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Research Article

Improving Kiln Feed Chemistry and Overburden Wasting through Controlled Consistent Quarry Material Mix: A Case Study at Union Bridge Cement Plant

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Keywords

Quarry,
Mining Sequencing,
Chemistry,
Raw Mill Feed,
Kiln Feed,
Clinker.

Abstract

Cement is made by milling clinker with a mix of grinded gypsum. The clinker is produced using a rotary kiln which burns a mixture of limestone, clay, magnesium, silica, and iron with desired atomic percentages. The quarry is the primary source of raw material for the rotary kiln in cement production. The consistency of material feed chemistry, in which the quarry plays a key role, is crucial for optimizing the performance of a rotary kiln. The quarry implemented a six-step methodology that comprised a modified 3D mining software modeling tool, a database computer loop prediction tools, and other tools to improve mining sequencing, optimize raw material usage, and provide consistent chemistry mix material for the kiln. By using overburden as a raw material in the mix, the quarry nearly universally reduces the environmental impact of squandering unwanted material in the quarry. This has a significant environmental impact since it requires less space to manage the overburden waste generated during mining. In addition, raw material usage was optimized for clinker production causing a reduction of 4% in sand usage as raw material, reduction in raw material purchase cost, reducing the variability of kiln feed chemistry, and producing high-quality clinker. The standard deviation of kiln feed LSF was improved by 45 percent, and the variability in kiln feed was reduced by 65 percent.

1. Introduction

Cement has been in use by humans throughout history, and its manufacturing process has undergone many changes. The high increase of economic growth around the world and the demand for rapid infrastructure development due to population growth is the underlying reason for the globally high cement demand [1]. By the end of 2019 the total production of cement in the world was 4.2 billion metric tons [2]. Fig. 1 shows a projection of cement usage until 2050 [2]. As Fig 1 shows, the demand for cement will continue to grow over the years. The cement industry plays a huge role in improving the living standards of people. Along with its advantages, the cement industry over the years has faced many challenges due to its social, political, environmental, and sustainability concerns [1]. In addition to this, most of the manufacturing companies face a global business environment that is becoming increasingly competitive. As a result, they look for ways to cut production costs without sacrificing product quality. Some of these opportunities, however, include reducing the outsourcing of raw material without reducing on the quality of the material.

In cement manufacturing, the quarry is the main source of raw material fed to the rotary kiln. The raw material feed is first ground at microscale in the raw mill and calcined prior to feeding to the rotary kiln. The quarry contributes about 70%-85% of the raw material that feeds the kiln. The other 20-30% of material are raw materials (clay, silica, and iron) that are normally outsourced and more expensive.

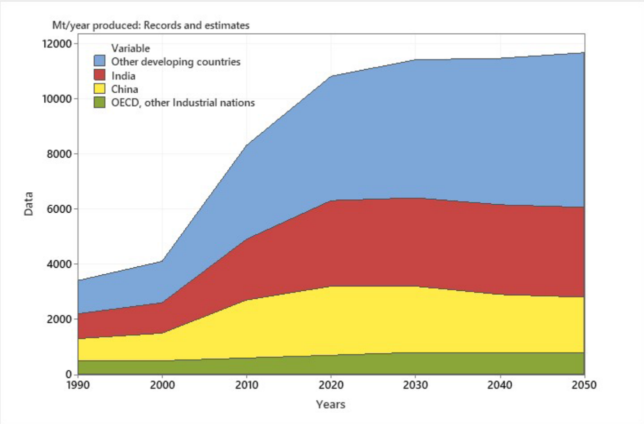

Figure 1. Projection of cement usage until 2050

Outsourcing has some social and political impacts around the world. It is therefore advantageous to use more local materials, such as using material sources from the quarry which is normally wasted.

The quarry reduces the environmental impact of wasting unused material, such as overburden, in the quarry by using it as raw material in the mix. This has a positive environmental impact since less land area is required to manage the overburden waste generated during

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mining. The quality of clinker and cement must not be compromised by the addition of this unused material.

This paper does not cover the chemical and mechanical processes in the manufacturing of cement. This paper solely presents methodology adapted by the case study quarry to improve mining sequencing to reduce overburden wasting, optimization raw material usage and to produce a mix of consistent chemistry for the kiln. It also shows the impact of the new methodology on reducing the variability of kiln feed chemistry and producing high-quality clinker.

2. Simple process description overview of cement manufacturing

Cement is produced from raw materials such as limestone, chalk, shale, clay, iron and sand. Quarried, crushed, finely ground, and blended to the precise chemical composition are the primary sources of these materials. Raw material mostly outsourced are added to the meal [3]. After mining, grinding and homogenizing the raw materials, calcination is followed by combustion of the resulting calcium oxide along with silica, alumina and ferrous oxide at high temperatures to form clinker; the clinker is then ground or milled together with other constituents (as gypsum, slag etc.) to produce cement [4& 5].

2.1. Quarrying

Quarry operation is the initial stage of cement manufacturing. Open-face quarries are the most common source of limestone, but underground mining is also an option [6]. To save raw material transportation costs, most cement facilities are located near quarries.

To get access to the raw material subsurface, exploration is conducted by drilling. Based on the exploration data, geological models are created with computer models to evaluate the limestone content. The model also helps to evaluate unusable material called overburden that must be extracted and wasted along with the extraction limestone. The unusable overburden waste which may be in large quantities must be stored in a large area on the surface. These quarry waste dumps have a negative impact due to their unstable conditions, constitute a potential source of contamination to the environment and in most cases contribute to a poor view in neighborhoods.

To optimize the quarrying process, economic mine plans are generated using computer software modeling simulations. Key input parameters for the models are economic factors, geotechnical stability requirements, and chemistry quality control measurements. The material is drilled, blasted, loaded, hauled, crushed, and conveyed to a storage dome.

2.2. Raw mill and blending silo

The raw milling is the second step in the cement production process. Raw milling comprises grinding raw materials into "raw meal" during the manufacture of cement. Raw meal is then fed to a cement kiln to form clinker, which is then ground to make cement in the cement mill. The raw mill can be vertical mills or ball mills with hot gas to improve dryness. The addition of the clay, sand, and iron to the limestone from the quarry result in the desired chemical composition for cement manufacturing at the raw mill. To improve the homogeneity of the raw meal material, the mix is conveyed to a blending silo which repeatedly blends the material to created homogeneity. This improves the consistency of the chemistry mix of the material.

2.3. Pyroprocessing

The pyroprocessing is the integral part of the cement manufacturing. Cement clinker is produced in a rotary kiln, which is a long cylindrical rotary furnace that rotates at 4 revolutions per minute. Temperatures range from 1400 to 1600 degrees Celsius, and energy usage vary depending on the manufacturing process [7]. Prior to the rotary kiln, the homogenous raw meal material from the blending silo is conveyed to the kiln preheat tower where the material is fed through multiple stage cyclones. Kiln preheater towers use hot gases to heat the kiln feed material. n the preheat tower, cyclones (stages) control the flow of gases and materials. As material flows down the tower, it is exposed to a temperature gradient, reaching kiln temperature at the bottom. These high temperatures, as well as abrasion, alkali attack, and buildup, are dealt with by lining the cyclones and tubes with refractory. The prestart of calcination of the material take place at the preheat tower prior to feeding the material to the rotary kiln. The process of calcination is the heating of solids at high temperature in the absence of air or oxygen (as opposed to combustion, which requires oxygen) in order to remove impurities or volatile substances. The material from the preheat tower feeds to the rotary kiln where further calcination takes place to form clinker. The hot clinker is cooled down through a cooler aeration system and transported by pan conveyors to a clinker silo for storage. Heating is provided by burning of fine coal which is generated by milling. Critical to this system are heat control, air flow, emission control, dust control and quality of raw meal material. Figure 2 shows a systematic diagram of the flow process of cement manufacturing. Note that this is a very simplified process description unique to the Union Bridge Plant. Key in the process flow is the path of gasses with the manufacturing plant and how environmentally is controlled before released. In addition, there are many instrumentations for measuring process variables and environmental variables like emissions of gasses.

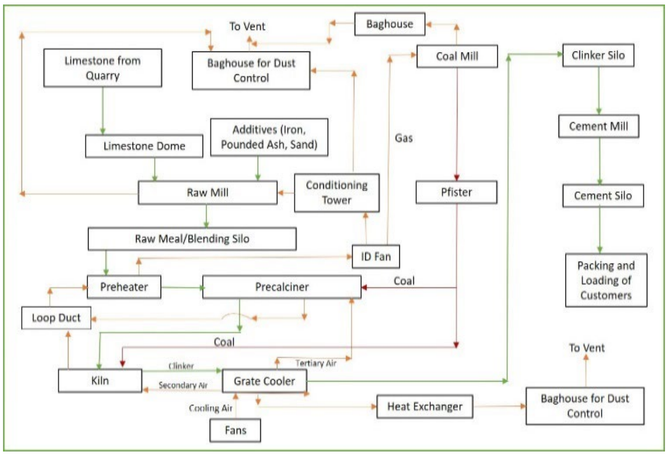

Figure 2. Cement Manufacturing Process Flow

2.4. Finish grinding of clinker

Clinker from the clinker silo is conveyed to the finishing mills where the final grinding takes place to produce cement. A little amount of gypsum is supplied during the final grinding process after the clinker has cooled and been stored in the clinker silo. Final grinding process mills are either vertical or ball mills. Gypsum serves a critical function in regulating the "cement setting" process. Sometimes crushed limestone is added at the final grinding stage. Based on customers' requirements on particle size and color, different products are produced. After the grinding process, the cement is bagged or transported in bulk to the marketplace.

3. Raw material feed quality

Cement plant operation success is dependent on the availability of high-quality raw materials in the amounts required Limestone is the basic raw material for cement production; limestone quality is assessed by the presence of suitable calcium, silica, aluminum, and iron oxides i.e., CaO, SiO_2, Al_2O_3, Fe_2O_3 [8]. The quality of cement also affects the concrete normally used for construction. Therefore, maintaining a consistent clinker and cement quality is key. Since the quarry contributes 70-80% of the raw material usage, controlling the quality and consistency at the quarry is critical. This means that any additional raw material added at the quarry must be done in a controlled faction with a methodology behind it. It also requires a very delicate process of control. Having a controlled consistent quality feed mix also helps to reduce the amount of outsourcing of raw material at the raw mill level. This section looks at what the quality of material entails and what variables are used as control measures to manage the quality.

3.1. Quarry and raw mill material quality

Cement raw mix is dependent upon the quality of mined limestone. The goal of the cement plant operation is to maintain the threshold limit of the undesirable oxides while keeping constant the quality parameters of the desirable oxides for the cement manufacturing [9]. The geological chemical composition of the material determines the quarry's quality. Other minerals may be present in the deposit that are not appropriate for cement production. The limestone may contain high concentrations of magnesuim which is not suitable for cement manufacturing. In other cases, the deposit may be intermixed with high alkaline formations which will not be suitable for the cement manufacturing. In addition, there is a large volume of topsoil and unsuitable soil that must be mined out first to expose limestone of suitable chemistry for the cement manufacturing and stored in stockpiles impacting the environment. In most cases, it is desirable to manage the unsuitable material by slowly blending it with the limestone as an raw material displacing some of the required outsourcing material needed. Limestone supplied from the quarry, is not guarantee of a high-quality therefore it is required that strict quality must be maintaing after directly extracting the limestone from one part of the quarry [10]. To achieve consistent quality from the quarry requires mixing (or blending) of limestone [11&12].

The primary requirement for developing acceptable raw mix for the cement plant is the calcium oxide (CaO) from the quarry. Secondary raw materials are required to achieve a balance of silica (SiO_2) from sand mining, alumina (Al_2O_3) from clays, and iron (Fe_2O_3) from slag, all of which are purchased from secondary sources. Lime saturation factor (LSF) Equation 1 is an index that helps in achieving the balance of the main oxides; it is presented as [13]:

$$LSF = \frac{100 \times CaO}{2.8SiO_2 + 1.18Al_2O_3 + 0.65Fe_2O_3} \quad [1]$$

If present over specific threshold limits of concentration, raw mix may contain some unwanted components that will reduce the cement plant's efficiency. Magnesium oxide (MgO) is the most important component, which functions as a fluxing agent when concentrations are low; however, when concentrations above 3.5 percent, it becomes an impurity in the cement produced. Another undesirable component is alkalinity which is measured by NaEQ. As mentioned raw meal consist of limestone silica (SiO_2) from sand mining, alumina (Al_2O_3) from clays, and iron (Fe_2O_3) from slag. The raw meal percentage proportion in the mix as feed for the raw mill is presented in Table 1. This table shows the raw meal material mix percentage for the Union Bridge Cement Plant.

Table 1. Raw meal material mix percentages

Raw Meal Material Mix	Percentage of Mix
Total Limestone (T)	82.8%
Total Iron (T)	0.5%
Total Sand (T)	6.8%
Total Fly Ash (T)	0.0%
Total Ponded Ash (T)	9.9%

The material mix is controlled with Gammmetrix analyzer and feeders to make sure an accurate and consistent volume and chemistry are regulated for the kiln. The chemistry targets for the quarry and raw meal are presented in Table 2. The quarry and quality department must make sure that these targets are met and standard devation is well controlled.

3.2. Kiln feed quality

A specified amount of calcium oxide (CaO), silica (SiO2), alumina (Al2O3), and iron is present in the kiln feed mix (Fe2O3). Impurities in raw materials, in addition to these basic oxides, show up in the kiln feed mix. Magnesia (MgO) levels in some facilities can reach 4.2 percent in the mix, resulting in unsound (expanding) cement if not carefully regulated [13]. At sintering temperatures, magnesium works as a flux, making the burning process significantly easier. A magnesia-rich kiln feed, on the other hand, has a tendency to "ball" readily in the burning zone, which is regarded an undesirable quality by operators.

Table 2. Dependent Chemistry quality measurable variables with expected controlled limits and standard deviations

Dependent Chemistry Variables	Quarry (%)			Raw Mill (%)		
	LL	MID	UL	LL	MID	UL
LSF	400	650	900	99	102	105
AR				1.35	1.4	1.45
SR				2.55	2.65	2.75
NaEq	0.25	0.35	0.45	0.30	0.35	0.40
Mag	2.0	3.0	4.0	1.95	2.1	2.25
K2O	0.31	0.38	0.45	0.40	0.45	0.50
Al2O3				2.8	2.9	3.0
Standard Deviation		250			3	

Potassium (K2O) and sodium (Na2O) oxides, often known as alkalis, are impurities that not only degrade cement quality but also cause significant operational issues, particularly in a preheater kiln. Potassium is the most common contaminant among the two alkalis, and the plant chemist must pay particular attention to it. Alkalis vaporize in the lower section of the burning zone, are transported to the rear of the kiln with the kiln gases, and condense again at a gas temperature of roughly 900 C during the burning process (1650 F). These alkalis react with sulfur dioxide, carbon dioxide, and chlorides in the kiln gases in the cooler region of the kiln. As a result, an internal alkali cycle is established, which might result in material quality compromises and ring forms in the kiln. They shouldn't be too abundant in the clinker; they shouldn't be recycled or allowed to build up in the kiln; and yet they're abundant in the raw materials. To address these issues, a well-controlled optimum mix is used.

The challenges of magnesia (MgO) and alkalis in kiln performance requires that most of these deposits be wasted. In most cement plants, these masive deposits create negative environmental impact since they are mostly wasted as spoil piles. The consistency of kiln feed through the pre-heating stage until the clinker is formed is critical to the performance of the kiln and creates a challenge for cement manufacturers. Less waste results by accommodating the waste material in the raw mill mix design. In addition, if these materials are used in the mix, it helps prolong the mine life, therefore eliminating the need to expand the mines. Also if these materials are used in the mix, they tend to serve as substitutes for additional commercial purchases of sand and bauxite which have a great impact on the enviroment and society as a whole. The chemistry targets for the case study Union Bridge cement plant kiln feed is presented in Table 3. The quarry and quality department must make sure that these targets are met and standard devation is well controlled.

Table 3. Dependent Chemistry quality measurable variables with expected controlled limits and standard deviations

Dependent Chemistry Variables	Kiln (%)			Clinker (%)		
	LL	MID	UL	LL	MID	UL
LSF	101	102	103.5	95.5	96.5	97.5
AR	1.35	1.40	1.45	1.45	1.50	1.55
SR	2.50	2.55	2.60	2.35	2.40	2.45
NaEq	0.30	0.35	0.40	0.50	0.55	0.60
Mag	1.95	2.1	2.25	2.75	3.00	3.25
K2O	0.40	0.45	0.50	0.60	0.65	0.70
Al2O3	2.9	3.0	3.1	5.1	5.3	5.5
Standard Deviation		1.5			<1	

4. Problem statement

Cement manufacture has been scrutinized for its environmental, social, and political implications over the years. For instance, the demand of raw material like sand as raw material for cement manufacturing has resulted in illegal mining in developing countries like India [14]. Mining of limestone requires removal of overburden and topsoil to expose the limestone deposit. The overburden and topsoil mined occupied space and erosion affect their stability. Considering the scrutiny, the industry looks for ways to create value, raise the efficiency of production processes and reduce emissions. The intent of this paper is to demonstrate methodologies used to improve the consistency of the kiln feed, therefore reducing sand usage and overburden waste dump impact.

4.1. Environmental and social ımpact of mining raw material

The public has been concerned about the environmental effects of mineral extraction. There is currently a lot of interest around the world in mining and its sustainability, with a focus on the need to move the mining industry to a more sustainable framework. The raw material extracted by mining activities are essential for the manufacturing world. As already mentioned, limestone which forms the main constituent for cement manufacturing is obtained by mining. The outsource raw material used for example silica obtained from sand are added to the mix as chemistry correction factor during cement manufacturing. These demonstrate how critical mining is to the cement industry. Unfortunately, the environmental and social problems resulting from mining include the depletion of natural resources and ecosystem degradation. Another increasing concern over environmental impacts are the illegal means by which such mining activities occur in most developing countries. For example, in most third world countries like India, it has been well documented in an article, the devastating social impact of sand mining on the environment and used the term "sand mafia" [15]. The article also indicated some of the impact of the illegal sand mining on Indian rivers and coasts. These were (1) losses of biodiversity (2) decline in land (3) decline in protection against extreme events like river floods, coastal storms and marine current (4) changes in water supply due to lowering of water table and pollution (5) damaged infrastructure like embankments (6) changes in landform and landscapes. This illegal mining of sand still is prevalent in most developing countries today. In addition, similar observation of social impact of sand mining on society was observed [16]. Finding a solution to reduce the volumetric need of sand as raw material for cement manufacturing will have an impact on such illegal activities. The lower the demand of sand as raw material for cement manufacturing due to the use of other substitute material, the less the need for sand as raw material. Figure 3 shows an illegal sand mining area along the coast of India. Figure 4 shows a sand-and-gravel stream bed (A) the nick point associated with a pit excavation, and (B) the upstream head cutting and downstream bed degradation that develop during high flows (Bliss (2017)).

Figure 3. Illegal sand mining activities along the India Coast (Photo Source: http://static.picturk.com/syngenta-exhibition/img/works/406d631630d7a30352438b3e8ac6fa19_slider.jpg)

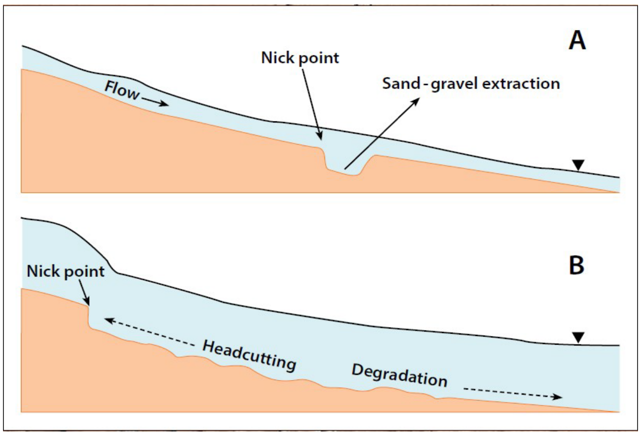

Figure 4. (A) the nick point that develops with a pit excavation, and (B) the upstream head cutting and downstream bed degradation that develop during high flows due to the impact of illegal sand mining along the coast of India (Diagram source: http://threeissues.sdsu.edu/three_issues_sandminingfacts01.html)

4.2. Quarry overburden wasting dumps impact on environment

Waste management is a global environmental challenge. The largest global waste producer is the mineral industry [16]. The generation of mining waste is estimated to be 50 times higher in terms of material volume, engendering immense environmental risks and liability. Mining practices usually generate extensive amounts of solid waste due the removal of overburden to expose minerals or ore which in the case of cement manufacturing is limestone. The overburden is stored in land fields called mine or waste dumps. These waste dumps erode and sometimes affect the quality of surface water. Another negative environmental impact caused by mining waste is the loss and degradation of natural areas. Furthermore, these dumps cover substantial areas that could have other uses. The key is to reduce the overburden volumetric removal using innovative tools for planning and using the material as in-situ raw material substitute for other raw materials used for manufacturing of cement. The more natural quarry in-situ material that can be used in the raw material mix for cement, the less the generation of large areas for overburden waste dumps and a reduction in demand for raw material like sand.

4.3. Improving clinker quality for consistent delivery through raw mill and kill feed

Cement clinker quality parameters are mostly measured by offline laboratory analysis or using online analyzers. Lime Saturation Factor (LSF), Silica Moduli (SM), Alumina Moduli (AM), dicalcium silicate or belite (C2S), tricalcium silicate or alite (C3S), tricalcium aluminate (C3A), and tetracalcium aluminoferrite (C4AF) concentrations are the clinker quality characteristics. There are extensive publications on quality of clinker and cement. The following publications [17, 18, and 19] have detail extensively the quality parameters of clinker and cement. Lime saturation factor (LSF), Silicate module and alumina module and alite (C3S) parameters module, are among the most critical elements of clinker production. For this paper two of these parameters are mentioned; namely, Silica Moduli (SM) and Alumina Moduli (AM). Silica Moduli (SM) predicts the amount of melt phase present in the burning zone of the kiln and was calculated from Equation 2:

$$SM = \frac{SiO_2}{Al_2O_3 + Fe_2O_3} \quad [2]$$

The Alumina Moduli (AM) determines the composition of liquid phase in the clinker, and was calculated from the formula given in Equation 3:

$$AM = \frac{Al_2O_3}{Fe_2O_3} \quad [3]$$

The formula in the equation is used to compute the Alumina Moduli (AM), which determines the composition of the liquid phase in the clinker. Keeping within target of this indicators as shown in section three of this manuscript is key. The raw material quality control in the quarry and at the raw mill dictates the output of the clinker quality targets. Improvements with lower standard deviation for these targets is dependent on the consistency of raw material mix at the quarry and raw mill. The intent of this paper is to present a simple overview of clinker quality.

5. Methodology adopted to solve problem statements

Raw material process optimization and its effect on cement production have been well documented and published. For example, [20] discussed optimization based on effective use of stacker and recovery systems for stockpiles staging of material in Domes. Two different material blending methods belonging two different cement factories were evaluated. It was concluded that raw meal standard deviations were reduced below 6% in both blending methods, resulting in a more stable and homogeneous production. In [21], focused on modeling and solving ingredient ratio optimization problem of blending process. A nonlinear time-varying (G-NLTV) model was adopted for raw material optimization. An optimal blending ingredient point method was established. Other publication [22, 23, 24, and 25] also discuss optimization of quarry production using different techniques. Even though there are established mathematical models and other methods showing how quarry blending can optimized some of these techniques are not easy to implement with operators in mind. Our paper is centered on using methodological procedures in six stages to have an impact on the problem statement mentioned with consideration of quarry operators as part of the solution. The intent of the manuscript is to demonstrate that innovative technology and a data feedback loop system can be used to optimized quarrying operation, optimize raw material blending and improve clinker quality. These innovative tools are extremely important for the cement industry to explore, given the growing expectations for the industry to have less impact on the environment and to achieve higher quality products for customers.

5.1. Quarry planning, and production sequencing

The concept of using 3D modeling in cement quarry planning and production sequencing is not as common as compared to the large mining operations like gold or copper. These 3D modeling software tools are mostly designed to fit mining operations rather than cement manufacturing quarries. Example of these software packages are Leapfrog/Edge, Datamine, Vulcan, Surpac, MineSight and Micromine. The 3D modeling tools helps in designing optimized quarry operations, therefore reducing large quarrying areas, avoiding excessive overburden removal wasting and improving quality mining. Since the 3D software programs were primary developed for mining companies and not cement quarries, to use them for quarry planning and production sequencing, they must be modified to fit the objectives of cement manufacturing. Key to cement manufacturing as noted herein are the chemical composition mix targets needed to manufacture clinker. The raw mill and kiln dependent quality targets noted in Section 3 of this manuscript is used as a cut-off for the 3D modeling of the cement quarry. For the case study, the Union Bridge quarry used an internally modified 3D modeling tool called GEOVIA. The application of the GEOVIA Surpac and Whittle Software tool was used with some modifications to fit the intent of the planning and sequencing for the cement manufacturing [26]. This manuscript is not intended to present details of the mining planning and production sequencing. It is intended to give an overview on how an existing mining software can be deployed in cement quarry planning to help provide process controls to reduce wasting and have a less negative impact on the environment.

5.1.1. Block modeling for cement quarry

A block model is a simplified picture of an ore body (limestone) and its surroundings made up of computer-generated "bricks" that represent small amounts of rock in a deposit (ore (limestone) and waste (overburden). Each "brick," or cell, holds data estimates like element grade, density, and other geological or engineering entity characteristics. In cement quarries the highest priority of the data is the chemistry of the natural deposit (limestone and overburden) and establishing the cut-off chemistry target as required for cement manufacturing. In modeling the blocks, each block is assigned a chemistry percentage (CaO, A_2O_3, K_2O, SiO_2 etc.) and densities by one of several methods like the Inverse Distance Squared, Ordinary Kriging, Multiple Indicator Kriging, and more estimate methods are available. The chemistry data are obtained through exploration drilling and drill cutting lab analysis. Figure 5 shows a typical standard block model framework in cement quarry modeling using Surpac.

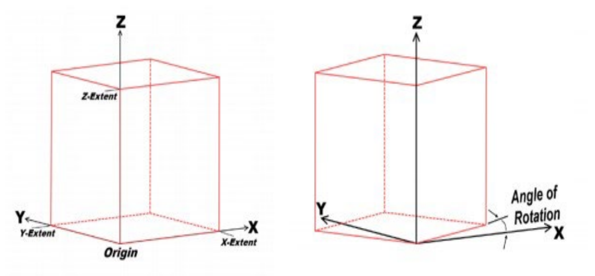

Figure 5. shows Standard block model framework [26]

Individual blocks are contained within this structure, each with its own length (X-increment), width (Y-increment), and height (H-increment) (Z-increment). A centroid (Xc, Yc, Zc) or a block origin can be used to specify the block position (Xmin, Ymin, Zmin). To define the entire possible model structure, the number of blocks in each coordinate axis direction is commonly stated. It's worth noting that not all modeling techniques necessitate a fully "filled" block model; blocks can be missing or absent from the framework. Figure 6 shows a typical model view in Surpac.

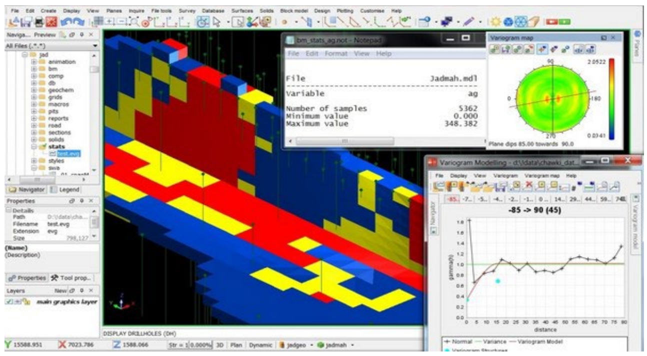

Figure 6. shows a typical view of the Surpac 3D modeling tool [26]

The block model is key for the design of an optimized quarry which can be mined to meet the intent of the design and to reach the cement manufacturing plant's goal. Key is that mining 3D model tools can be modified to achieve the cement quarry block model's objective. The computation block model is used to calculate the reserves of the quarry which means how much of usable volumetric limestone exists in-situ. Details of the different types of reserve calculations will not be presented in this manuscript.

5.1.2. Quarry ultimate pit design planning for cement quarry

Quarry Design Planning is the process of maximizing the exploitation of mineral reserves for maximum added value while remaining consistent with the business enterprise's strategic goals and objectives. The strategy has significant operational benefits, and most mining professionals are familiar with it. The 3D computer modeling tools mentioned herein are used to accomplish this. The computation of reserves already mentioned is imported in a 3D software program available for a potential open-pit quarry/pit design and defines the limits of the mineable minerals and not the geological fringes of the deposit. Figure 7 shows a typical ultimate optimized quarry/pit design using GEOVIA Surpac software.

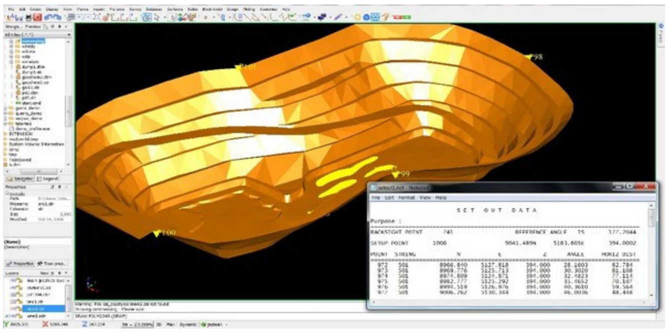

Figure 7. shows a typical Ultimate Optimization Quarry Design Using Surpac [26]

A Strategic Mine Plan is the first stage of quarry planning that sets the economic and technical direction for the project. The correct strategy is vital for the economic, social, and environmental success of the project. Input data are needed for the ultimate pit. Technical optimization with pit optimizations from GEOVIA Surpac requires critical inputs for the model. These are categorized as follows:

- *Geotechnical data:* The greatest angles in Surpac are limited to the cardinal points' azimuths (N-S-E-W-NE-NW-SE-SW). The slopes are determined by the rock type, allowing for the avoidance of geometric zone definitions. This allows for multiple maximum slopes to be assigned to these blocks depending on their 'rock type' property, as well as varied slopes to be obtained depending on the depths. The geotechnical aspect of the design is extremely critical because of the possibility of pit/quarry wall failures. All data required for the modeling and design is included.
- *Economic data:* The most sensitive parameters for establishing the form of the final pit and the ore quality cut-off grades are the economic statistics. When evaluating the cost of processing extraction and the selling price of metal, there are numerous issues to consider. The default beginning value is the current market price of $7,000 per ton of copper. This is the price on which a number of discounts will be applied in order to study the behavior of the various pits obtained. The extraction cost ($/t) is included in the economic data. Each form of sterile rock or ore has its own extraction cost. The pit optimizer will evaluate each block and determine if it is ore or sterile based on the selling price. The ore processing cost is also factored into the optimization simulation. If the block does not contain enough metal to be considered ore, the content of the block alone permits it to be removed from the optimizer. Surpac pit optimization will not even calculate their value and will treat them as sterile by default. The block will be processed if the content of the block makes processing lucrative (based on the software's calculations). This can be a significant disadvantage. Metal is assigned a price of $/ton in the model. It does not change with the passage of time. Pit optimization will take care of and optimize pits containing several metals, as well as set different prices for different types of ore (if they are in different blocks).
- *Mining Data:* Ramp width, gradient, switchback width and gradient, minimum radius for curves, truck stopping distances (laden and unloaded – at maximum permissible or feasible speeds), and more are among the data used for mine planning. Needs for drainage planning, such as drainage gradients for benches and berms Minimum mining widths – pit bottoms, bench ends, stage cut-back widths, preferred effective bench mining widths, and essential safety features (e.g. safety ramp run-offs; etc.)

In most pit designs as described herein, the key driver is to generate technical-economic parameters of exploitation, then to evaluate and achieve Net Present Value (NPV). Technically, optimization in the XZ plane and in the XY plane generates the best pits from a technical standpoint supplied by Surpac's pit optimization utilizing the $/unit approach. In this case the key is to drive more profit for the optimized pit. This is not the case for cement quarries: economics do not drive the optimization of the pit but rather the quality mix requirements needed to meet the production of a consistent quality cement. Therefore, key input data for cement quarry optimization planning are the chemistry targets, the mining operation cost, the geotechnical data, and mining data. Therefore, the general Surpac software using for mining pit cannot be used for the same optimization model for cement quarries. Therefore, this requires that the Surpac software be manipulated to fit the cement modeling concept and that takes some technical skills. This manipulation of the software was employed for our study. If this is the case, it means that the quarry planning design for cement manufacturing requires adequate knowledge of cement manufacturing process and quality requirement.

5.1.3. Quarry production sequencing for cement quarry

Achieving the right chemistry quality target for cement manufacturing and a lower cost of mining requires that mining sequencing of bench faces, and depth are achieved. Also, material movement during production is critical. As part of the quarry planning, the production scheduling optimization techniques must be achieved. This has not become common in cement quarry mining. This paper seeks to show how an optimization model with an efficient solution method can address the Long-term Cement Quarry production scheduling using GEOVIA Whittle Software. Figure 8 shows a typical generated long-range production schedule sequencing of material and quality to achieve an optimized quarry. This is critical to make sure that the quarry life is achieved based on the optimized quarry design and plan. Also critical is meeting the chemistry quality targets of the kiln by supplying 85% of quality limestone to the raw mill with consistency and less variation.

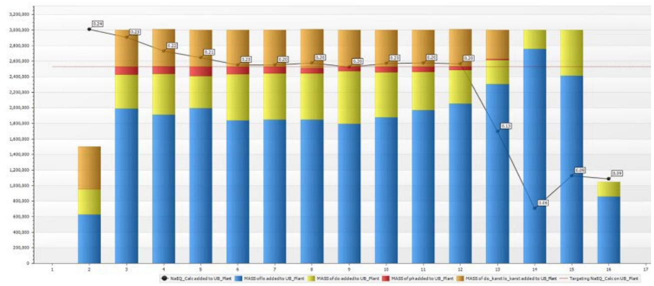

Figure 8. shows a typical production schedule for the different material and chemistry

5.2. Quality control using data management systems and display tools to help with consistent raw material mix in quarry

To achieve the quarry design requirements in operation and production mix scheduled chemistry targets, data driven control loop tools are used. This is a unique system architecture which is the first of its kind in the cement manufacturing industry. Digital transformation and the use of data to achieve operational excellence is becoming the new norm in the manufacturing industry. The concept involves maximizing existing investments by leveraging underlying applications, technology, and data-driven analytics. It also depends on bringing data, assets, and resources together with legacy systems and ensuring a smooth transition towards digitization. In addition, this helps in maintaining plantwide sustainability across all stages and ensuring maximum productivity and efficiency. The cement industry is adapting to this new way of doing business but still struggles to fully embrace the concept. Digitization involves data extraction, data storage, data transformation, graphics, and feedback loops. It reduces human controls which normally result in many errors in operations and it maximizes efficiency. This requires a massive infrastructure development and technical skills. The truth is that the idea of digitization and data analytics to show graphical displays of cement quarry operation is not common. In most cases in the quarry, only one data point showing output is issued and is based on a belt scale. In recent years, chemistry data from a cross-belt analyzer installed on the quarry beltline is used for adjustment of quality in the raw mill. Unfortunately, none of these data are used in a feedback loop to improve quarry planning and improve quality in the quarry. Therefore, this leads to a deviation from optimized quarry operation and a high standard deviation of feed quality from the quarry. There is a long-term impact on the quarry life and environmental because of excessive mining of unplanned overburden and creation of large waste dumps. Figure 9 shows the technological activities and data management interaction between different hubs to provide feedback to the active mining process with the quarry and for calibration and reconciliation of the various models used for the improvements. The intent of the architecture of the data management system is to provide a closed loop for improving quarry operational processes, meet the needs of the customer (cement manufacturing kiln feed quality) and to make sure that the intended requirements of all engineering designs are achieved.

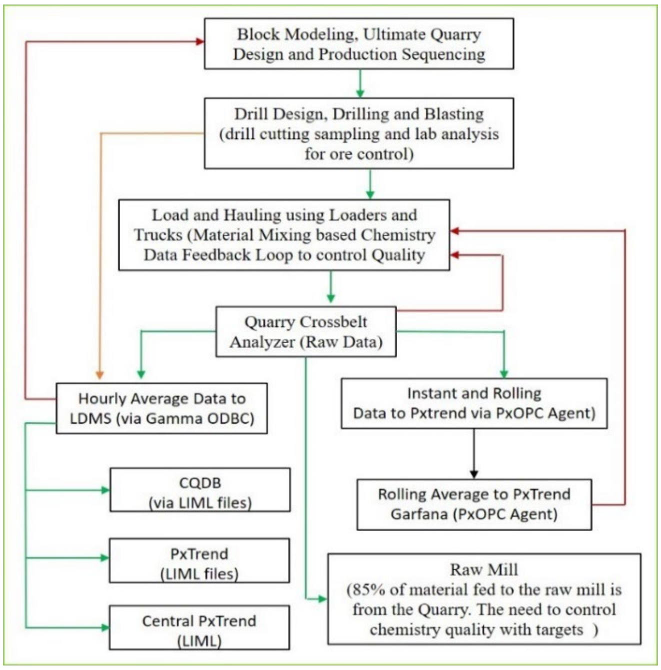

Figure 9. Technology Activities and interaction of Data Management Systems with the quarry system life-cycle process

Digital transformation marks a radical rethinking of how technology, people, and processes combine to create and deliver value. As shown in Figure 9, this initiative required a massive infrastructure investment which involved creating a database management closed feedback loop. The key is that the raw chemistry analysis is obtained using a cross-belt analyzer provided by Thermoscientific. The raw chemistry data obtained through the cross-belt analyzer is stored in two database systems called the LDMS (Laboratory Data Management System) and PXTrend. LDMS is a comprehensive laboratory information management system. PSCL's LDMS is unique in its focus on cement manufacturing. Most labs have adopted electronic recording: LDMS extends the concept by integrating instruments and analysis devices to reduce errors and increasing throughput. Improved efficiency of lab work is achieved through test scheduling and tracking. The data stored and manipulated in LDMS can be extracted in hourly intervals to complete analytics. The LDMS allows for a database to be created for chemistry data of drill hole cuttings. The drill hole chemistry data include the GPS coordinates of the holes. This data set is used to refine the block model in quarry optimization and to calibrate the model as feedback data. This allows refinement of the quarry and meeting specific KPI's (Key Performance Indicators). Modern process plants produce enormous amounts of data as captured by the cross-belt analyzer: countless process values, reports, batch data and status information of intelligent field devices run every millisecond through bus lines, are processed in automation systems and output on multiple screens. With PxTrend the process data over many years can be called up company-wide from several automation systems and data sources. PxTrend's architecture allows a user-friendly access to process data via PC, tablet, or smartphone (Figure 10). Grafana (PxOPC(agent)) is displayed graphically to operators via tablets to help manage the mix blend in real-time to meet targets. In addition, PxTrend can save data nearly real-time, and use all the relevant data to increase the plant productivity and to optimize the processes with a maximum efficiency. The long-term archiving of the data together with company-wide access to these data aid in decision-making based on secured data.

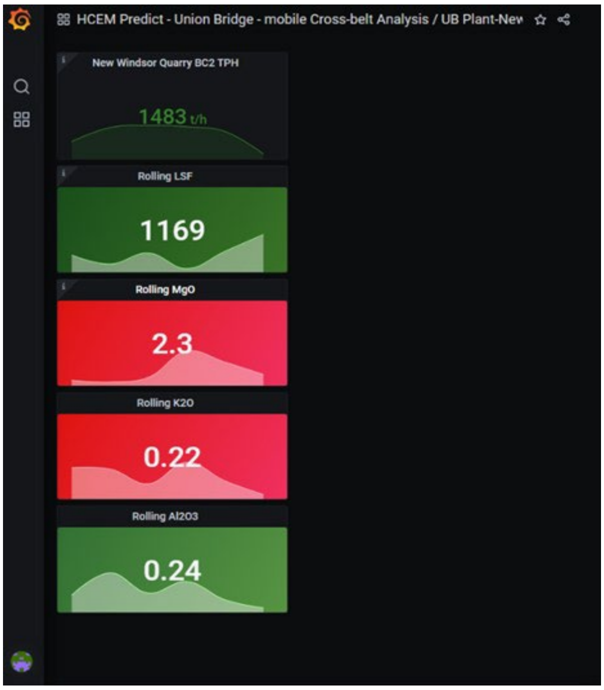

Figure 10. Data Dashboard Installed on Tablets in Loader Operators Cabin to help make instant changes to material mix if off targets. Red coded data means off target, green means on target.

Loader Operators have tablets installed in their loaders displaying the quality target data (Figure 10) in real-time allowing operators to make changes to limestone mix and adding overburden (shale) in a controlled manner. Descriptive analysis using the historic data through PxTrend is used to understand performance and management variations. The data are also used for statistical analysis to see trends and compare to targets. This allows for better planning, control of quarry raw material quality and mining to meet the intent of design. This aspect of improving operational process and optimization using data management is critical to cement manufacturing efficiencies and the reduction of environmental impacts. Overburden mining and creation of dumps are better managed because of the use of data. The precise mix of quality raw material feed from the quarry to the raw mill based on data helps reduce the usage of raw materials like sand which is illegally mined in many developing countries. The importance of such a feedback control loop to maintain consistent quality material with less variation is critical to the sustainability of the quarry operation and the cement manufacturing. The positive impact of such advanced data management tools to manage quarry operation also has a dramatic impact on the reduced usage of sand for cement manufacturing and a reduced production of waste dumps since some of the overburden mined can be used in the mix to achieve quality controlled targets. This manuscript stresses how existing tools can be accommodated to improve operational excellence through modifications of the tools and using data architecture management as feedback for operational improvements to meet required quality targets.

5.3. Quality control using data management systems to help with consistent raw material mix of raw meal

Raw mill feed as mentioned is a combination of limestone mix from the quarry in which quality is controlled to meet specific chemistry targets, This mix includes the addition of additive reclaimed ponded ash which adds aluminum (obtained from power plants), sand which adds silica, and reused iron slag which adds iron. Figure 11 shows the data management system and quality control architecture used to make sure the quality of the raw mill feed meets specific chemistry targets. Each material has individual silos and automated feeders. The feeder's rate is controlled by chemistry blend targets and analytics using computer software. This enhances consistency to the blending silo prior to feeding the material directly to the inlet of the kiln. The closed control loop shown in Figure 5 is fully automated and unique.

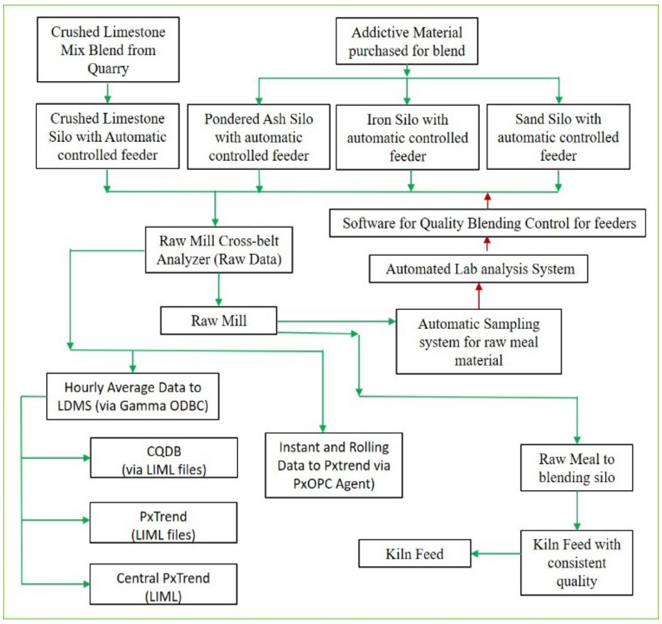

Figure 11. Data management architecture used to control the quality of raw mill feed

6. Results and discussion

The impact of using modified existing computer software modeling tools and data management control architecture to control raw material feed to the kiln is evaluated herein. The impact on reduction of sand usage, overburden removal and quality of kiln feed is evaluated based on a statistical analysis of process capabilities. In process capability analysis, stable process under statistical controlled are evaluated as Cp,Cpk and Ppk. Where Cp, Cpk and Ppk are evaluated using the equation 4, 5 and 6 below:

$$Cp = \frac{(USL - LSL)}{(6\sigma)} \quad [4]$$

$$Cpk = min\frac{(USL - \mu,\ \mu - LSL)}{(3\sigma within)} \quad [5]$$

$$Ppk = min\frac{(USL - \mu,\ \mu - LSL)}{(3\sigma\ overall)} \quad [6]$$

The values for Cpk and Ppk will converge to almost the same value because sigma and the sample standard deviation will be identical. In other words, if Cpk very close to Ppk, the process is likely in statistical control. The closer the Cpk is closer to 1 or greater than 1, this means the process is well-controlled within targets and there is less variability in the process. This also shows consistency and an optimized process.

6.1. Reduction of raw material (sand) in raw material mix and its impact

Reducing the use of sand has a positive impact on the sand mafia in developing countries. The use of technology and innovative data management control helps reduce raw material usage, especially sand. The addition of waste material like shale in a controlled manner helps substitute the use of outsourced sand. In 2020, the production of clinker increased as compared to 2019. In normal cases, the use of sand should also increase by 4% per clinker production. The use of sand was 9.6% per clinker production basis in 2020 compared to 10.2% per clinker production basis. This shows a 6.3% decrease in sand use because of the implementation of a strict controlled mix in the quarry and at the raw mill. It also amounts to a decrease in cost of sand raw material purchase. In addition, the cost of clinker production decrease. This result shows that using advanced technology, innovation and a data management control loop system plays an important role in reducing raw material use. The cement industry must adopt innovative technology and data analytics systems to drive process optimizations and improvement. Such optimization processes will improve operation and have a significant impact on the environment.

6.2. Reduction of overbudern removal and it impact on environmental

The mining plan developed using modified 3D software allows for precision on the mining sequence of quarry operation. It allows for precise mining and avoids over mining of overburden waste which create stockpiles that impact the environment. The models allow for precise control of the limits of overburden needed to be removed to expose the exact required quality of limestone and dolomite. In addition, the software allows for predictive modeling to allow addition of some of the overburden material to be used in the quarry material mix for clinker production. The only constraint is that the overburden material (shale) is a source of high alkalinity which can easily affect the quality of clinker and subsequently affect cement quality. Therefore, it needs to be precisely controlled within the specific chemistry target. The data management architecture for the quarry allowed for this and therefore the overburden waste was reduced by over 150,000 metric tons per year by using it in the mix.

6.3. Analysis showing improvement in quality due to quarry control mix feedback from data management

Chemistry data collected from 2019 was compared with 2020 when the step changes were made in the quarry to see the effect on quality. A process capability analysis was conducted to compare the data of critical chemistry targets used to evaluate the quality of material from the quarry, raw mill, and kiln feeds. This section describes the impact on quality due to the implementation of control loop systems put in place in the quarry and raw mill in 2020.

6.3.1. Process Capability Analysis of Quarry Quality Data

MgO within the quarry mix needs to be controlled for consistency. Lack of consistency can cause liquid formation in the kiln that causes damage, thus there must be a lower standard deviation and better process control to avoid variability in MgO in the quarry mix. Table 4 and Figure 12 show the output of the process capability data analysis for MgO within the quarry mix for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 15%. Also, the Cpk which is a good indicator for process control improved by 5%.

Table 4. The process capability analysis data result for MgO within Quarry mix material for 2019 vs. 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	2	2	Pp	0.37	0.42
Target	3	3	PPL	0.27	0.47
USL	4	4	PPU	0.46	0.37
Sample Mean	2.75	3.12	Ppk	0.27	0.37
Sample N	1087	759	Cpm	0.35	0.41
StDev (σ) (Overall)	0.912	0.795			
StDev (σ) (Within)	0.782	0.786			
			Potential Capability Results		
				2019	2020
			Cp	0.46	0.42
			CPL	0.35	0.48
			CPU	0.58	0.37
			Cpk	0.35	0.37

Table 5. The process capability analysis data result for K_2O within Quarry mix material for 2019 vs. 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	0.31	0.31	Pp	0.17	0.26
Target	0.34	0.38	PPL	0.45	0.55
USL	0.45	0.45	PPU	-0.11	-0.03
Sample Mean	0.49	0.45	Ppk	-0.11	-0.03
Sample N	1083	759	Cpm	0.13	0.19
StDev (σ) (Overall)	0.135	0.091			
StDev (σ) (Within)	0.128	0.087			
			Potential Capability Results		
				2019	2020
			Cp	0.18	0.27
			CPL	0.48	0.57
			CPU	-0.11	-0.03
			Cpk	-0.11	-0.03

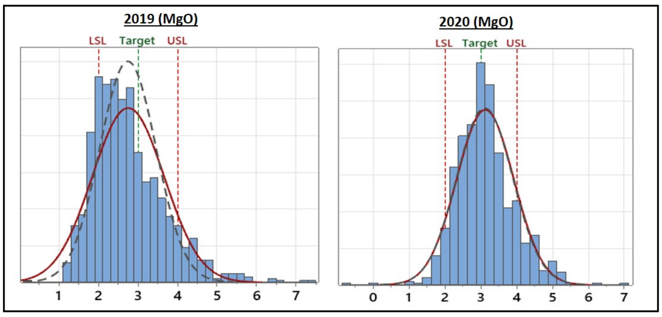

Figure 12. Shows the normal distribution of MgO data for 2019 vs 2020

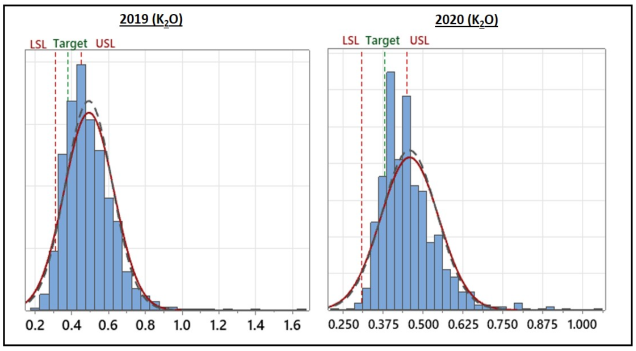

Figure 13. Shows the normal distribution of K_2O data for 2019 vs 2020

Shale, which is the source of K_2O and a measure of the impact of alkalinity in the quarry mix, was also evaluated. Table 5 and Figure 13 show the output of the process capability data analysis for K_2O within the quarry mix for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 49%. Also, the Cpk, a good indicator for process control, is improved by 267%.

6.3.2. Process capability analysis of raw meal quality data

To measure the impact of alkalinity on the raw mill, the data to be considered is NaEQ. Table 6 and Figure 14 show the output of the process capability data analysis for NaEQ within the raw mill throughput into the blending silo for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 101%. The Cpk, a good indicator for process control, is improved by 34%.

Table 6. The process capability analysis data result for NaEQ within raw mill output material for 2019 vs. 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	0.30	0.30	Pp	0.37	0.74
Target	0.35	0.35	PPL	0.17	0.38
USL	0.40	0.40	PPU	0.56	1.10
Sample Mean	0.32	0.33	Ppk	0.17	0.38
Sample N	5642	4709	Cpm	0.32	0.50
StDev (σ) (Overall)	0.045	0.023			
StDev (σ) (Within)	0.015	0.011			
			Potential Capability Results		
				2019	2020
			Cp	1.13	1.58
			CPL	0.53	0.80
			CPU	1.73	2.35
			Cpk	0.53	0.80

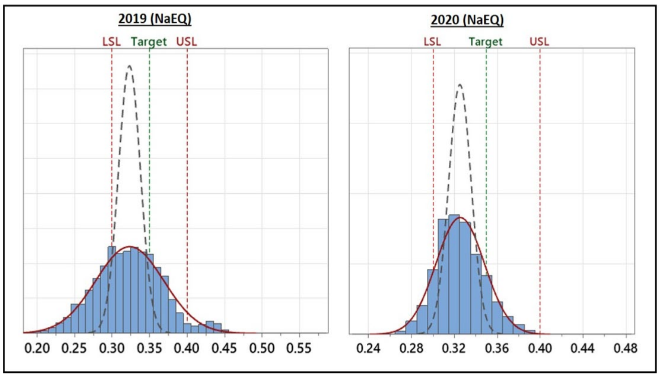

Figure 14. shows the normal distribution of NaEQ data for 2019 vs 2020

To measure the impact of liquids formation in the Kiln, the data to be considered is MgO. Table 7 and Figure 15 shows the output of the process capability data analysis for MgO within the raw mill throughput for the blending silo for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 215%. The Cpk, a good indicator for process control, is improved by 233%.

6.3.3. Process capability analysis of kiln feed quality data

To measure the impact of alkalinity on the kiln feed coming from the blending silo, the data to be considered is NaEQ. Table 8 and Figure 16 show the output of the process capability data analysis for NaEQ within the Kiln Feed from the blending silo into the Kiln for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 53%. The Cpk, a good indicator for process control, is improved by 20%. This is significant in the quality of clinker production.

Table 7. The process capability analysis data result for MgO within raw mill output material for 2019 vs. 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	1.95	1.95	Pp	0.10	0.33
Target	2.10	2.1	PPL	-0.16	0.25
USL	2.25	2.25	PPU	0.37	0.41
Sample Mean	1.72	2.06	Ppk	-0.16	0.25
Sample N	5642	4709	Cpm	0.08	0.32
StDev (σ) (Overall)	0.480	0.152			
StDev (σ) (Within)	0.065	0.043			
			Potential Capability Results		
				2019	2020
			Cp	0.77	1.17
			CPL	-1.18	0.89
			CPU	2.71	1.46
			Cpk	-1.18	0.89

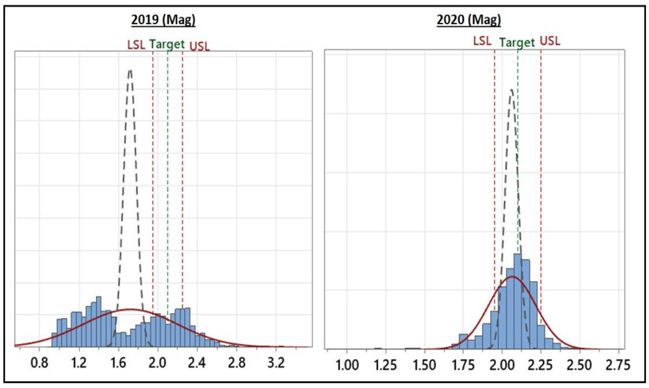

Figure 15. shows the normal distribution of MgO data for 2019 vs 2020

Table 8. The process capability analysis data result for NaEQ within Kiln Feed material for 2019 vs. 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	0.30	0.30	Pp	0.42	0.65
Target	0.35	0.35	PPL	0.36	0.57
USL	0.40	0.40	PPU	0.48	0.72
Sample Mean	0.34	0.34	Ppk	0.36	0.57
Sample N	8222	6912	Cpm	0.42	0.63
StDev (σ) (Overall)	0.039	0.026			
StDev (σ) (Within)	0.009	0.008			
			Potential Capability Results		
				2019	2020
			Cp	1.81	2.19
			CPL	1.56	1.94
			CPU	2.06	2.44
			Cpk	1.56	1.94

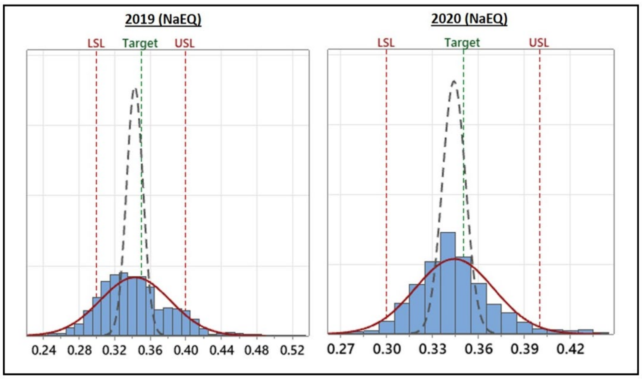

Figure 16. shows the normal distribution of NaEQ data for 2019 vs 2020

Table 9 and Figure 17 show the output of the process capability data analysis for MgO within the quarry mix for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 248%. Also, the Cpk, a good indicator for process control, is improved by 139%. This is significant in the quality of clinker production.

Table 9. The process capability analysis data result for MgO within Kiln Feed material for 2019 v.s 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	1.95	1.95	Pp	0.11	0.39
Target	2.10	2.1	PPL	-0.11	0.32
USL	2.25	2.25	PPU	0.33	0.47
Sample Mean	1.81	2.07	Ppk	-0.11	0.32
Sample N	8222	6912	Cpm	0.09	0.38
StDev (Overall)	0.441	0.127			
StDev (Within)	0.061	0.020			
			Potential Capability Results		
				2019	2020
			Cp	0.82	2.51
			CPL	-0.78	2.00
			CPU	2.42	3.01
			Cpk	-0.78	2.00

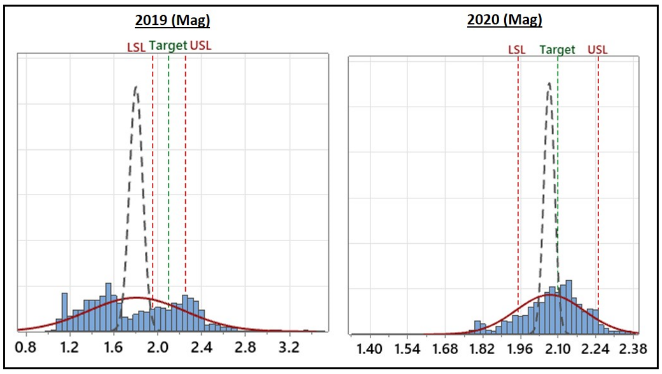

Figure 17. shows the normal distribution of MgO data for 2019 vs 2020

Table 10 and Figure 18 show the output of the process capability data analysis for LSF within the kiln feed from the blending silo for 2019 and 2020. The control loop had an impact, improving the standard deviation in 2020 by 45%. Also, the Cpk a good indicator for process control, is improved by 65%. This is significant in the quality of clinker production. LSF is a key indicator in the consistency of the kiln feed and its impact on the clinker quality.

Table 10. The process capability analysis data result for LSF within kiln feed material for 2019 vs. 2020

Process Data			Overall Capability Results		
	2019	2020		2019	2020
LSL	101.0	101.0	Pp	0.18	0.25
Target	102.0	102.0	PPL	0.07	0.19
USL	103.5	103.5	PPU	0.28	0.32
Sample Mean	101.5	101.92	Ppk	0.07	0.19
Sample N	8228	6913	Cpm	0.14	0.20
StDev (Overall)	2.366	1.637			
StDev (Within)	1.498	0.991			
			Potential Capability Results		
				2019	2020
			Cp	0.28	0.42
			CPL	0.11	0.31
			CPU	0.45	0.53
			Cpk	0.11	0.31

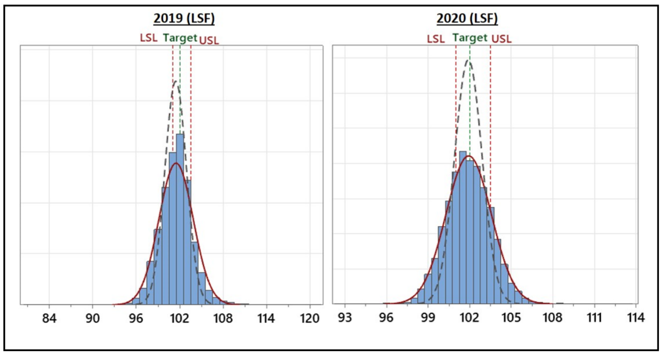

Figure 18. shows the normal distribution of LSF data for 2019 vs 2020

7. Conclusion

Quarry operation plays a significant role in cement manufacturing. The quarry is the main source of raw material for cement manufacturing. Even though the quarry plays such a significant role in the cement manufacturing, little attention is dedicated to its operation to understand its impact on the environment and significant impact on the quality of clinker quality based on kiln feed. In addition, cement manufacturing has not adopted innovative technologies and digitization in the quarry to improve the operations. This paper is the first of its kind that has been published for the cement industry, to show how existing technology and data management for controlled feedback loops can be used to improve quarry operation. Also, by using data management control feedback loops to control mix design at the raw mill, a significant improvement is also made to the quality. The paper shows a significant reduction in quarry overburden wasting, a reduction in outsourced sand usage as an additive, significant improvement in kiln feed quality when quarry modeling software tools are used for planning, and the adoption of a data management architecture control loop feedback system.

Declaration of Conflicts of Interest

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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