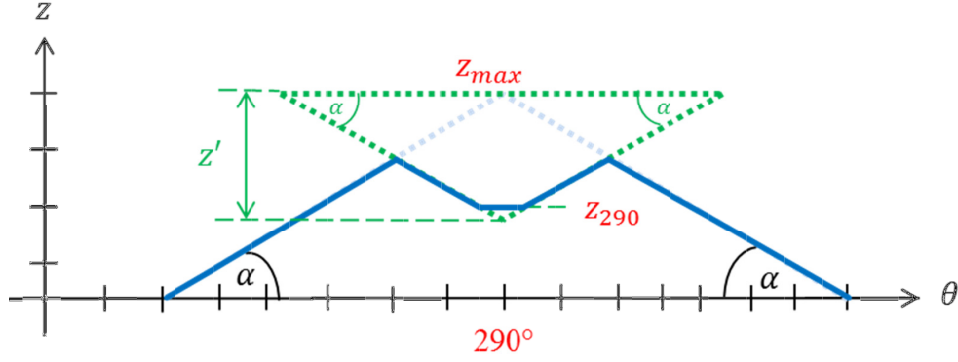


Figure 44. Live Stockpile mathematical modelling

As previously indicated, above the Emergency Reclaimer position, an ultrasonic sensor is installed to measure the height of the coal stockpile after reclaiming process. This value is another key input for the DS-CQMM (z_{290}). The value of the maximum height allowed for the stockpile inside the dome is required in order to be used for calculation of the inverted triangle's height. However, this triangle has an offset due to the emergency reclaimer width. This displacement is calculated using the diagram given in Figure 45.

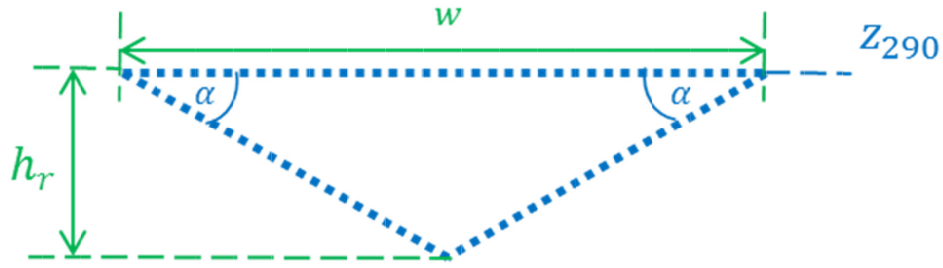


Figure 45. Additional height calculation due to emergency reclaimer width

The height of the triangle is calculated as follows:

$$\tan \alpha = \frac{h_r}{w/2}$$

$$h_r = \frac{w}{2} \tan \alpha \quad (24)$$

where w is the width of the emergency reclaimers, and h_r is the height of the offset pyramid.

The value calculated in equation (24) is added to the difference between the maximum allowed height of the stockpile and the height measured by the ultrasonic sensor; in that way the pyramid is displaced to the correct height.

The total height of the shifted pyramid is calculated as follows:

$$z' = z_{max} - z_{290} + h_r \quad (25)$$

where z' is the total height of the inverted pyramid; z_{max} is the stockpile's maximum height allowed inside the dome; and z_{290} is the height measured by the ultrasonic sensor and retrieved from the DCS database.

This height is needed in order to calculate the points of the base of the pyramid that are the starting and ending points in the algorithm (Figure 46).

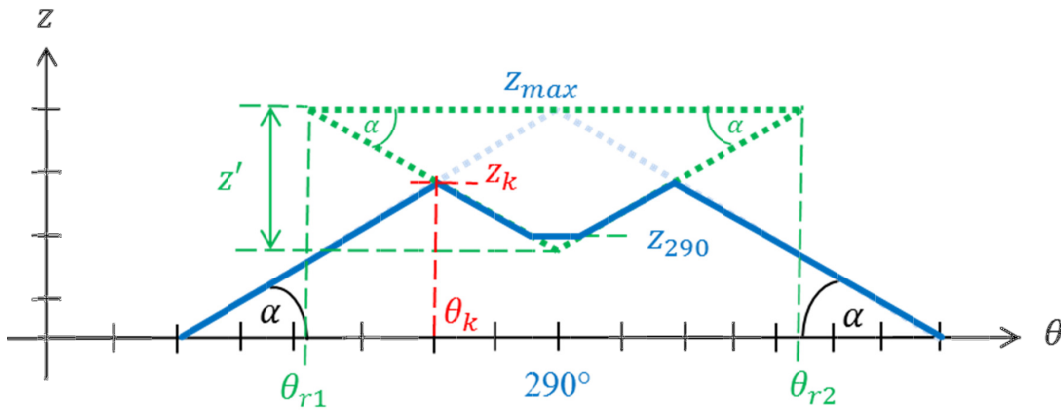


Figure 46. Live Stockpile calculation points

By using the calculated height in equation (25), one can calculate the points on the base of the pyramid as follows:

$$\tan \alpha = \frac{z'}{\theta_{290} - \theta_{r1}}$$

$$\theta_{r1} = \theta_{290} - \frac{z' \cdot CF_2}{\tan \alpha} \quad (26)$$

$$\tan \alpha = \frac{z'}{\theta_{r2} - \theta_{290}}$$

$$\theta_{r2} = \theta_{290} + \frac{z' \cdot CF_2}{\tan \alpha} \quad (27)$$

where θ_{r1} is the initial point of the base of the pyramid; θ_{r2} is the final point of the base of the pyramid; θ_{290} is the angle where the emergency reclaimer is located; and z' is the inverted pyramid height.

Equations (26) and (27) determine the starting and ending parameter for the algorithm that is shown in Figure 47. The flat portion of the stockpile generated by the emergency reclaimer is created using the following calculations:

$$\theta_{rec1} = \theta_{290} - \frac{w}{2} \cdot CF_2 \quad (28)$$

$$\theta_{rec2} = \theta_{290} + \frac{w}{2} \cdot CF_2 \quad (29)$$

where θ_{rec1} is the initial point of the flat part of the stockpile due to the emergency reclaimer; and θ_{rec2} is the final point of the flat part of the stockpile due to the emergency reclaimer.

The algorithm begins calculating z' with (25) and then calculates the initial and final points of the base of the inverted triangle (i.e. θ_{r1}, θ_{r2}) for starting the reclaiming process from θ_{r1} to θ_{rec1} , which is the point where the flat portion of the stockpile begins, and ends in θ_{rec2} at z_{290} height, which is retrieved from the DCS database. Then, the algorithm reclaims the last part of the pyramid ending at θ_{r2} .

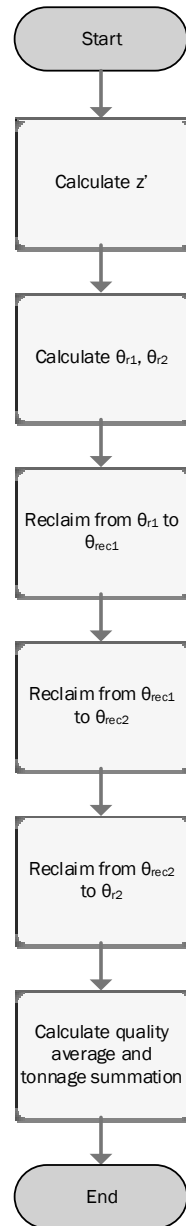


Figure 47. Reclaiming part for Live Stockpile Application

Finally, the average value of each quality tag is calculated, and the total summation of the tonnage of the reclaimed coal is displayed.

The program is executed for each angle θ_k from the initial point to the final point on θz plane. Initial and final points depend on which part of the triangle the algorithm is built. In Figure 48, the height z_k corresponds to each angle θ_k .

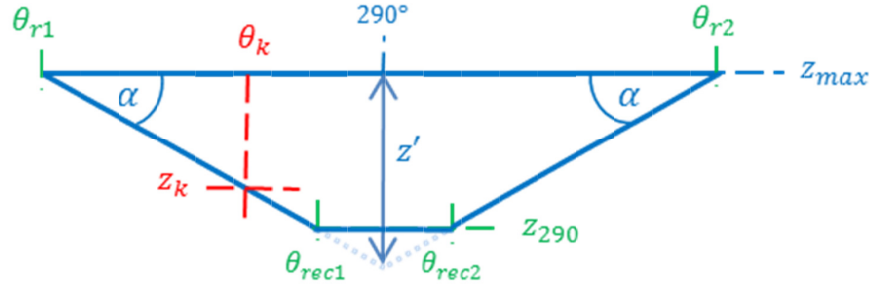


Figure 48. Height calculation for inverted pyramid at Live Stockpile

From the diagram in Figure 48, the following is obtained:

$$\tan \alpha = \frac{z_{max} - z_k}{|\theta_k - \theta_{r1}|}$$

$$z_k = z_{max} - \tan \alpha \cdot |\theta_k - \theta_{r1}| \cdot CF_1 \quad (30)$$

Equation (30) is valid when θ_k is in the range $(\theta_{r1}, \theta_{rec1})$. When θ_k is in the next range (i.e. θ_{rec1} and θ_{rec2}) the height z_k is a constant value:

$$z_k = z_{290} \quad (31)$$

Finally, when θ_k is within the range $(\theta_{rec2}, \theta_{r2})$ the height is deducted following the same deduction as above:

$$z_k = z_{max} - \tan \alpha \cdot |\theta_k - \theta_{r2}| \cdot CF_1 \quad (32)$$

In summary, z_k is calculated as follows:

$$z_k = \begin{cases} z_{max} - \tan \alpha \cdot |\theta_k - \theta_{r1}| \cdot CF_1, & \text{when } \theta_{r1} \leq \theta_k < \theta_{rec1} \\ z_{290}, & \text{when } \theta_{rec1} \leq \theta_k < \theta_{rec2} \\ z_{max} - \tan \alpha \cdot |\theta_k - \theta_{r2}| \cdot CF_1 & \text{when } \theta_{rec2} \leq \theta_k < \theta_{r2} \end{cases} \quad (33)$$

The length of the emergency reclaimer is considered in the third dimension (i.e. ρz plane). Figure 49 shows the influence of the emergency reclaimer's length on the Live Stockpile. Dashed lines represent the coal stockpile before reclaiming, while full line shows the residual coal due to a dead volume originated by the emergency reclaimer's length. The green dashed line delimits the dead volume zone of the Live Stockpile that will define the equations within the algorithm.

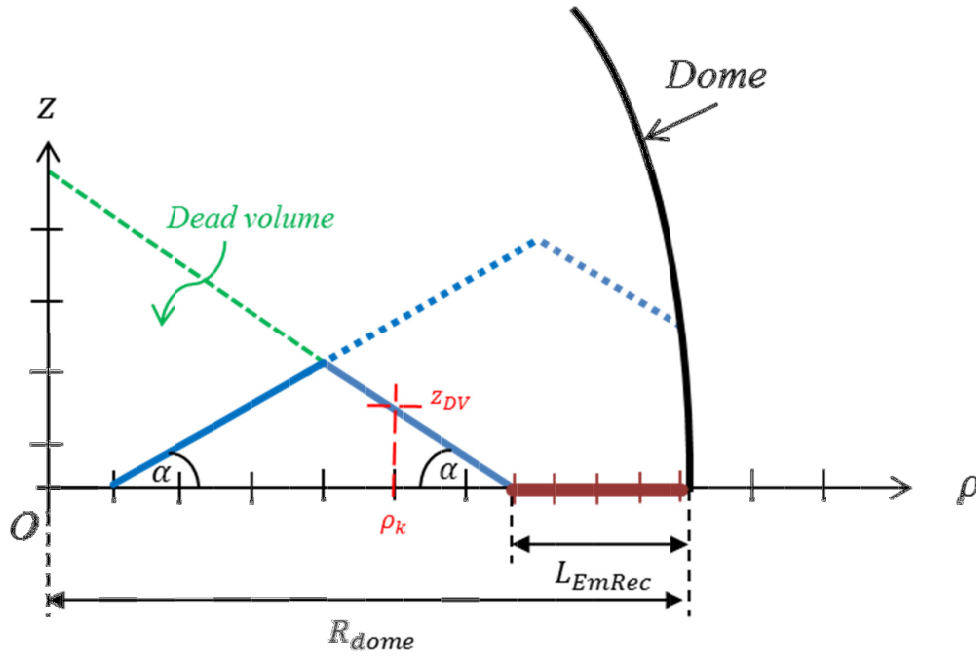


Figure 49. Reclaiming process at ρ axis in Live Stockpile Application

The dead volume has a triangle shape in plane ρz determined by the angle of repose of coal (α). The process of the algorithm is designed in such a way that heights higher than z_{DV} of coal on ρz plane are deleted from the Dynamic table in the DS-CQMM database during the reclaiming process. The z_{DV} height is calculated as follows:

$$\tan \alpha = \frac{z_{DV}}{R_{dome} - L_{ER} - \rho_k}$$

$$z_{DV} = (R_{dome} - L_{ER} - \rho_k) \tan \alpha \quad (34)$$

The algorithm begins checking if the current height stored in the Dynamic table in the DS-CQMM database is higher than the calculated with equation (33). If it is higher (which means that there is coal stored at that point), then the program retrieves the average of quality values from points above the calculated height and stores them into a temporal matrix for calculating the average values of total reclaimed coal. Then algorithm starts checking if the height is higher than the dead volume delimitation height calculated with equation (34) on ρ axis. If it is higher, the Live Stockpile Application retrieves the summation of the tonnage of the coal that is above z_{DV} at ρ_k . This summation value is assigned to the temporal matrix mentioned above. Finally, all data corresponding to the values where heights are higher than z_{DV} are deleted from the Dynamic table and stored into the Reclaim table, both in the DS-CQMM database.

The average quality values and the total summation of tonnage are shown in a display window developed in the GUI. The reclaiming algorithm of the Live Stockpile Application described above is shown in the flowchart in Figure 50.

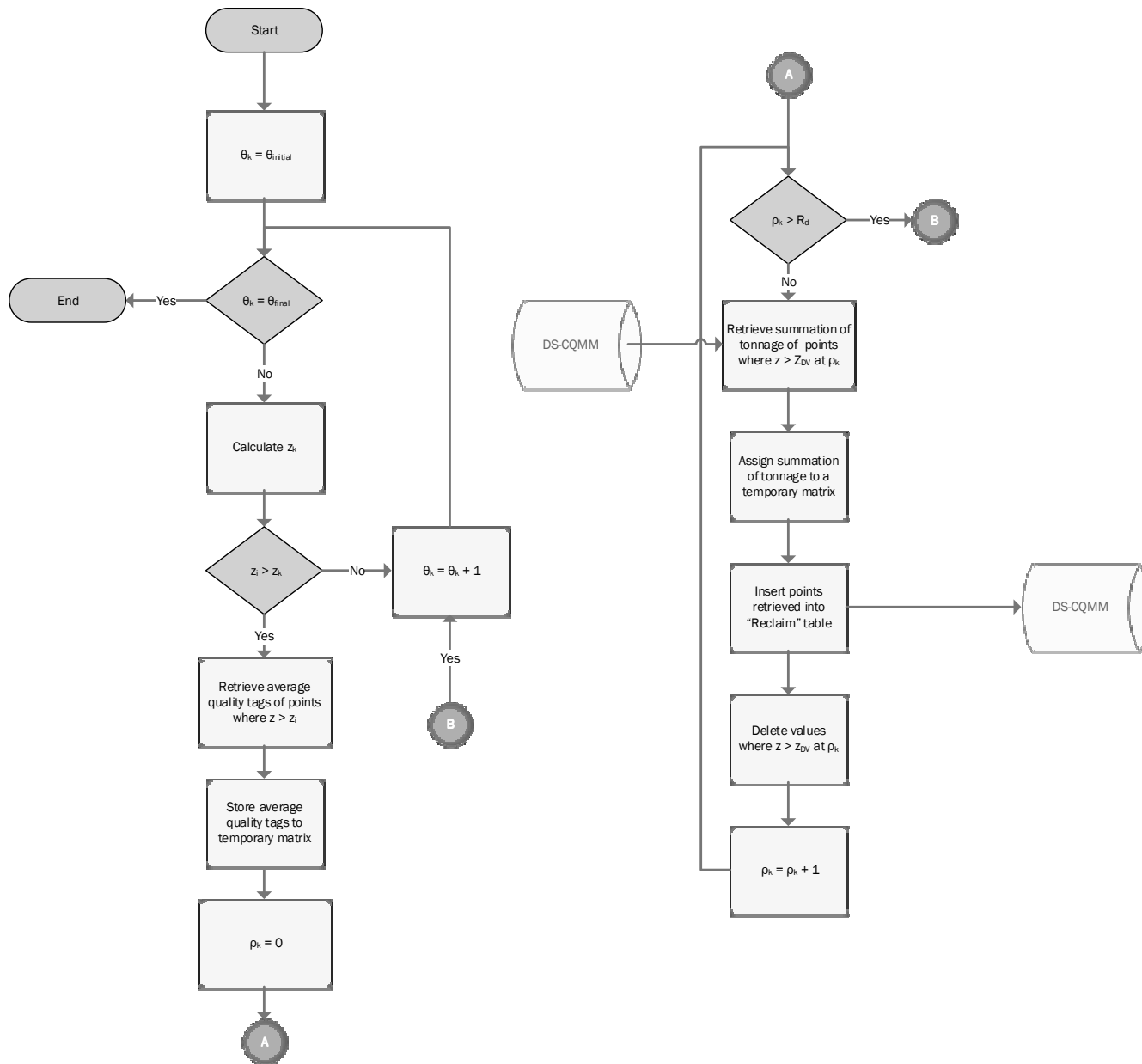


Figure 50. Reclaiming algorithm on Live Stockpile Application

2.7.4 Graphical User Interface (GUI) and simulation of Live Stockpile Application

As in a previous Application, a number of simulations are performed to test and debug the Live Stockpile Application. Figure 51 shows the layout of the GUI where different buttons for displaying the various quality distributions of the coal stockpile are provided (a). The stockpile's shape can also be presented, and a specific button shown in (b) is included for that purpose.

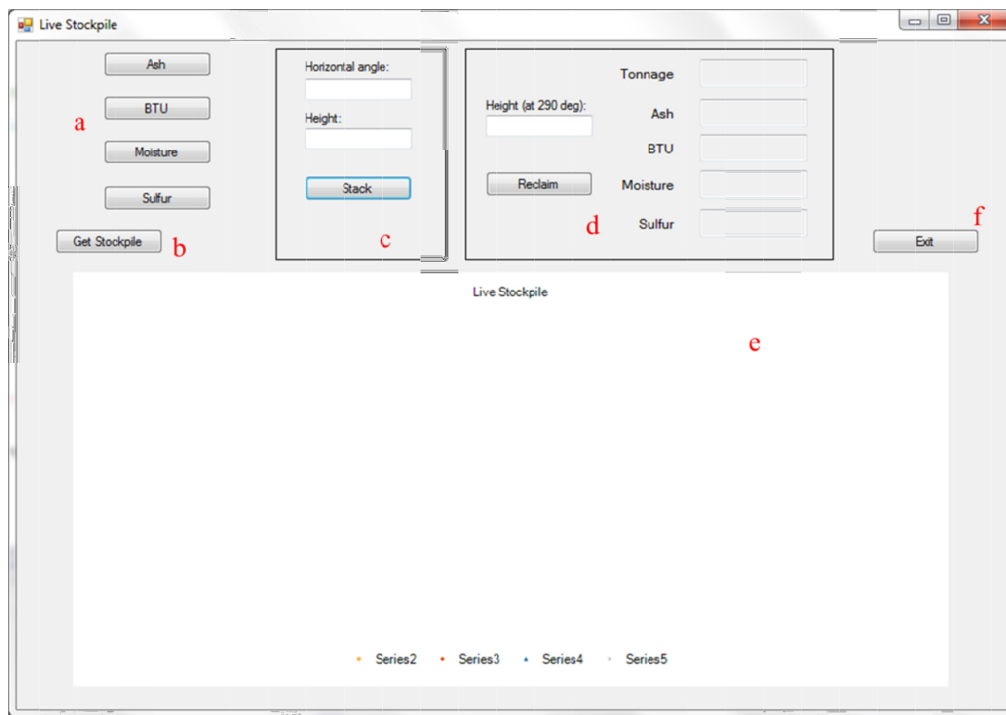


Figure 51. GUI of Live Stockpile Application: (a) Coal quality buttons, (b) “Get Stockpile” button that retrieves the actual stockpile’s shape, (c) stacking part, (d) reclaiming part, (e) graphic display area, (f) “Exit” button

Area (c) shows the stacking part of the Live Stockpile Application. There are two key inputs: angular position of the boom of the stacker (θ_0) and stockpile’s height (z_0) measured by the ultrasonic sensor. Both values are retrieved from the DCS database.

The reclaiming part of the Live Stockpile Application is also different in the display area. In area (d), the only required input is the final height of the stockpile after the reclaiming process (z_{290}). It also shows the display window of the average values of different quality tags of reclaimed coal and the total tonnage summation of this reclaimed volume.

The stockpile's shape and quality distribution are displayed as presented in area (e). Finally, in order to close the database connection and the Live Stockpile Application, "Exit" button (f) needs to be selected.

Chapter 3

Results and Discussion

3.1 Mine Description

This research was conducted at a surface coal mine located in southeastern Mississippi in the United States. The mine is a subsidiary of one of the largest coal producers (2.2 billion tons of coal reserves including unconsolidated mining operations) in North America.

The mine has an annual production of approximately 4.4 million tons of coal and 35 million bank cubic yards of overburden. There are a total of three thin coal seams ranging from 3 ft. to 8.5 ft.

The mine's major customer is a 582 megawatt Integrated Gasification Combined Cycle (IGCC) generating plant. Coal is shipped from the mine and delivered to the power plant through a Lignite Delivery Facility (LDF), which is located between the coal mine and the power plant. The DS-CQMM is a custom-made solution designed for the LDF of this surface coal mine.

3.2 DS-CQMM Model

The case study shown in this Chapter starts with an empty dome. Coal flows from the crusher to the dome. It is then stacked, reclaimed, and analyzed using different Applications developed to simulate what would actually be conducted in the mine.

3.2.1 Delay Time Application

The screen of the Delay Time Application is shown in Figure 52. The actual delay time in seconds (g) and the calculated delay time (f) are shown for each belt conveyor. The scroll bar (e) can be used to increase or decrease the velocity rate of the belt conveyor with ranges between 5 and 11 feet per second with increments of 1 foot per second. The changes of velocities for each belt conveyor can be achieved independently. The transfer towers are represented by a labeled square (c) that contains the actual reside time of coal (d) inside the tower. Raw data retrieved from the Coal Analyzer database (k) is passed to the next stage for further analysis and processes. The total time coal remains on the conveyor belts and towers (Figure 52h) is the summation of all final delay times. The program starts by activating “Start Simulation” button (i), and closes database connections and the Delay Time Applications through “Close” button (j).

Prior to the start of the simulation, velocities can be established by scrolling the bars and setting them up to the desired value. During the simulation process they also can be changed dynamically. By selecting the “Start” button, the Delay Time Application establishes a connection with the local database installed on the hard disk (emulating Coal Analyzer database) and sends the query for retrieving the desired quality information. In a real system (i.e. mine) the connection is established with the Coal Analyzer server that is exactly the same as the local server generated for running the tests.

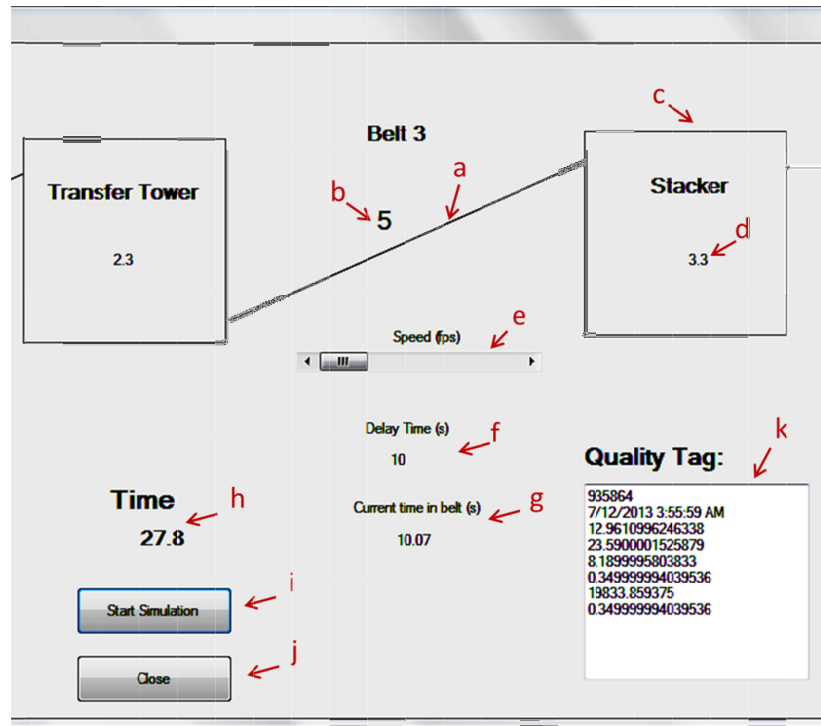
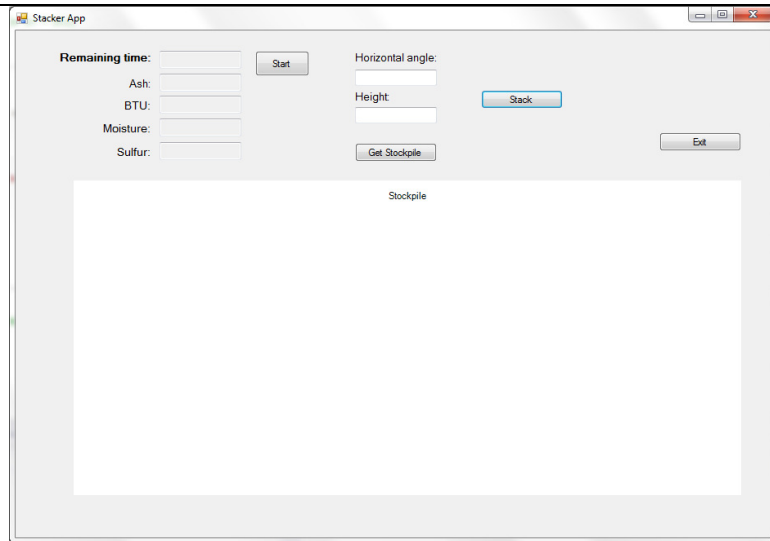


Figure 52. Detail of Simulation Software for Delay Application

3.2.2 Stacker Application

Figure 53 shows the sequence of the stockpile building process. The two key inputs of the Stacker Application (θ_0 and z_0) are shown as keyboard inputs. In the mine, these two inputs are retrieved automatically from the DCS database.

If one supposes that the boom of the stacker is positioned at angle 65° and the stacking process begins until the stockpile reaches the maximum height (i.e. 85 ft.) as shown in Figure 53b. The boom of the stacker rotates to angle 70° and later to 75° , and stacks coal up to 85 ft. as shown in Figure 53c-d. It is important to emphasize that the rotational angle of the stacker (θ_0) is stored in the DCS database by the PLC and the height of the stockpile (z_0) is measured by the ultrasonic sensor and stored in the same database.



a) Empty Dome

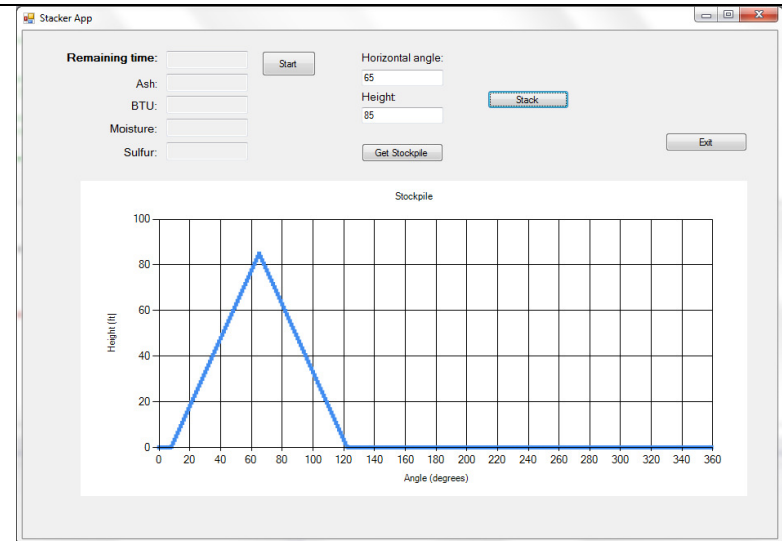
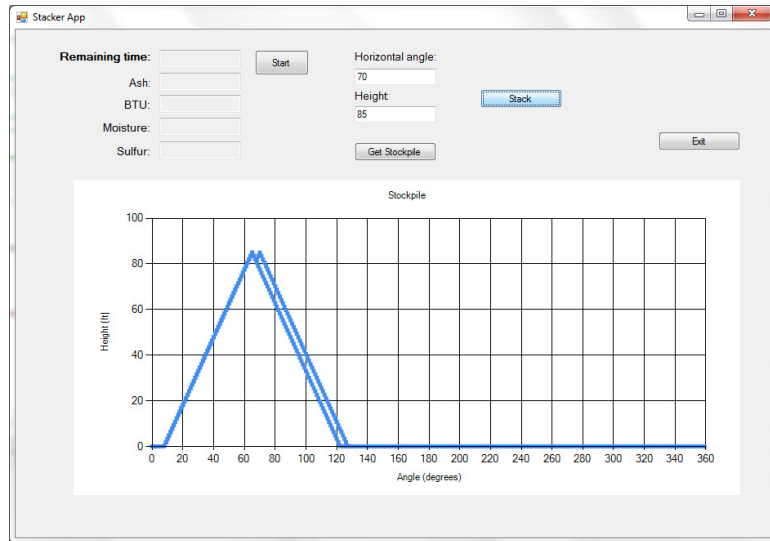
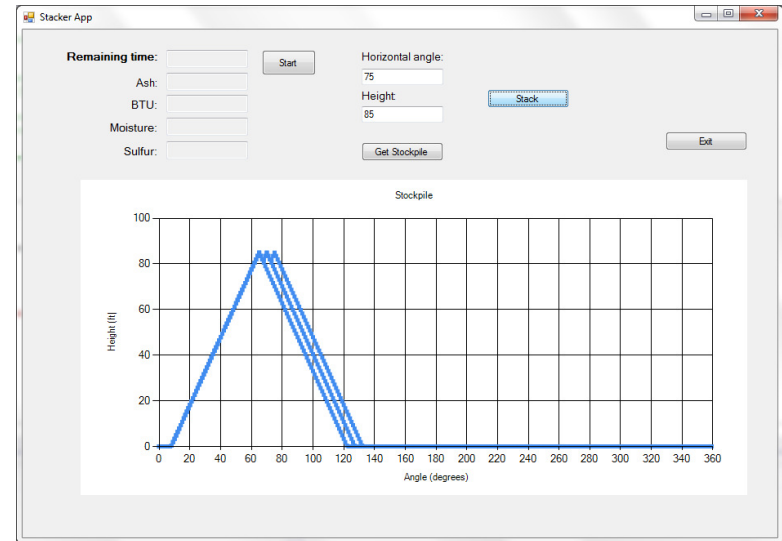
b) $\theta_0 = 65^\circ$, $z_0 = 85\text{ft}$.c) $\theta_0 = 70^\circ$, $z_0 = 85\text{ft}$.d) $\theta_0 = 75^\circ$, $z_0 = 85\text{ft}$.

Figure 53. Sequence of stockpile building process

In case the operator decides to stack coal in a different location than the continuous stockpile, because the quality has a given characteristic or for any other reason, the Stacker Application is able to build that stockpile. Figure 54 shows that a stockpile of coal is stacked at 160° up to the maximum height. It should be noted that the left branch of the stockpile does not overlap the existing branches.

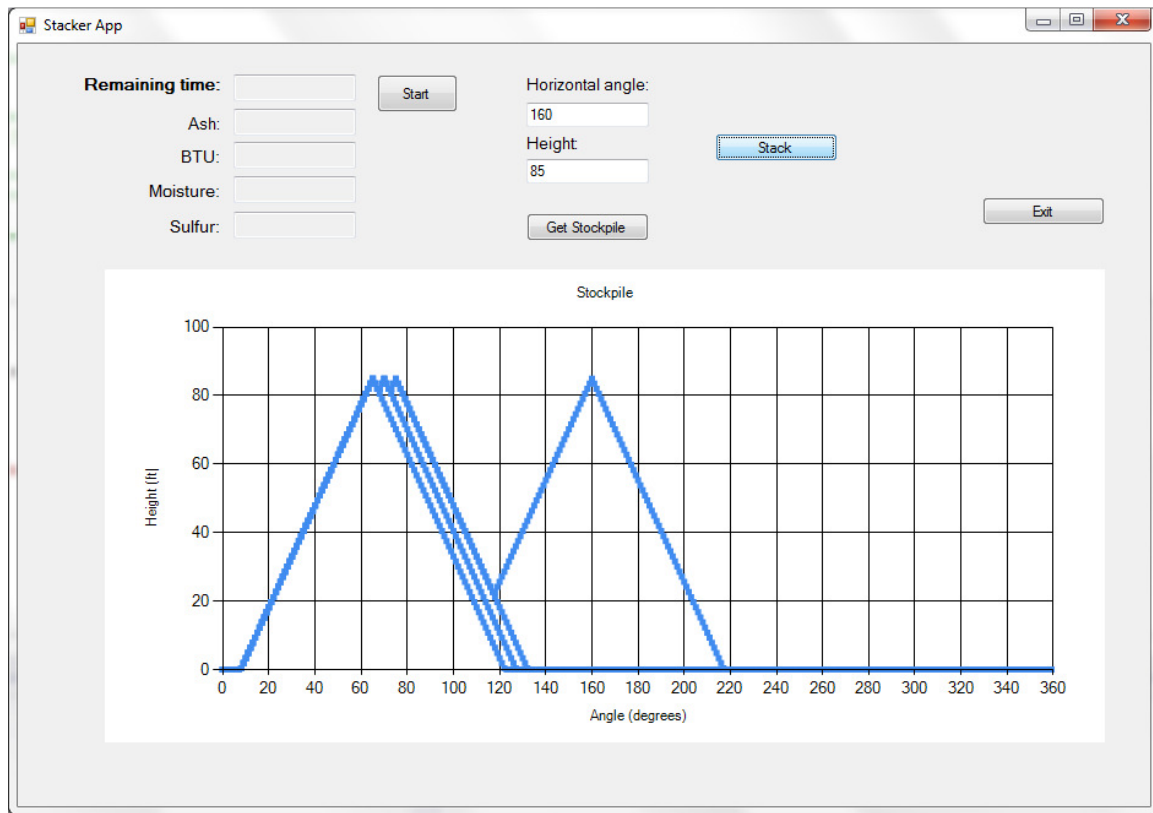


Figure 54. Stockpile stacked at 160° .

The algorithm should be robust enough to keep the circular continuity of the dome; that means that angle 0° and 360° should be the same physical point and the branches of the stockpiles must be built correctly and subjected to the this constraint. Figure 55 shows that the stockpile is stacked at angle 20° and its left branch reaches negative values on the θ -axis. The algorithm is

designed to handle these types of cases by assigning to each point of the branch the correct angle implying the preservation of circular continuity.

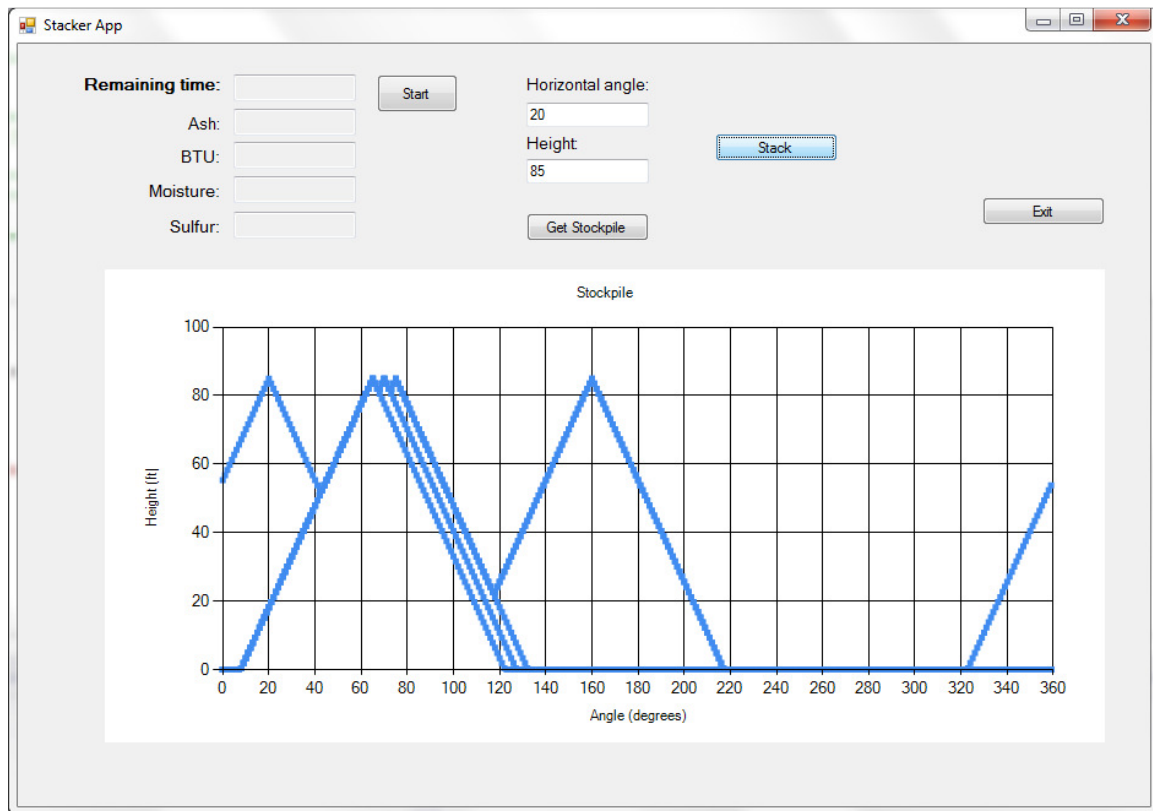


Figure 55. Stockpile stacked at 20°.

The final shape of the existing stockpile can be retrieved and shown in the display window by selecting “Get Stockpile” button. The algorithm retrieves the maximum height of each and every angle of the plane and plots the results as shown in Figure 56.

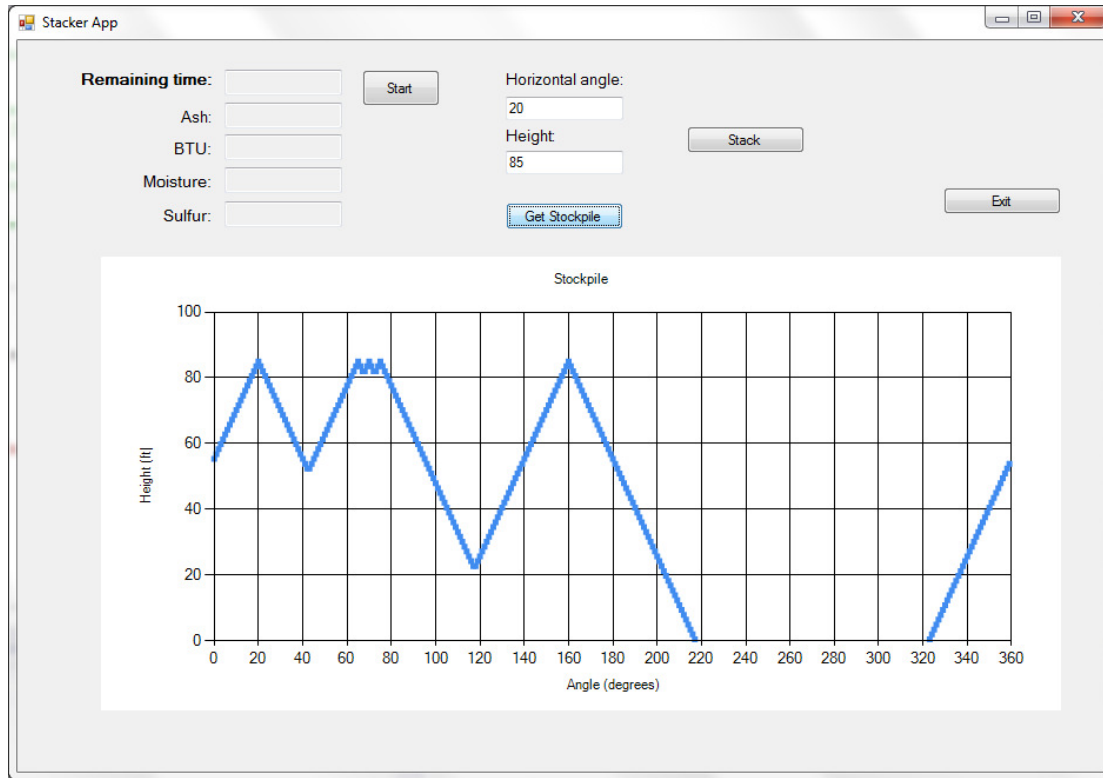


Figure 56. Shape of the existing coal stockpile

The red dashed frame in Figure 57 indicates an essential part of the Stacker Application: the Coal Quality Analyzer output in real-time of the actual batch of coal that is being transported through the conveyor system and its remaining time to reach the boom of the stacker.

Integration between the Stacker Application and the Delay Time Application is implemented in order to allow the operator to know the exact time remaining for that particular batch of coal to reach the boom of the stacker. This feature provides an extra benefit to the stacking process.

The “Start” button that initiates the timer and triggers the queries is implemented for testing purposes; that action is automatically started when new data is available from the Coal Analyzer database.

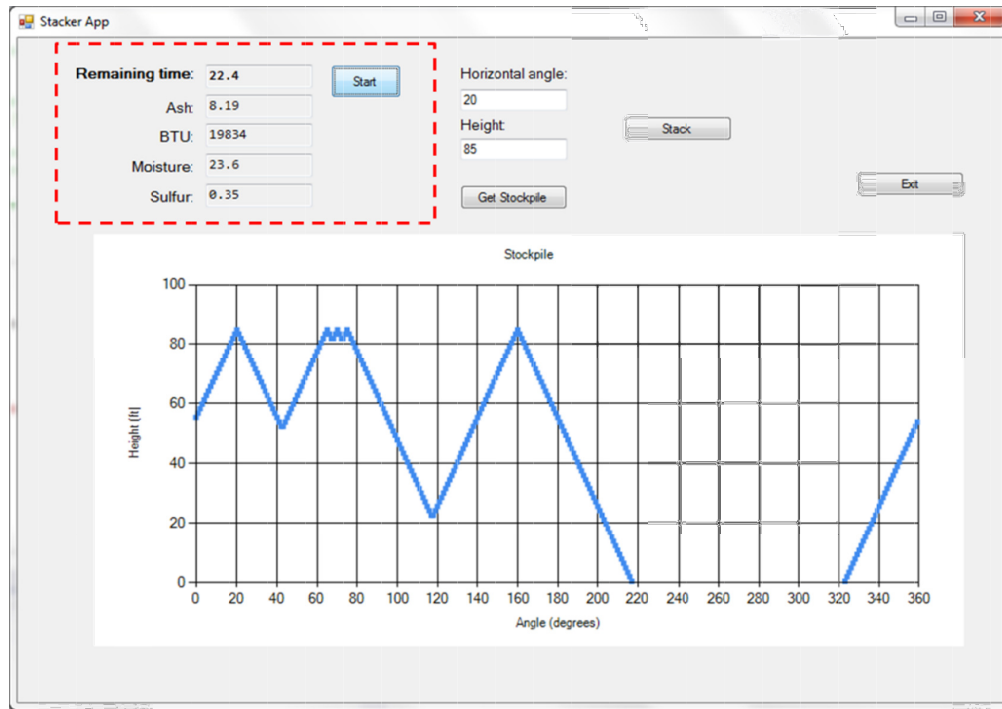


Figure 57. Remaining time and Analyzer real-time output window

Every combination of angle and height points and its associated quality tags are stored in the Stacker and Dynamic tables in the DS-CQMM database.

3.2.3 Reclaimer Application

After stacking coal inside the dome, it is important to know the range of coal quality and its location. It is also important that the operators have an intuitive interface. For that purpose, the Reclaimer Application provides the location of coal and, depending on the quality tag, it shows the range of quality distribution differentiated by colors.

Additionally, the Reclaimer Application provides values of coal quality in numerical values, dividing the dome by angle and height ranges and displaying them in a table. This is

implemented in a separate table for each quality tag and tonnage so that when the operator needs to know or “forecast” the other quality tags based on that table, all that is required is to make a simple cells selection.

The example starts from the stockpile that has been created with the Stacker Application. When the Reclaimer Application is launched, it displays the actual shape of the coal stockpile as shown in Figure 58. The display area shares the same concept as the Stacker Application where the stockpile is shown in two dimensions on plane θz where the radius is constant and coincides with the radius where the peak of the stockpile is located ($\rho = \rho_{peak}$).

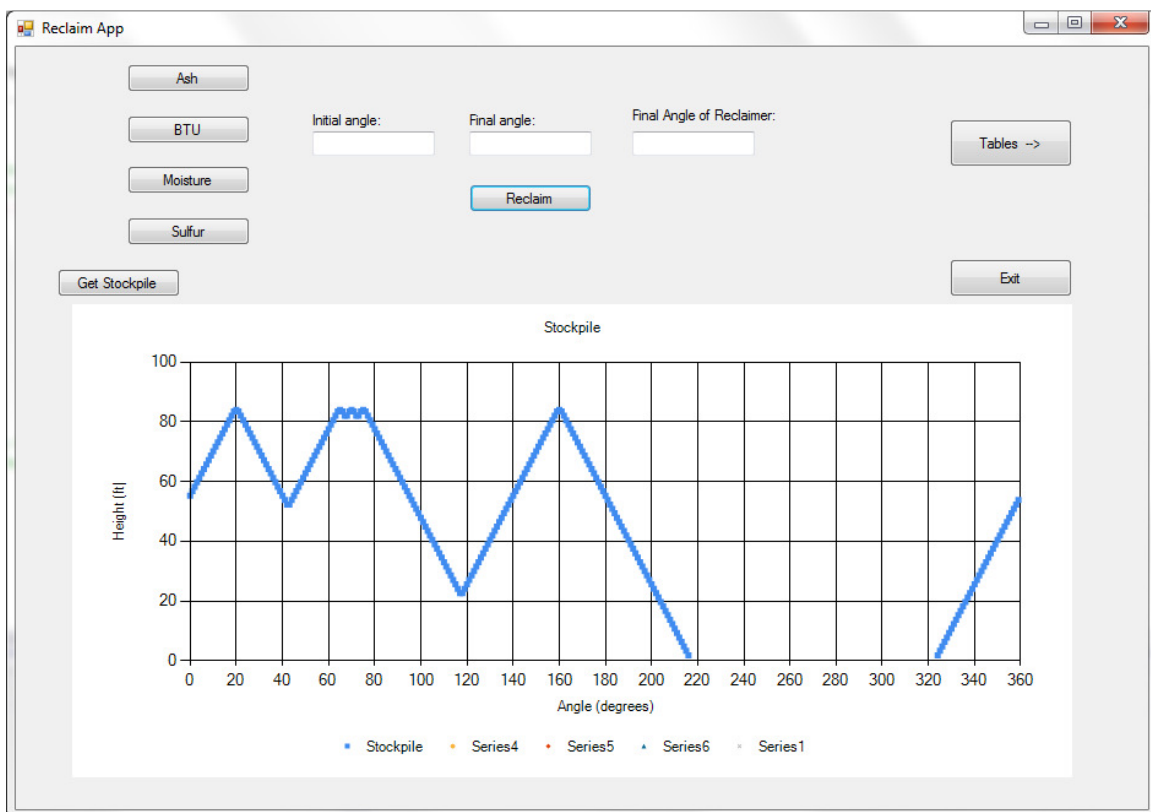


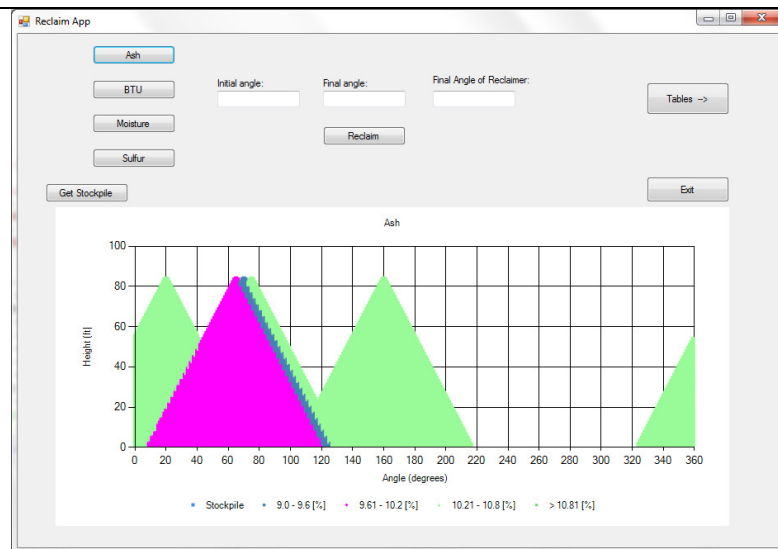
Figure 58. Actual stockpile's shape in Reclaimer Application

Now that the stockpile's actual shape is known, one can see the distribution of coal quality on the chart. Four coal quality tags are available in different colors for display. By selecting the corresponding buttons, the Reclaimer Application displays the quality distribution associated with the quality tag.

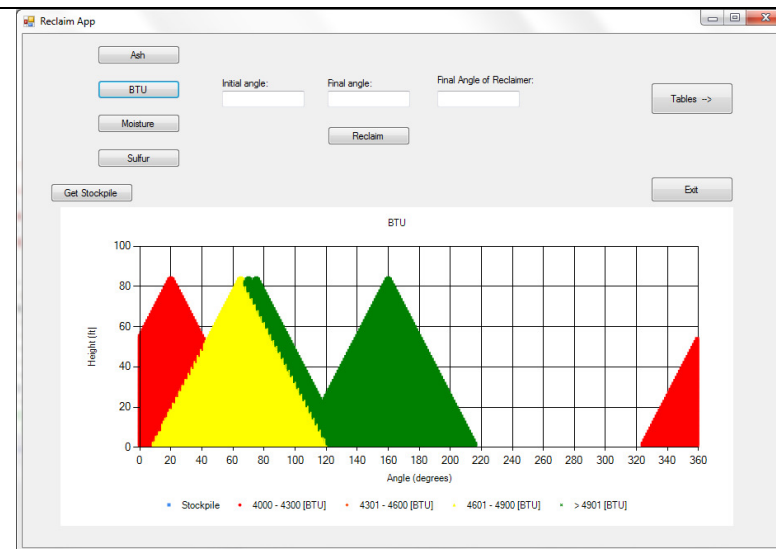
Figure 59 shows the different quality distributions in the dome. Figure 59a shows the distribution of ash. If one takes a generic point of the chart, it can be noted from the colors that the coal stacked at angle 80° and 60 ft., for instance, shows ash content between 9.61% and 10.20%.

Figure 59b shows the BTU distribution. The color ranges are shown at the bottom of the chart. If one take the point at angle 80° and height of 60 ft., it can be seen that the quantity of BTU per pound at this point is somewhere between 4,601 BTU/lb and 4,900 BTU/lb.

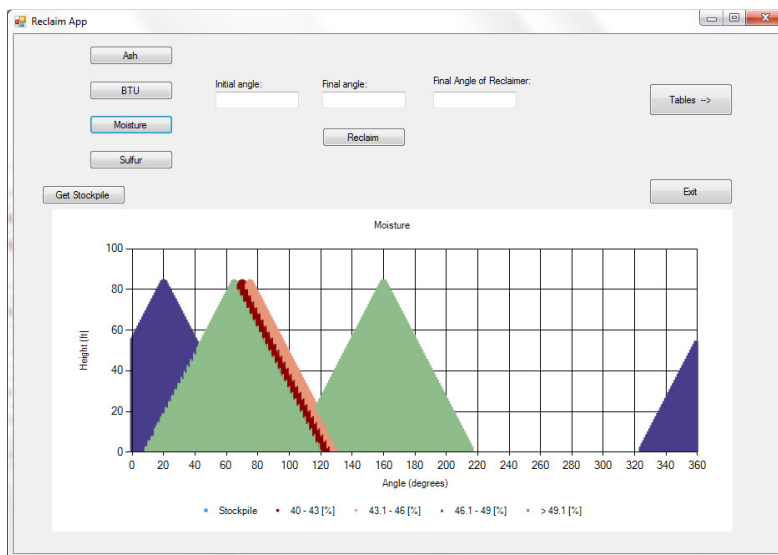
The moisture distribution is shown in Figure 59c. By taking the point at angle 80° and height of 60 ft., one may note that the moisture corresponding to the coal stacked at that point is between 46.1% and 49%. The same concept is applied to sulfur distribution (Figure 59d) where at this specific point it ranges between 0.92% and 0.94%.



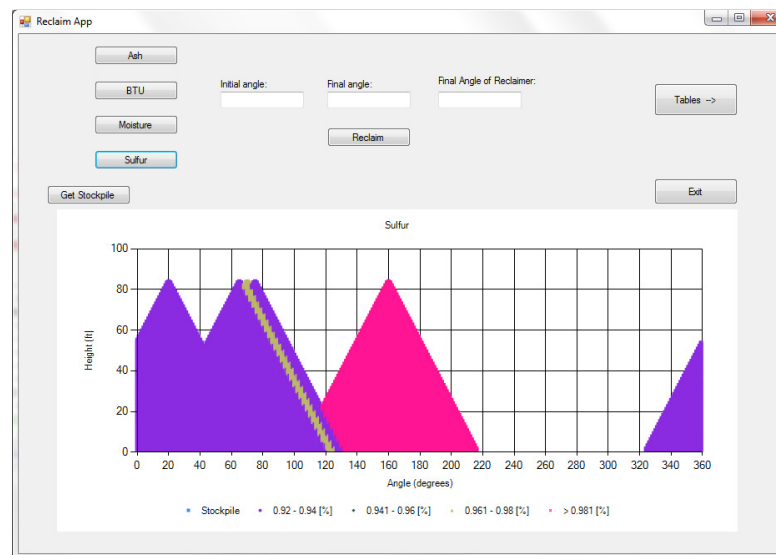
a) Ash distribution



b) BTU distribution



c) Moisture distribution



d) Sulfur distribution

Figure 59. Coal Quality distribution inside the Dome

Once the operator decides what portion of the stockpile will be reclaimed – either using a graphical (Reclaiming Application) or numerical (Forecast Tool) approach – the reclamation process is performed. After finishing reclaiming coal, the Reclaimer Application retrieves the required inputs from the DS-CQMM and DCS databases, and displays the remaining shape of coal stockpile inside the dome. This is shown in Figure 60, where the reclaimed coal has been removed from the dome starting at angle 5° and ending at angle 90° where the final angle of the Reclaimer (φ) is 30° .

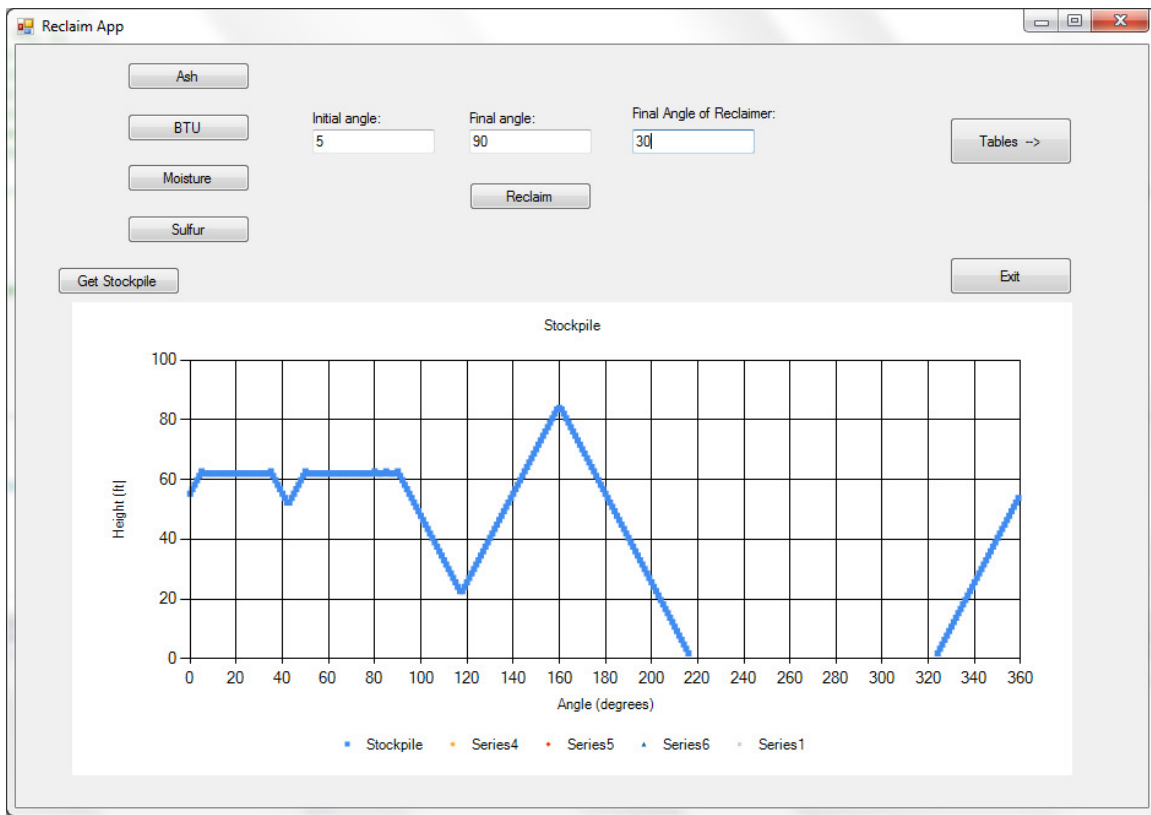


Figure 60. Stockpile's shape after coal reclaiming process from 5° to 90° and final Reclaimer angle of 30°

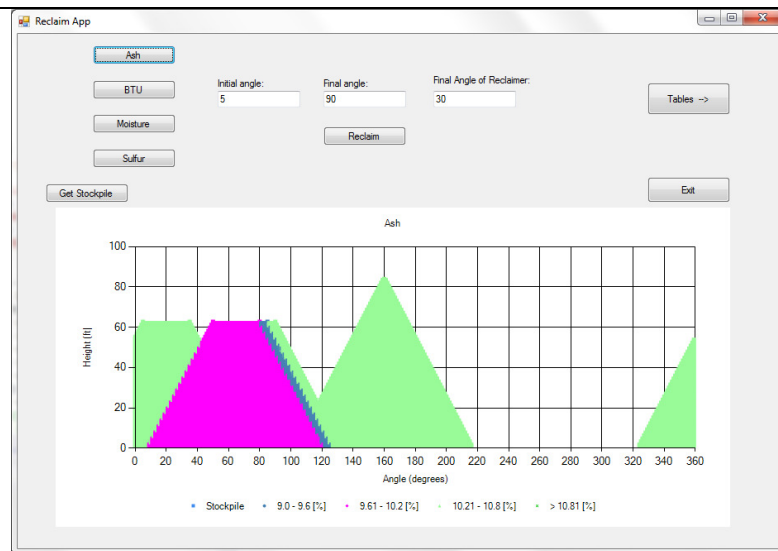
The peak of the stockpile is located at $\rho_{peak} = 109 \text{ ft.}$, so the final height of the reclaimed coal stockpile is $z_r = 63 \text{ ft.}$

The dome is discretized by 1-foot-height blocks, which means that the numerical values are rounded to the immediate integer. For this reason, it is possible to observe that the flat area of the stockpile in Figure 60 contains some “bumps” caused by the numerical rounding.

Figure 61 shows the different quality distributions of the remaining stockpile after the reclaiming process. Figure 61a, 10b, 10c, and 10d give the ash, BTU, moisture, and sulfur distributions, respectively. This graphical approach is useful for giving the operator a broad idea of the coal quality for a given portion of the dome in an easy and intuitive way. The operator is able to determine the range of a given quality tag for a particular quantity of coal stacked into the dome. Guided by the axis labels, it is possible to know where the coal is located for further reclaiming purposes.

The Forecast Tool is used for a more accurate approach and for an interactive way of calculating the average quality of a specific portion of coal. This tool displays an expandable menu where the quality tag tables are contained. Each table consists of cells that show the calculated average of quality within the range of angle and height that are shown on the headers of rows and columns. There is also a table for the summation of the tonnage using the same range division.

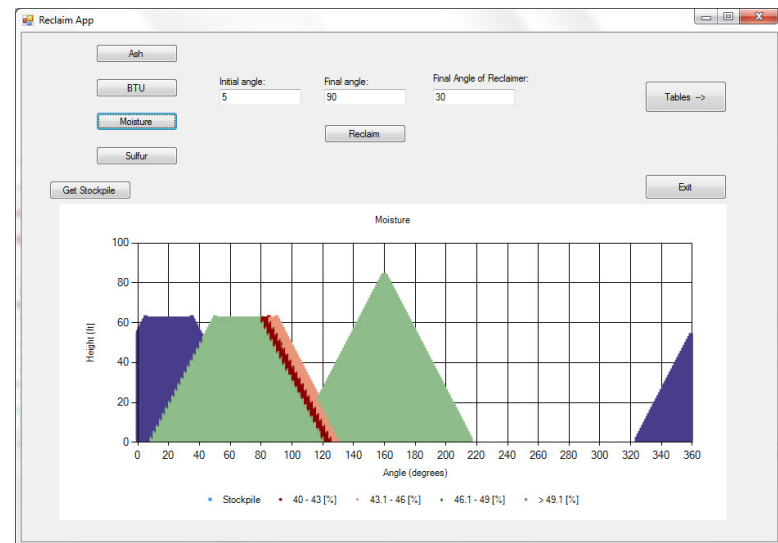
Figure 62 shows the scroll-down menu with the different options of coal quality tags and tonnage tables to be displayed in the grid.



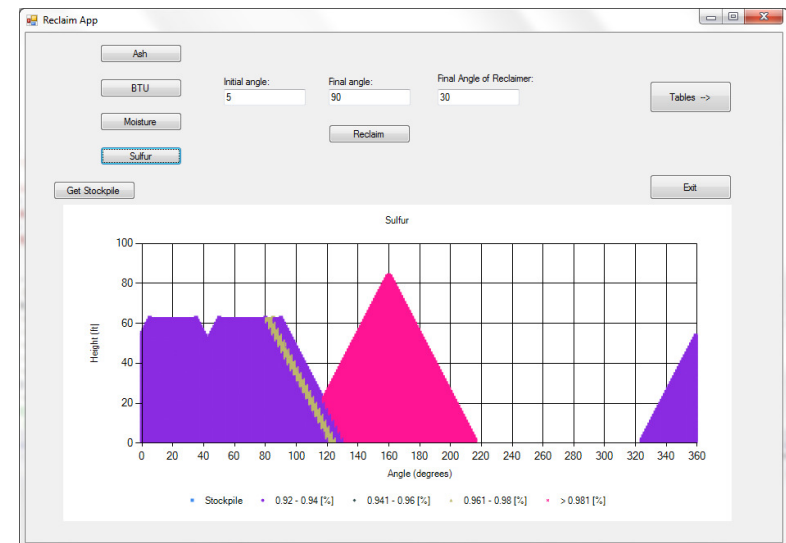
a) Ash distribution



b) BTU distribution



c) Moisture distribution



d) Sulfur distribution

Figure 61. Coal quality distribution after reclaiming process from 5° to 90° and final Reclaiming angle of 30°

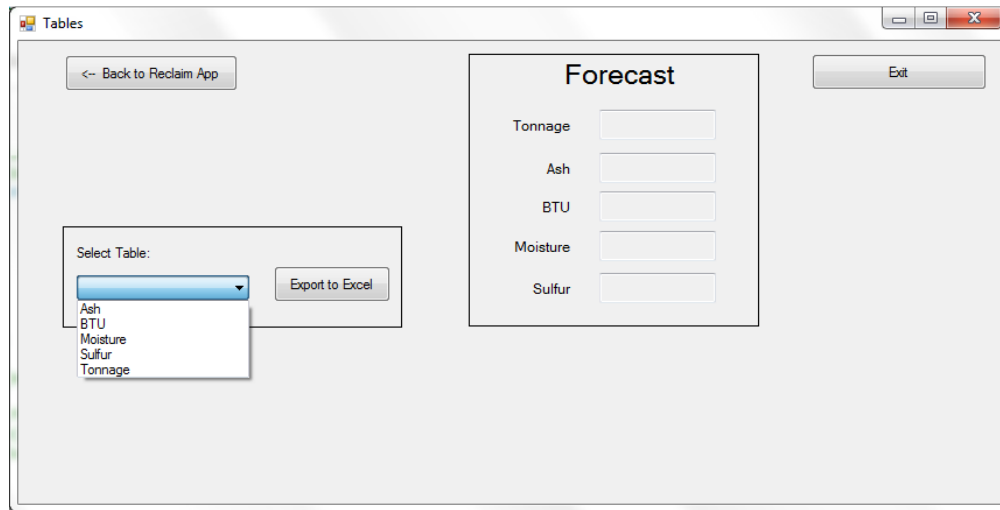


Figure 62. Forecast Tool menu

By selecting one of the tables in Figure 62, the Forecast Tool queries the Dynamic table in the DS-CQMM database and retrieves the average of the quality within the ranges if the option chosen is a quality tag, and retrieves the summation of the tonnage within the range if tonnage is chosen.

Figure 63 shows four tables for different quality tags. It is important to note that the range of angles displayed in the tables is from 0° to 200° . This range corresponds to the storage area of the dome; in other words, the area that does not belong to the Live Stockpile part.

The division ranges of the rows and columns of the tables are performed as follows: angle divisions (every 20°) and height divisions (every 5 ft.). These values could be changed internally in the program code.

Tables

Forecast

Tonnage: .00

Ash: 0

BTU: .0

Moisture: 0

Sulfur: 0

Select Table: Ash

Export to Excel

Exit

	0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140	140 - 160	160 - 180	180 - 200
80 - 85	0	0	0	0	0	0	0	9.86	9.86	0
75 - 80	0	0	0	0	0	0	0	9.86	9.86	0
70 - 75	9.87	9.87	9.71	9.6	9.81	0	0	9.86	9.86	0
65 - 70	9.87	9.87	9.71	9.63	9.69	0	0	9.86	9.86	0
60 - 65	9.87	9.87	9.71	9.69	9.58	0	0	9.86	9.86	0
55 - 60	9.87	9.87	9.71	9.71	9.61	0	0	9.86	9.86	0
50 - 55	9.87	9.87	9.72	9.71	9.62	0	0	9.86	9.86	9.86
45 - 50	9.87	9.86	9.71	9.71	9.62	9.81	9.86	9.86	9.86	9.86
40 - 45	9.87	9.84	9.71	9.71	9.6	9.81	9.86	9.86	9.86	9.86
35 - 40	9.87	9.81	9.71	9.71	9.62	9.7	9.86	9.86	9.86	9.86
30 - 35	9.87	9.78	9.71	9.71	9.69	9.58	9.86	9.86	9.86	9.86
25 - 30	9.87	9.76	9.71	9.71	9.59	9.86	9.86	9.86	9.86	9.86
20 - 25	9.87	9.73	9.71	9.71	9.71	9.64	9.86	9.86	9.86	9.86
15 - 20	9.86	9.71	9.71	9.71	9.71	9.63	9.86	9.86	9.86	9.86
10 - 15	9.84	9.71	9.71	9.71	9.71	9.61	9.85	9.86	9.86	9.86
5 - 10	9.81	9.71	9.71	9.71	9.71	9.63	9.8	9.86	9.86	9.86
0 - 5	9.78	9.71	9.71	9.71	9.71	9.69	9.72	9.86	9.86	9.86

a) Ash table

Tables

Forecast

Tonnage: .00

Ash: 0

BTU: .0

Moisture: 0

Sulfur: 0

Select Table: BTU

Export to Excel

Exit

	0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140	140 - 160	160 - 180	180 - 200
80 - 85	0	0	0	0	0	0	0	4990	4990	0
75 - 80	0	0	0	0	0	0	0	4990	4990	0
70 - 75	4260	4260	4730	4807	4910	0	0	4990	4990	0
65 - 70	4260	4260	4730	4777	4924	0	0	4990	4990	0
60 - 65	4260	4260	4730	4740	4932	0	0	4990	4990	0
55 - 60	4260	4260	4730	4730	4935	0	0	4990	4990	0
50 - 55	4260	4260	4698	4730	4872	0	0	4990	4990	4990
45 - 50	4260	4279	4721	4730	4854	4910	4990	4990	4990	4990
40 - 45	4260	4356	4730	4730	4824	4910	4990	4990	4990	4990
35 - 40	4260	4425	4730	4730	4785	4922	4990	4990	4990	4990
30 - 35	4260	4514	4730	4730	4740	4927	4990	4990	4990	4990
25 - 30	4260	4585	4730	4730	4730	4894	4990	4990	4990	4990
20 - 25	4260	4662	4730	4730	4730	4877	4990	4990	4990	4990
15 - 20	4288	4725	4730	4730	4730	4845	4988	4990	4990	4990
10 - 15	4355	4730	4730	4730	4730	4814	4978	4990	4990	4990
5 - 10	4433	4730	4730	4730	4730	4776	4967	4990	4990	4990
0 - 5	4511	4730	4730	4730	4730	4739	4960	4990	4990	4990

b) BTU table

Tables

Forecast

Tonnage: .00

Ash: 0

BTU: .0

Moisture: 0

Sulfur: 0

Select Table: Moisture

Export to Excel

Exit

	0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140	140 - 160	160 - 180	180 - 200
80 - 85	0	0	0	0	0	0	0	46.3	46.3	0
75 - 80	0	0	0	0	0	0	0	46.3	46.3	0
70 - 75	52.1	52.1	48.4	46.5	43.1	0	0	46.3	46.3	0
65 - 70	52.1	52.1	48.4	47.3	43	0	0	46.3	46.3	0
60 - 65	52.1	52.1	48.4	48.2	43	0	0	46.3	46.3	0
55 - 60	52.1	52.1	48.4	48.4	44	0	0	46.3	46.3	0
50 - 55	52.1	52.1	48.7	48.4	44.6	0	0	46.3	46.3	46.3
45 - 50	52.1	52	48.5	48.4	45.2	43.1	46.3	46.3	46.3	46.3
40 - 45	52.1	51.3	48.4	48.4	46	43.1	46.3	46.3	46.3	46.3
35 - 40	52.1	50.8	48.4	48.4	47.1	43	46.3	46.3	46.3	46.3
30 - 35	52.1	50.1	48.4	48.4	48.2	43.2	46.3	46.3	46.3	46.3
25 - 30	52.1	49.9	48.4	48.4	48.4	44.2	46.3	46.3	46.3	46.3
20 - 25	52.1	49.9	48.4	48.4	48.4	45.1	46.3	46.3	46.3	46.3
15 - 20	51.9	48.4	48.4	48.4	48.4	45.6	46.2	46.3	46.3	46.3
10 - 15	51.3	48.4	48.4	48.4	48.4	46.3	45.8	46.3	46.3	46.3
5 - 10	50.7	48.4	48.4	48.4	48.4	47.3	45.2	46.3	46.3	46.3
0 - 5	50.1	48.4	48.4	48.4	48.4	48.2	44.7	46.3	46.3	46.3

c) Moisture table

Tables

Forecast

Tonnage: .00

Ash: 0

BTU: .0

Moisture: 0

Sulfur: 0

Select Table: Sulfur

Export to Excel

Exit

	0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140	140 - 160	160 - 180	180 - 200
80 - 85	0	0	0	0	0	0	0	0.99	0.99	0
75 - 80	0	0	0	0	0	0	0	0.99	0.99	0
70 - 75	0.93	0.93	0.92	0.93	0.93	0	0	0.99	0.99	0
65 - 70	0.93	0.93	0.92	0.93	0.94	0	0	0.99	0.99	0
60 - 65	0.93	0.93	0.92	0.92	0.95	0	0	0.99	0.99	0
55 - 60	0.93	0.93	0.92	0.92	0.94	0	0.99	0.99	0.99	0
50 - 55	0.93	0.93	0.92	0.92	0.94	0	0.99	0.99	0.99	0.99
45 - 50	0.93	0.93	0.92	0.92	0.94	0.93	0.99	0.99	0.99	0.99
40 - 45	0.93	0.92	0.92	0.92	0.93	0.93	0.99	0.99	0.99	0.99
35 - 40	0.93	0.92	0.92	0.92	0.93	0.94	0.99	0.99	0.99	0.99
30 - 35	0.93	0.92	0.92	0.92	0.92	0.95	0.99	0.99	0.99	0.99
25 - 30	0.93	0.92	0.92	0.92	0.92	0.94	0.99	0.99	0.99	0.99
20 - 25	0.93	0.92	0.92	0.92	0.92	0.94	0.99	0.99	0.99	0.99
15 - 20	0.93	0.92	0.92	0.92	0.92	0.94	0.98	0.99	0.99	0.99
10 - 15	0.92	0.92	0.92	0.92	0.92	0.93	0.98	0.99	0.99	0.99
5 - 10	0.92	0.92	0.92	0.92	0.92	0.93	0.97	0.99	0.99	0.99
0 - 5	0.92	0.92	0.92	0.92	0.92	0.92	0.97	0.99	0.99	0.99

d) Sulfur table

Figure 63. Forecast quality tables

Figure 63a shows the “Ash” table. At angle 80° and 60 ft. height, the ash average in the range from 60° to 80° and from 55ft. to 60 ft. is 9.71%, which is consistent with the graphical range (9.61% and 10.20%).

The BTU table (Figure 63b) shows that for the same point (80° , 60 ft.) the average value is 4,730 BTU per pound, which is consistent with the graphical approach that shows the range between 4,601 BTU/lb. and 4,900 BTU/lb.

The Moisture table is shown on Figure 63c. By taking the example point at 80° and 60 ft., the average value of moisture content is 48.4%. Figure 63d shows the Sulfur table where the average value for that point is 0.92%. Both are consistent with their corresponding point in the graphical approach, which is 46.1% to 49% for moisture and 0.92% to 0.94% for sulfur.

There is an essential difference between the graphical and numerical approach. The highest height value for this example shown in the charts for the stockpile is around 63 ft. Recall that the GUI in two dimensions is developed in a plane that corresponds to a constant radius coincident with the stockpile’s peak radius (i.e. $\rho = \rho_{peak}$). Since the reclaiming process is performed in a perpendicular plane, it can not be completely reflected in the charts. However, this is avoided in the tables where the database is queried for the entire content of the dome. For this reason, the heights of the stockpile in the charts and in the tables are not consistent due to the existence of remainig coal “behind” the charts’ plane. That coal is stacked to a greater height than is shown in the graphical approach.

The Tonnage table uses a different concept. Figure 64 shows that it shares the same layout as the quality-tag tables; the difference is that the queries against the DS-CQMM database are different. The value displayed in cells is a total summation of the tonnage contained in the ranges shown in the headers of the rows and columns.

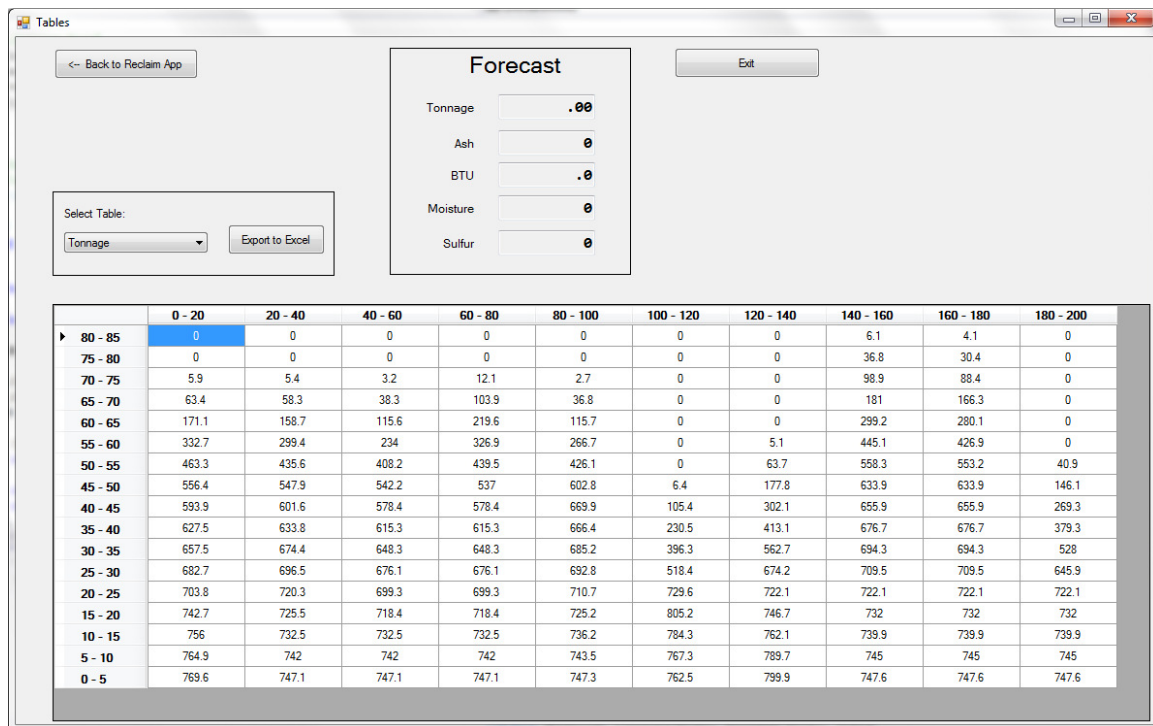


Figure 64. Forecast Tonnage table

The operator can switch between the different tables for performing a “reclaiming forecast” process based on the values displayed in cells. This is achieved by selecting the cells to be reclaimed; then the Forecast Tool returns the four coal quality tags’ average values and a total summation of the tonnage that will be reclaimed within that selection.

Assume that the operator needs to forecast a given portion of coal for reclaiming and its location inside the dome based on the quantity of coal. The “Tonnage” table should be selected for starting the process. By selecting which part of the dome’s coal will be reclaimed, the Forecast

Tool returns the total value of tonnage and the average of the four coal quality tags within the selected cells. Figure 65 shows a forecast process by selecting a range of cells.

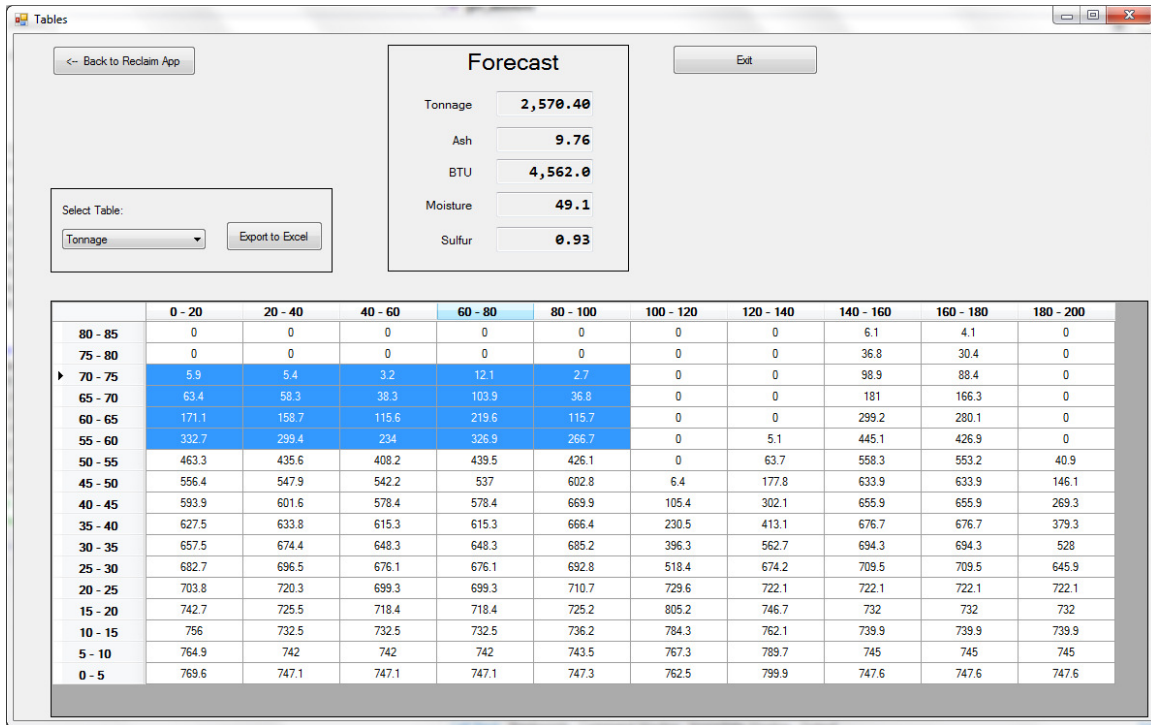


Figure 65. Reclaiming forecast from angle 0° to 100° and from 55 ft. to 75 ft. height

In this particular example, it was desired to know the quality and total tonnage of reclaimed coal from angle 0° to angle 100° and from 55 ft. to 75 ft. height. According to the queries, the reclaimed coal will have the following features:

- Total tonnage reclaimed: 2,570.40 tons.
- Average Ash content: 9.76%.
- Average BTU content: 4,562.0 BTU per lb.
- Average Moisture content: 49.1%.
- Average Sulfur content: 0.93%.

If the operator needs to know these values from another location inside the dome, then another selection needs to be performed. For instance, Figure 66 shows the selection range from angle 120° to angle 180° and from 50 ft. to 85 ft. of height.

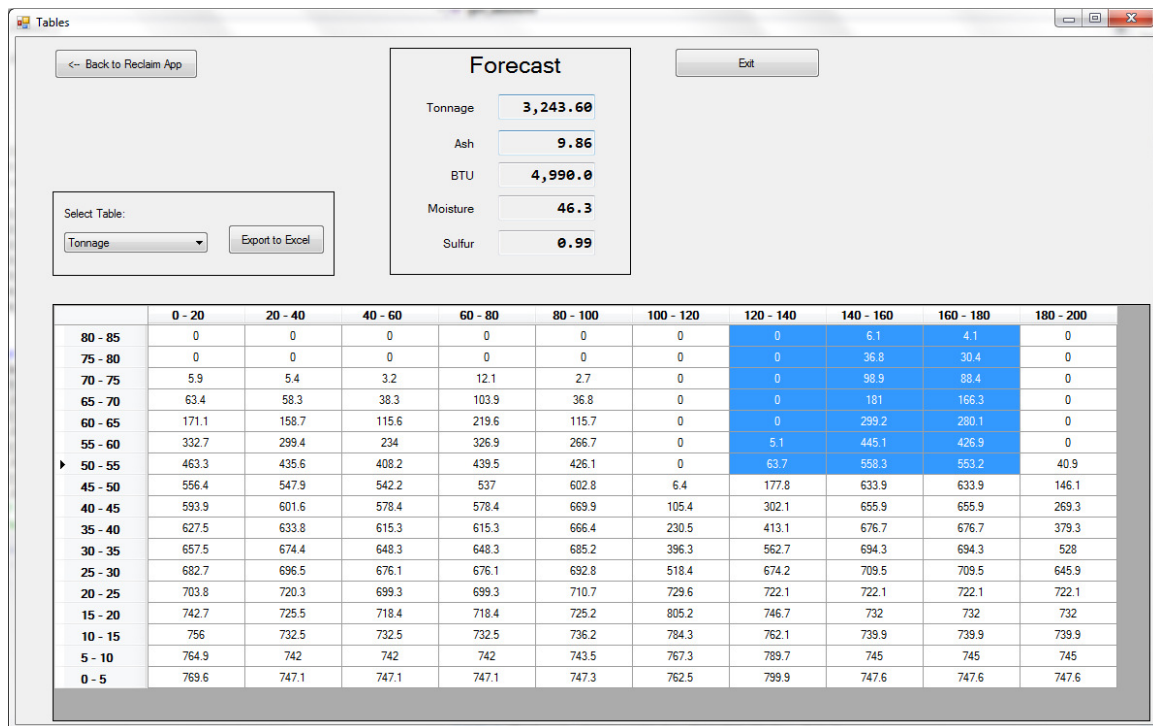


Figure 66. Reclaiming forecast from angle 120° to 180° and from 50 ft. to 85 ft. height

The Forecast Tool returns the following values:

- Total tonnage reclaimed: 3,243.60 tons.
- Average Ash content: 9.86%.
- Average BTU content: 4,990.0 BTU per lb.
- Average Moisture content: 46.3%.
- Average Sulfur content: 0.99%.

A very useful feature of the Reclaimer Application is the ability to export data to Microsoft Excel worksheets. Figure 67 shows the four quality-tag tables in different worksheets. Figure 67a- d show the Ash, BTU, Moisture, and Sulfur quality-tag tables.

The worksheets are populated with the Forecast Tool table values. By clicking on the “Export to Excel” button, the Application launches MS Excel and creates different worksheets labeled with the quality tag name, using the same division used in the Forecast Tool tables.

Height (ft)	0-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200
80-85	0	0	0	0	0	0	0	9.9	9.9	0
75-80	0	0	0	0	0	0	0	9.9	9.9	0
70-75	9.9	9.9	9.7	9.6	9.8	0	0	9.9	9.9	0
65-70	9.9	9.9	9.7	9.6	9.7	0	0	9.9	9.9	0
60-65	9.9	9.9	9.7	9.7	9.6	0	0	9.9	9.9	0
55-60	9.9	9.9	9.7	9.7	9.6	0	9.9	9.9	9.9	0
50-55	9.9	9.9	9.7	9.7	9.6	0	9.9	9.9	9.9	9.9
45-50	9.9	9.9	9.7	9.7	9.6	9.8	9.9	9.9	9.9	9.9
40-45	9.9	9.8	9.7	9.7	9.6	9.8	9.9	9.9	9.9	9.9
35-40	9.9	9.8	9.7	9.7	9.6	9.7	9.9	9.9	9.9	9.9
30-35	9.9	9.8	9.7	9.7	9.6	9.9	9.9	9.9	9.9	9.9
25-30	9.9	9.8	9.7	9.7	9.6	9.9	9.9	9.9	9.9	9.9
20-25	9.9	9.7	9.7	9.7	9.6	9.9	9.9	9.9	9.9	9.9
15-20	9.9	9.7	9.7	9.7	9.6	9.9	9.9	9.9	9.9	9.9
10-15	9.8	9.7	9.7	9.7	9.6	9.9	9.9	9.9	9.9	9.9
5-10	9.8	9.7	9.7	9.7	9.6	9.8	9.9	9.9	9.9	9.9
0-5	9.8	9.7	9.7	9.7	9.7	9.7	9.9	9.9	9.9	9.9

a) Ash worksheet

Height (ft)	0-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200
80-85	0	0	0	0	0	0	0	4990	4990	0
75-80	0	0	0	0	0	0	0	4990	4990	0
70-75	4260	4260	4730	4803	4910	0	0	4990	4990	0
65-70	4260	4260	4730	4771	4927	0	0	4990	4990	0
60-65	4260	4260	4730	4738	4930	0	0	4990	4990	0
55-60	4260	4260	4730	4730	4893	0	4990	4990	4990	0
50-55	4260	4260	4700	4730	4870	0	4990	4990	4990	4990
45-50	4260	4284	4723	4730	4851	4910	4990	4990	4990	4990
40-45	4260	4359	4730	4730	4821	4910	4990	4990	4990	4990
35-40	4260	4433	4730	4730	4780	4924	4990	4990	4990	4990
30-35	4260	4518	4730	4730	4738	4926	4990	4990	4990	4990
25-30	4260	4593	4730	4730	4730	4891	4990	4990	4990	4990
20-25	4260	4669	4730	4730	4730	4875	4990	4990	4990	4990
15-20	4291	4726	4730	4730	4730	4842	4987	4990	4990	4990
10-15	4363	4730	4730	4730	4730	4810	4976	4990	4990	4990
5-10	4439	4730	4730	4730	4730	4773	4967	4990	4990	4990
0-5	4511	4730	4730	4730	4730	4739	4960	4990	4990	4990

b) BTU worksheet

Height (ft)	0-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200
80-85	0	0	0	0	0	0	0	46.3	46.3	0
75-80	0	0	0	0	0	0	0	46.3	46.3	0
70-75	52.1	52.1	48.4	46.6	43.1	0	0	46.3	46.3	0
65-70	52.1	52.1	48.4	47.4	43	0	0	46.3	46.3	0
60-65	52.1	52.1	48.4	48.2	43.1	0	0	46.3	46.3	0
55-60	52.1	52.1	48.4	48.4	44.1	0	46.3	46.3	46.3	0
50-55	52.1	52.1	48.6	48.4	44.7	0	46.3	46.3	46.3	46.3
45-50	52.1	51.9	48.5	48.4	45.2	43.1	46.3	46.3	46.3	46.3
40-45	52.1	51.3	48.4	48.4	46.1	43.1	46.3	46.3	46.3	46.3
35-40	52.1	50.7	48.4	48.4	47.2	43	46.3	46.3	46.3	46.3
30-35	52.1	50.1	48.4	48.4	48.2	43.2	46.3	46.3	46.3	46.3
25-30	52.1	49.5	48.4	48.4	48.4	44.3	46.3	46.3	46.3	46.3
20-25	52.1	48.9	48.4	48.4	48.4	45.2	46.3	46.3	46.3	46.3
15-20	51.9	48.4	48.4	48.4	48.4	45.6	46.2	46.3	46.3	46.3
10-15	51.3	48.4	48.4	48.4	48.4	46.4	45.8	46.3	46.3	46.3
5-10	50.7	48.4	48.4	48.4	48.4	47.4	45.1	46.3	46.3	46.3
0-5	50.1	48.4	48.4	48.4	48.4	48.2	44.7	46.3	46.3	46.3

c) Moisture worksheet

Height (ft)	0-20	21-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200
80-85	0	0	0	0	0	0	0	0.99	0.99	0
75-80	0	0	0	0	0	0	0	0.99	0.99	0
70-75	0.93	0.93	0.92	0.93	0.93	0	0	0.99	0.99	0
65-70	0.93	0.93	0.92	0.93	0.94	0	0	0.99	0.99	0
60-65	0.93	0.93	0.92	0.92	0.95	0	0	0.99	0.99	0
55-60	0.93	0.93	0.92	0.92	0.94	0	0.99	0.99	0.99	0
50-55	0.93	0.93	0.92	0.92	0.94	0	0.99	0.99	0.99	0.99
45-50	0.93	0.93	0.92	0.92	0.94	0.93	0.99	0.99	0.99	0.99
40-45	0.93	0.92	0.92	0.92	0.93	0.93	0.99	0.99	0.99	0.99
35-40	0.93	0.92	0.92	0.92	0.93	0.94	0.99	0.99	0.99	0.99
30-35	0.93	0.92	0.92	0.92	0.92	0.95	0.99	0.99	0.99	0.99
25-30	0.93	0.92	0.92	0.92	0.92	0.94	0.99	0.99	0.99	0.99
20-25	0.93	0.92	0.92	0.92	0.92	0.94	0.99	0.99	0.99	0.99
15-20	0.93	0.92	0.92	0.92	0.92	0.94	0.98	0.99	0.99	0.99
10-15	0.92	0.92	0.92	0.92	0.92	0.93	0.98	0.99	0.99	0.99
5-10	0.92	0.92	0.92	0.92	0.92	0.93	0.97	0.99	0.99	0.99
0-5	0.92	0.92	0.92	0.92	0.92	0.92	0.97	0.99	0.99	0.99

d) Sulfur worksheet

Figure 67. Exported values to Microsoft Excel worksheets

Finally, Figure 68 shows the tonnage in MS Excel worksheet. All tables are updated every time the Dynamic table in the DS-CQMM database is changed.

	Horizontal Angle (degrees)									
	0 - 20	21 - 40	41 - 60	61 - 80	81 - 100	101 - 120	121 - 140	141 - 160	161 - 180	181 - 200
80 - 85	0	0	0	0	0	0	0	9.5	6.7	0
75 - 80	0	0	0	0	0	0	0	49.3	41.2	0
70 - 75	11.2	10.2	5.9	22.8	4.8	0	0	124.9	111.7	0
65 - 70	87.7	81	54	138.7	50.8	0	0	230.4	212.2	0
60 - 65	221	204.2	149.8	276.4	148.5	0	0	372.8	349.4	0
55 - 60	414.9	372.7	291.9	404.1	325.8	0	5.1	547.7	524.3	0
50 - 55	571.4	539.5	512.1	543.4	528	0	88.7	683.3	678.2	59.6
45 - 50	672.6	660.8	655.1	649.9	724	12.9	223.1	763.4	763.4	185
40 - 45	716.8	721.7	698.5	698.5	796.9	132.2	369.1	789.9	789.9	329.7
35 - 40	756.9	761.1	742.5	742.5	798.7	285.5	509.4	814.2	814.2	468.7
30 - 35	792.4	807.8	781.7	781.7	822.1	473.6	682.2	834.9	834.9	640.4
25 - 30	821.9	834.6	814.1	814.1	833.6	633.2	817.8	853	853	789.4
20 - 25	846.8	862.6	841.6	841.6	854.7	875.3	867.7	867.7	867.7	867.7
15 - 20	888.8	871.1	864	864	871.7	952.7	894.2	879.5	879.5	879.5
10 - 15	903.9	880.2	880.2	880.2	884.4	933	910.7	888.5	888.5	888.5
5 - 10	914.1	891.2	891.2	891.2	892.7	916.7	939	894.3	894.3	894.3
0 - 5	769.6	747.1	747.1	747.1	747.3	762.5	799.9	747.6	747.6	747.6

Figure 68. Tonnage worksheet

3.2.4 Live Stockpile Application

This is a specific part of the dome that covers the area from angle of 200° to 360° . The emergency reclaimer is installed at ground level at angle of 290° . Live Stockpile is characterized by its dynamic behavior of continuous stacking and reclaiming processes increasing and decreasing its height regularly.

When the Live Stockpile Application is launched, the stockpile's actual shape is displayed for the mine operator. Since the data shown in the display area is retrieved from the database from angle 200° to 360° , there could be some parts of the branches of other stockpiles from other parts

of the dome that were stacked into parts that do not belong to the Live Stockpile area. This situation is shown in Figure 69 where the initial display shows two branches of stacked stockpiles.

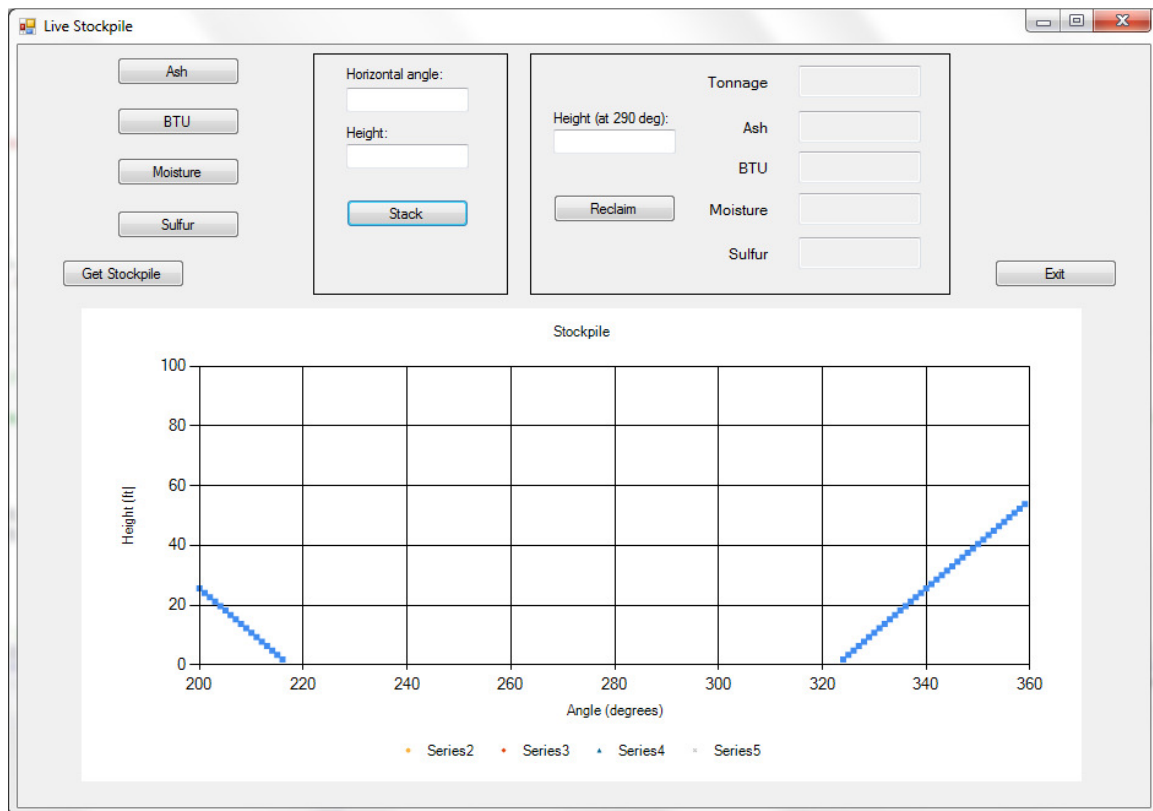


Figure 69. Live Stockpile Application initial display

After displaying the actual state of the stockpile within the Live Stockpile area, the stacking process can start. As in the Stacker Application, the boom of the stacker rotates and its rotational angle is measured by the encoders through the PLC, which provides this value to the DCS database.

Suppose that the angular position of the boom of the stacker is 240° . It stacks coal up to 85 ft. Its height is measured by the ultrasonic sensor located at the boom of the Stacker and stored in the DCS database. The stockpile's final shape is shown in Figure 70a.

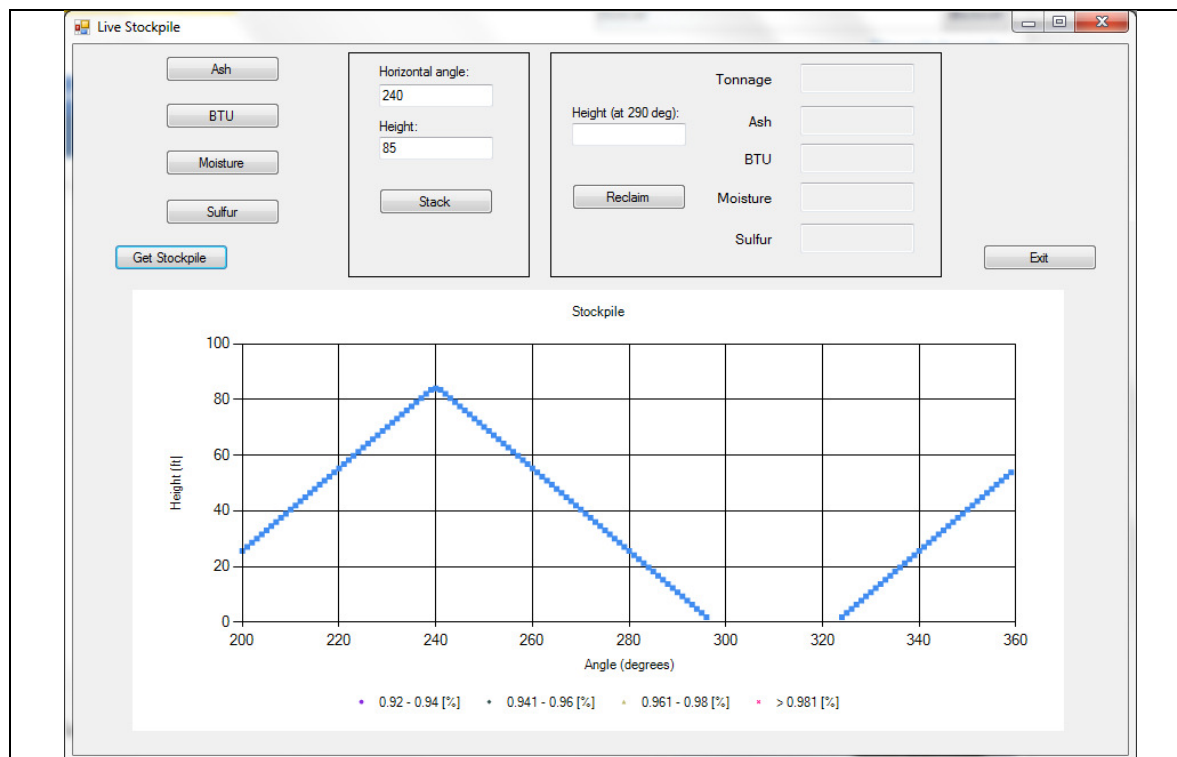
At this point, the blocks containing the tonnage and quality tags created by stacking part of the Live Stockpile Application are stored in the Dynamic and Stacker tables in the DS-CQMM database.

If one assumes that the boom of the stacker moves to angle 290° (which is the position where the Emergency Reclaimer is installed) and stacks up to 85 ft. (the maximum height designed to be stacked inside the dome), the shape of the stockpile is created as shown in Figure 70b.

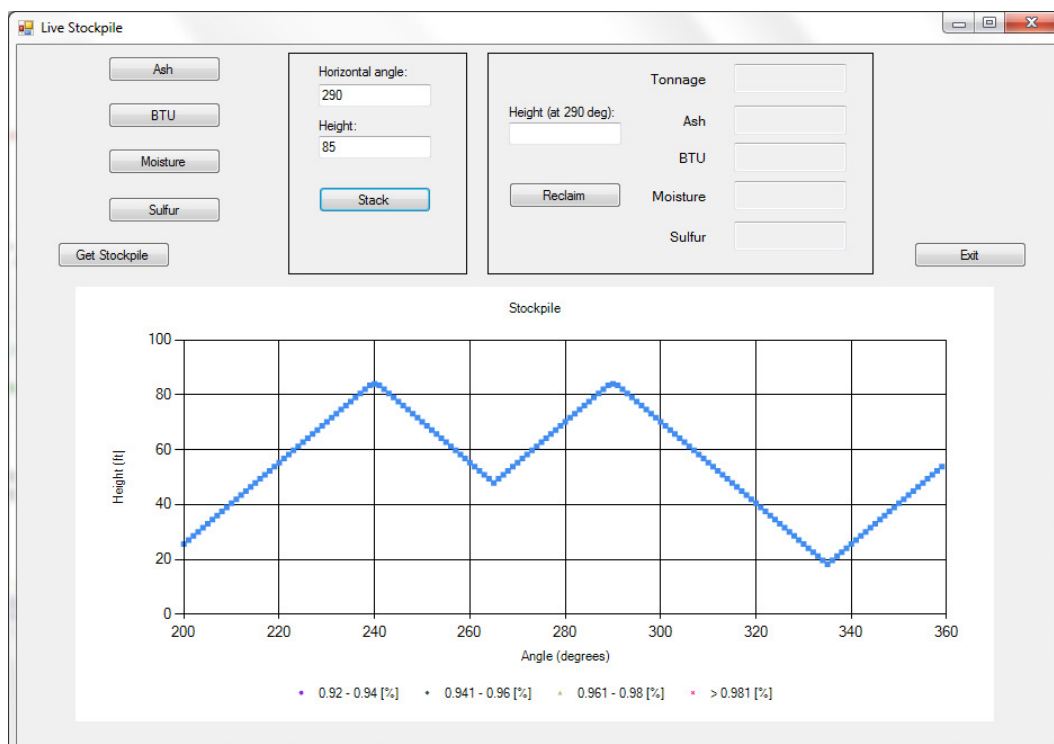
This stockpile has a dynamic behavior, increasing and decreasing its height constantly. An ultrasonic sensor is installed above the emergency reclaimer at the dome for measuring the Live Stockpile's height even if the boom of the stacker is not located at this angle.

The quality distribution display part of this Application is similar to the previous Reclaimer Application; it shows the distribution of the coal quality inside the dome by selecting quality tags buttons.

Figure 71a shows the ash distribution. Let's take any given point of the stockpile, such as angle 300° and 40 ft. The ash content of that particular point of the coal stockpile is in the range between 9.0% and 9.6%.



a) Stacking at 240° up to 85 ft.

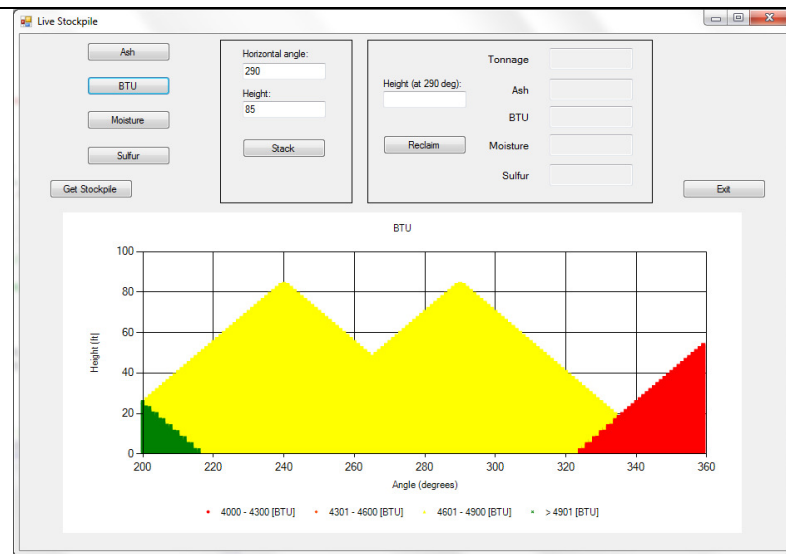


b) Stacking at 290° up to 85 ft.

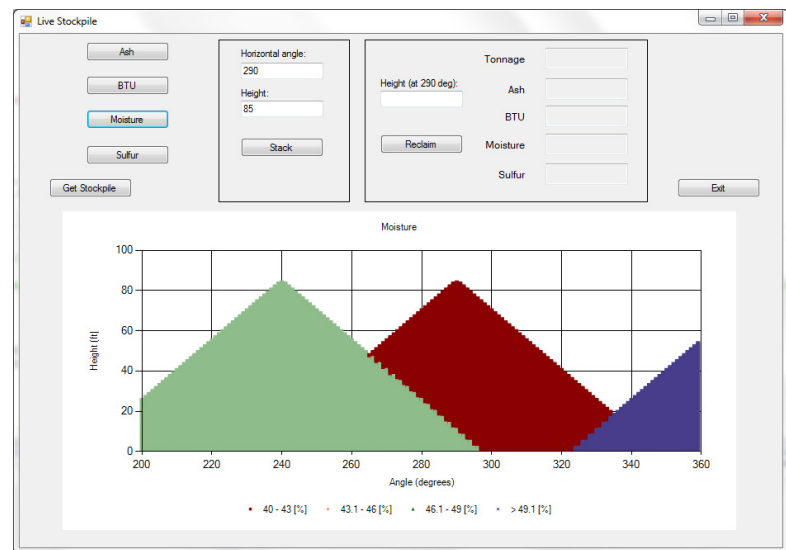
Figure 70. Stacking process at Live Stockpile area



a) Ash distribution



b) BTU distribution



c) Moisture distribution



d) Sulfur distribution

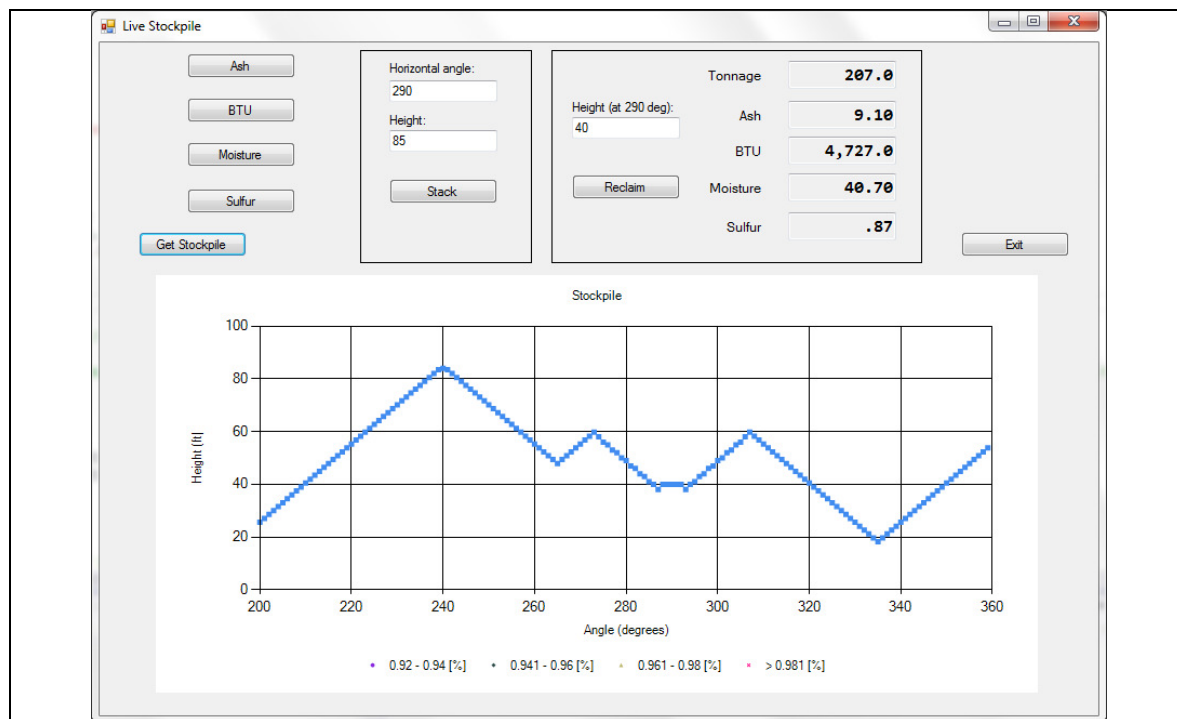
Figure 71. Coal quality distribution at Live Stockpile

The BTU per pound distribution is shown in Figure 71b. By considering the same point as for ash distribution, one may note that the range of BTU for that point is between 4,601 BTU/lb. and 4,900 BTU/lb. Figure 71c shows the moisture content distribution. At 300° and 40 ft. height the moisture content of the stacked coal is between 40% and 43%. Finally, the sulfur content distribution is shown in Figure 71d. The content of sulfur on the stacked coal is between 0.92% and 0.94%.

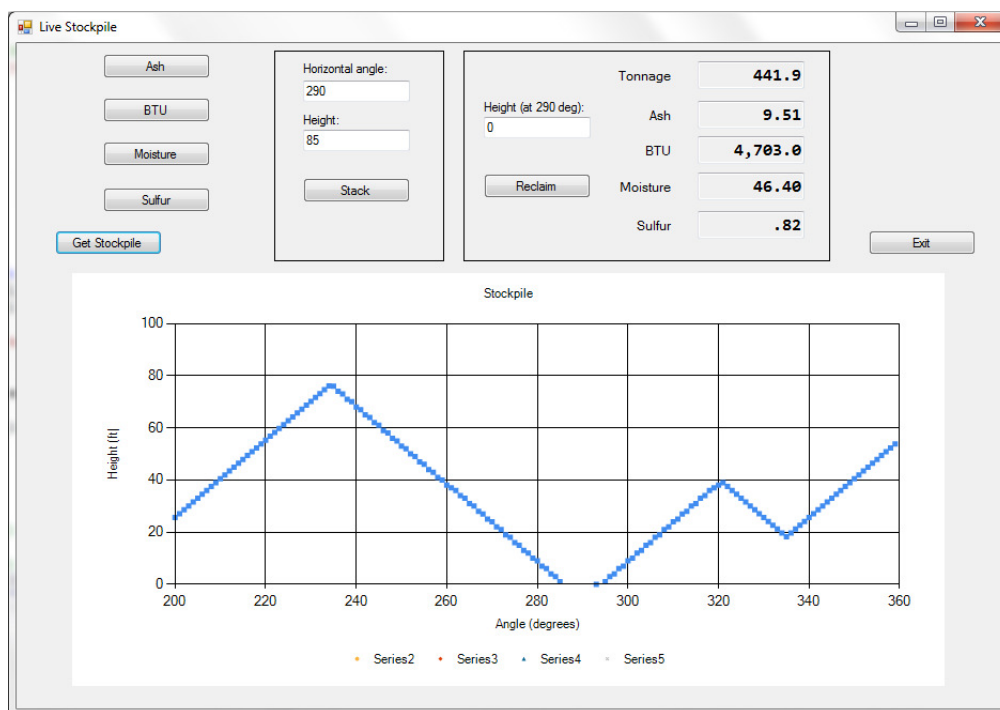
If the operator activates the emergency reclaimer, the stockpile will decrease its height due to the reclaiming process. The ultrasonic sensor provides the height and the Live Stockpile Application builds the stockpile. Figure 72a shows the shape of the stockpile after being reclaimed to 40 ft. It has a flat zone due to the width of the emergency reclaimer. The slope of the reclaimed part has the same slope as the rest of the stockpile, which is the angle of repose of coal.

If the operator keeps reclaiming all the available coal at the Live Stockpile, then the final height eventually will become zero. This situation is shown in Figure 72b. The stockpile has the flat zone due to the width of the emergency reclaimer. It is important to note that, along with the final shape of the stockpile, the numerical values of the average of the quality tags and the total summation of the tonnage of the reclaimed coal are shown.

The Live Stockpile Application can show the quality distribution at any moment. Figure 73 shows the different quality distributions after the reclaiming process. The ash, BTU, moisture, and sulfur distribution are shown in Figure 73a-d, respectively.



a) Stockpile's shape after reclaiming to 40 ft.



b) Stockpile's shape after reclaiming to ground level

Figure 72. Reclaiming process at Live Stockpile

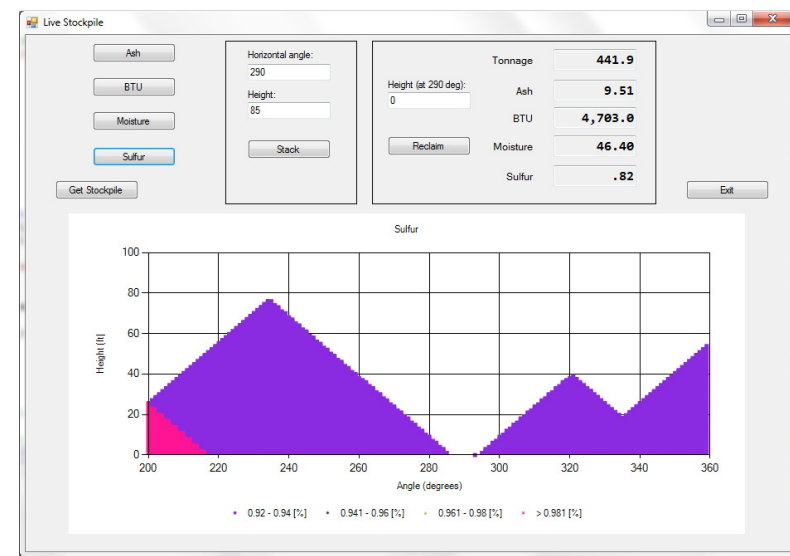
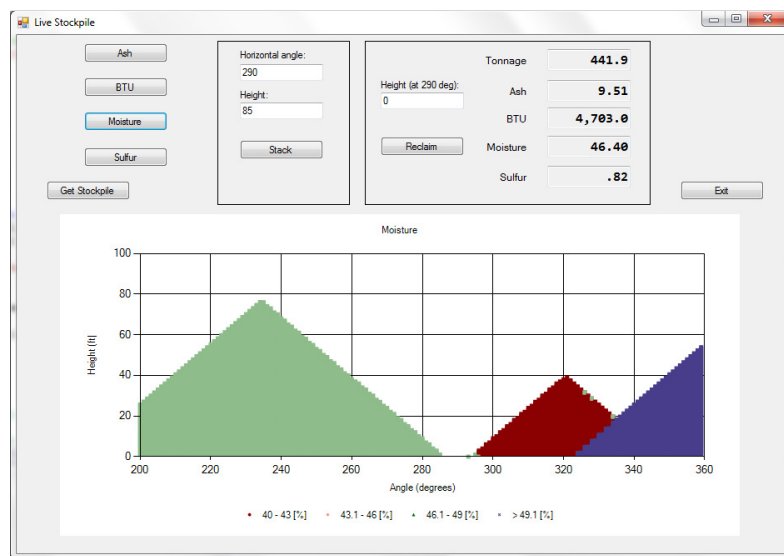
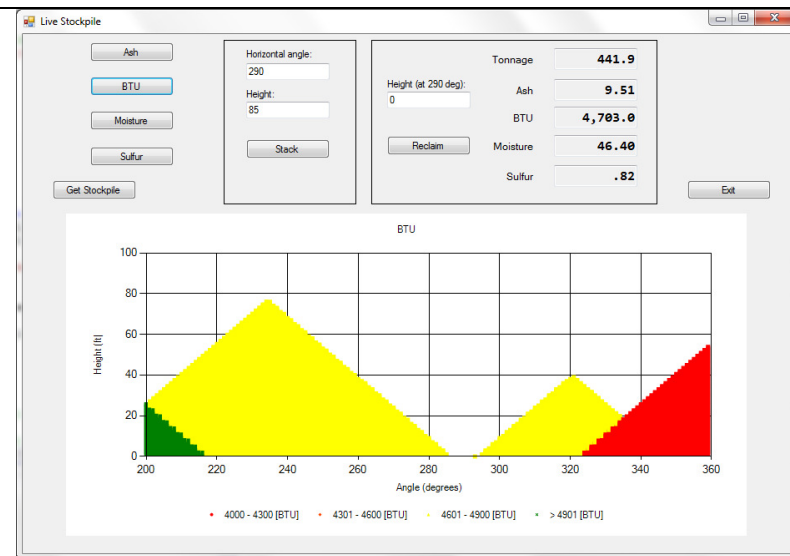
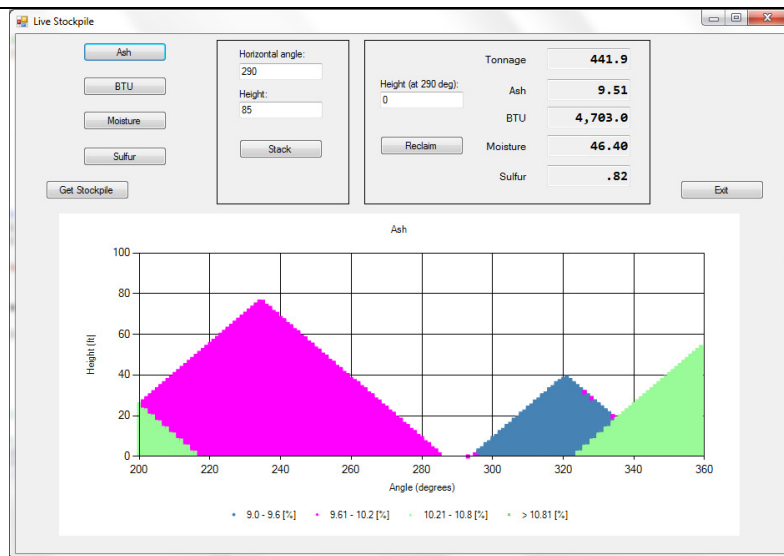


Figure 73. Coal quality distribution after reclaiming process at Live Stockpile

3.3 Sample of data in DS-CQMM database

Table 4 shows a sample of one of the tables of the DS-CQMM database which contains the exact location of each block inside the dome, its quality values and its tonnage. Each row contains the timestamp and ID associated with every property of every block of the dome.

For instance, at 11:36 am at 123°, 20 ft. of height, and 116 ft. of radius, a block of 0.07086 tons with 9.86% of ash content, 4,990 BTU/lb., 46.3% of moisture, and 0.986 % of sulfur is stacked or reclaimed (depending on the table) into the dome. The purpose of showing Table 4 is merely illustrative; it is intended to show a small sample of random rows stored in any of the three tables of the DS-CQMM database.

Table 4. DS-CQMM database sample

Id	Time	Horizontal Angle (degrees)	Height (ft.)	Radius (ft.)	Tonnage (tons)	Ash (%)	BTU (BTU/lb.)	Moisture (%)	Sulfur (%)
6561655	11/20/14 11:22	11	1	43	0.026267	9.71	4730	48.4	0.919
6562471	11/20/14 11:22	12	1	94	0.057421	9.71	4730	48.4	0.919
6583618	11/20/14 11:23	22	15	97	0.059254	9.71	4730	48.4	0.919
6584614	11/20/14 11:23	23	1	139	0.08491	9.71	4730	48.4	0.919
6755104	11/20/14 11:26	53	40	102	0.062308	9.71	4730	48.4	0.919
6755828	11/20/14 11:26	53	47	123	0.075136	9.71	4730	48.4	0.919
6895518	11/20/14 11:29	71	1	151	0.092241	9.71	4730	48.4	0.919
6896244	11/20/14 11:29	72	60	132	0.080634	9.71	4730	48.4	0.919
6911017	11/20/14 11:29	74	66	112	0.068417	9.71	4730	48.4	0.919
6912739	11/20/14 11:29	74	44	125	0.076358	9.71	4730	48.4	0.919
6913558	11/20/14 11:29	74	36	94	0.057421	9.71	4730	48.4	0.919
7086759	11/20/14 11:32	102	9	155	0.094684	9.71	4730	48.4	0.919
7087483	11/20/14 11:32	102	4	133	0.081245	9.71	4730	48.4	0.919
7088207	11/20/14 11:32	103	28	155	0.094684	9.71	4730	48.4	0.919
7088932	11/20/14 11:32	103	22	127	0.07758	9.71	4730	48.4	0.919
7201568	11/20/14 11:34	116	19	89	0.054367	9.81	4910	43.1	0.931
7202559	11/20/14 11:34	117	18	29	0.017715	9.81	4910	43.1	0.931
7203555	11/20/14 11:34	118	18	92	0.0562	9.81	4910	43.1	0.931
7224117	11/20/14 11:36	123	20	116	0.07086	9.86	4990	46.3	0.986
7224565	11/20/14 11:36	123	24	52	0.031765	9.86	4990	46.3	0.986
7225109	11/20/14 11:36	123	28	104	0.06353	9.86	4990	46.3	0.986
7225471	11/20/14 11:36	124	12	87	0.053145	9.86	4990	46.3	0.986
7225921	11/20/14 11:36	124	15	120	0.073304	9.86	4990	46.3	0.986

Chapter 4

Summary, Conclusions, and Recommendations for Future Research

Chapter 1 provided a brief introduction to importance of coal quality management in the mining industry, coal blending techniques, coal analyzers, and different uses of dome storage in mining and other fields. This chapter also provides a problem statement and scope of the work on development of the Coal Quality Management Model for Dome Storage (DS-CQMM).

Chapter 2 proposed a technical approach to development of the DS-CQMM) model. This customized model was developed using mathematical models and computer algorithms. The relative position and different coal properties (ash, BTU, moisture, sulfur) and tonnage of the coal stored inside the dome were determined. Discretization of the dome in three dimensions was described in order to determine the volume of stacked coal inside the dome. The different Applications described in this methodology were divided into the Delay Time Application, Stacker Application, Reclaimer Application, and Live Stockpile Application. The Stacker Application included a sub-process called Volume Calculation while the Reclaimer Application provided an additional feature called the Forecast Tool. This chapter also described the database interaction within the DS-CQMM model.

Chapter 3 provided the results of the implementation of the DS-CQMM. The Applications' GUI was tested and a case study for the DS-CQMM was presented. The coal was stacked inside the dome showing the quality tags and tonnage, and then graphical and numerical interpretation of

results during the reclaiming process. After the reclaiming process, the shape and quality of the remaining coal was shown. Finally, the Live Stockpile area inside the dome was presented when coal was stacked and reclaimed.

Chapter 4 presented a brief summary of the main topics addressed in this project. It also included a final analysis of the DS-CQMM and its capabilities of providing quality distribution and tonnage of coal stored inside the dome.

The results of the use of the DS-CQMM model can be summarized as follows:

- User-friendly and intuitive interface was developed.
- Robust mathematical models for different DS-CQMM Applications were implemented.
- Mathematical model for volume calculation was developed and implemented.
- Interaction between DS-CQMM Applications and databases was established.
- Algorithm for three-dimensional assignment of coal properties during the stacking process was developed.
- Algorithm for reclaiming process based on reclaimer's operations was developed.
- Coal quality distribution display in graphical mode and numerical values was displayed.
- Useful tool to forecast coal reclaiming process was implemented.
- Resulting numerical values can be exported to Microsoft Excel worksheets for further analysis.
- The DS-CQMM was presented to and verified by the mine management in order to satisfy their requirements for the specific mine and power plant.

The DS-CQMM model developed through this research provided graphical and numerical distribution of coal quality and its relative position inside the dome by integration of a variety of technologies. Further research should focus on enhancing the existing DS-CQMM as follows:

- Developing a three-dimensional view of the coal stockpile. This model incorporates a three-dimensional model to a certain extent. Further focus should be placed on retrieving the coordinates for each point (already established in the present research project) and displaying a 3D graphic differentiating quality tags by colors.
- The volume calculation can be enhanced by using weight scales integrated at the belt conveyor system. The research should be focused on integrating the data generated by the scale and the Delay Time Application in order to “attach” the weight of each batch of coal along with its quality.
- An additional input can be implemented in the DS-CQMM. This input is the Quality Target (QT), which is the quality required for reclaimed coal. The research should focus on developing an optimization algorithm that allows the DS-CQMM to show the possible areas of the stockpile that can be reclaimed in order to meet the QT. One of the restrictions of the optimization algorithm can be the total tonnage of reclaimed coal.
- Stockpile height measurement can be upgraded by utilizing an Unmanned Aerial Vehicle (UAV) such as a quadrotor (or quadcopter), which would carry a measurement device (e.g. LIDAR) and would determine the stockpile’s height. The research should focus on

wireless integration of the UAV's on-board microprocessor and the DS-CQMM for building a more accurate 3D model.

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