Enhancing Operational Efficiency in Crushers Through the Use of an Industry 4.0 Based Crusher Control System

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In the aggregate and mining industry, an excessive flow rate of raw material from the feeder, caused by irregularities in the raw material being processed by crushers, can lead to blockages or excessive strain on the crusher. Conversely, a low flow rate of raw material can result in high energy consumption by the crusher, despite operating at a low capacity. The issues encountered in the first group result in excessive energy usage in the secondary and tertiary groups. The study focuses on a system that utilizes artificial intelligence and is based on industry 4.0 principles. The system aims to maintain production in the crusher within a specific range by controlling the flow rates of the feeders using an algorithm. This control is done automatically without the need for user intervention. The system optimizes energy consumption while maximizing production capacity and ensures uninterrupted operation.

The system was developed during the installation phase at an aggregate pilot plant in the Kahramanmaraş Evri region. It assesses the material capacity data using a belt scale on the crusher, feeder, and output conveyor. This data is then compared to the limit values stored in the database, and the system generates an information signal to initiate the required control actions. Based on this matching result, it sends information to the inverter, coordinates the production cycle, manages and documents the process stages using a structured learning system and artificial intelligence logic. The installation procedure was conducted using two distinct density gradation inputs. As a consequence of the reporting, the records in the report were compared during both the active and inactive states of the system. The project achieved an efficiency of 22% in terms of energy consumption per unit capacity. Based on the whole yearly energy usage, a total of 368609.7 kg of carbon emissions were averted. The facility's aggregate crushing capacity was increased by 40%.

Keywords; Aggregate Production, Process Monitoring, Process Control, Artificial Intelligent, Industry 4.0

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1. INTRODUCTION

The crushing-screening sector plays a significant role in processing inorganic chemicals obtained from nature and bringing them to the industry. In 2021, our country's raw ore output amounted to around 814 million tons, representing a 15% growth compared to the previous year. The production comprises 561 million tons, which accounts for 69% of the overall output. This includes cement and building raw materials (561 million tons), industrial raw materials (103 million tons), coal (94 million tons), metallic minerals (38 million tons), and natural stones (18 million tons). Turkey has consistently ranked among the top three countries globally in terms of total exports for a significant period of time. In the aggregate and mining business, the primary focus in recent years has been on boosting production capacity and decreasing energy costs in facilities due to the steady increase in productivity demands.

As a part of our project, data from certain sensors are used to automate the primary crushing process. This algorithmic approach allows for control and correction steps to be executed continuously within a predetermined limit range without any need for user intervention. The research is intended to assist the "Twin Transformation in Industry" by increasing output and product capacity per unit time while also reducing energy costs. It focused on integrating green and digital transformation into the mining and aggregate industries.

Aso et al. [1] developed a computerized aggregate plant (CAP) employing microcomputers and communication technologies to break and separate rocks in an aggregate plant using crushers and screens. The implementation of machine control involved the use of operation control and feedback control, both of which were based on the quantity control technique. This approach successfully accomplished economic optimization and labor savings, aligning with the key objectives. Hulthen et al. [2] devised a monitoring and control system for a cone crusher. This system incorporates a two-variable online algorithm that determines the eccentric speed and set point based on real-time CSS (closed side setting) variable feed data. Arman [3] examined the fundamental operational principles, selection criteria, and factors to be considered in the use of crushing, screening, and conveying machinery. The study involves calculating the energy needed to break materials at specific capacities for different types of stones using the work index. Legendre et al. [4] investigated the factors that contribute to jaw crushers' low efficiency. They measured and reported electrical power values during the experimental crushing process, which involved roughly 600 g of aggregate. The results demonstrated a 10% decrease in energy efficiency due to crumbling. Salhaoui et al. [5] enhanced productivity in an industrial concrete production facility by implementing a drone-based monitoring system. This system is capable of seamlessly connecting with industrial sensors, PLCs, and the cloud in real time. It uses an IoT gateway as a middleware to securely exchange data across various systems. and successfully implemented cost-reduction measures. In their study, K. Bhadani et al. [6] looked at a full-scale tertiary crushing process in an aggregate production plant. They used both standard band-cut samples and design of experiments (DoE) to do this. The focus was on quantifying the interaction between crusher and screen performance, as well as overall process performance. Additionally, continuous process monitoring was carried out using band-cut samples.

The notion that the Industry 4.0 paradigm would eliminate errors and losses in production entirely, coupled with the assertion that the circular economy will enhance firms through environmental, social, and economic metrics, underscores the significance of both concepts as essential frameworks for sustainable corporate performance [7]. The literature review revealed a favorable and strong correlation between circular economy and sustainable company performance [8, 9, 10, 11, 12, 13]. Furthermore, the impact of Industry 4.0 technologies on sustainable business performance indicates that they facilitate the circular economy and enhance sustainability [9]. Agrawal et al. emphasize the necessity of Industry 4.0 technologies in advancing the circular economy's contribution to sustainable business performance [14].

When doing research, the examination includes both national and foreign patents. The patent [CN 2022/115445694A] describes an image recognition-based jaw crusher that utilizes automated control to regulate the gap between the movable and fixed jaw plates in real-time. Additionally, it provides feedback on whether the crushed material meets the necessary grain size requirements [15]. The patent [CN 2019/110193396A] describes a sophisticated control system that autonomously regulates the distance between the moving jaw and the stationary jaw [16]. [CN2019/209866306U] discloses an automated control system designed to prevent the jaw crusher from ceasing operation as a result of excessive load [17]. [EP 2004/1433531A1] pertains to a system designed to halt the operation of units only after a specific amount of time has elapsed. This method, as compared to traditional crushing systems, effectively prevents crushed material from remaining on the distribution conveyor [18]. The patent application [KR2023/0017556A] describes a system that utilizes an artificial intelligence-powered data analysis unit to assess the connectivity and operational status of various facilities. A data acquisition unit gathers the information for this analysis. The system then uses this analysis to determine the production period and production rate, taking into account the facility's connectivity and operational status [19]. [CN 2021/112264178A] pertains to an adaptive control technique for jaw crushers that acquires real-time data on material level, pressure, and speed of the mobile jaw crusher and subsequently compares this data with device-specific information [20]. The patent [CN 2021/112973841A] pertains to the technological domain of automated control of cone crushers, specifically focusing on a constant power controller and adaptive feeding [21].

The company conducted capacity and energy efficiency studies and filed a patent application in 2021 for the " A Crusher Supported by Artificial Intelligence " [22]. The application was granted a patent certificate on October 23, 2023. The present study developed an energy-efficient, value-added, sustainable, and cyclical production-oriented ecosystem. The ecosystem implements a smart production methodology by utilizing Industry 4.0

infrastructure and an algorithm that incorporates artificial intelligence production technology.

2. MATERIAL AND METHOD

The operating system of crusher plants consists of three distinct crushing processes: primary, secondary, and tertiary, which are determined based on stone gradation (Figure 1).

The primary group reduces rock sizes up to 1500 mm to a ratio of 5:1. Initially, a storage area known as a bunker moves rocks obtained by blasting from nature to a device known as a feeder. The feeder then delivers the rocks to the crushers for the crushing process. Once the product is crushed to the proper gradation, it undergoes sieving using intermediate sieves and is then kept in piles. If not, it is sent to the next crushing group via conveyors in order to be reduced to the necessary gradation.

The aggregate manufacturing process may detect irregularities in the raw material flow rate from the feeder, requiring user intervention. The crusher becomes overloaded with surplus raw material if the raw material flow rate surpasses the production requirement limit. This has a negative impact on the quality of the final product and may result in a temporary halt in production. Superfluous halts have a negative impact on the facility's capacity and diminish the expected efficiency of its operation. The crusher cannot operate at its maximum output capacity if the feeder introduces the raw material at a low rate of flow. This scenario results in a decline in production efficiency, and superfluous energy consumption takes place as if the entire facility were operating at maximum capacity, despite production being below the predetermined capacity. This study aims to maintain production in the crusher within a predetermined upper limit range without human intervention using an artificial intelligence-supported algorithm. This is achieved by utilizing information gathered from sensors regarding the flow rates of feeders and crushers.

An algorithm is used to compute the flow rates (in tons per hour) of the crushed product on the belt conveyor below the crusher. This calculation is based on the engine data (current and power) received from the crusher engine (30) and the feed data (speed) received from the feeder engine (40). A belt scale (80) will be installed on the belt conveyor to facilitate this calculation. An AI-assisted controller (10) is used to convert feed flow rate data and verify if these three data points fall within the limits stored in the database (20). It then generates a confirmation signal and a warning signal and sends a signal to the frequency converter (50) to adjust the feed flow rate accordingly (Figure 2)

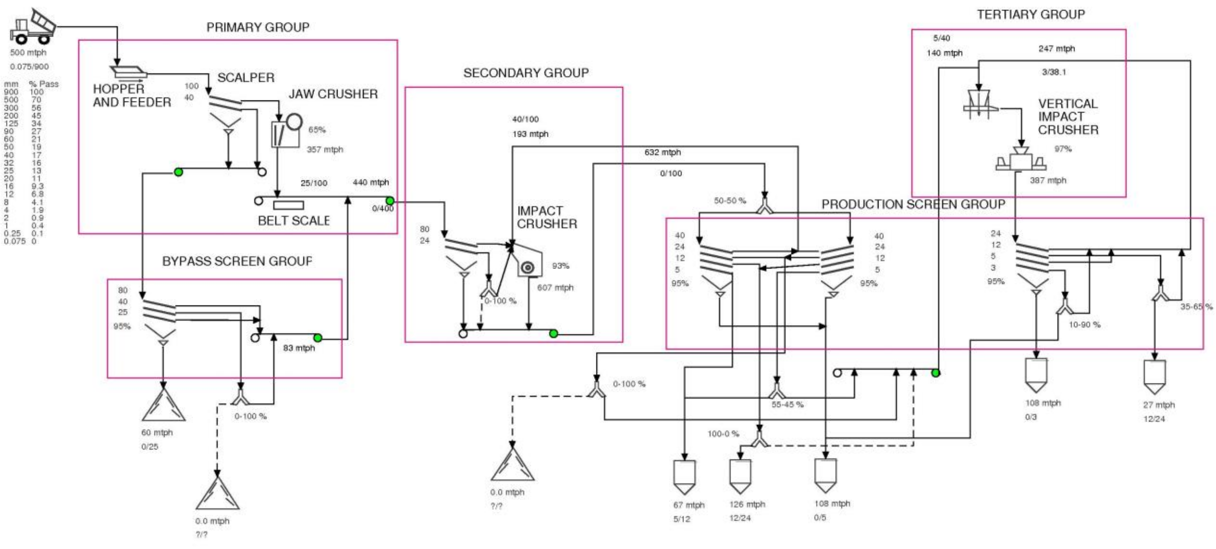

Figure 1. The layout of a crushing plant

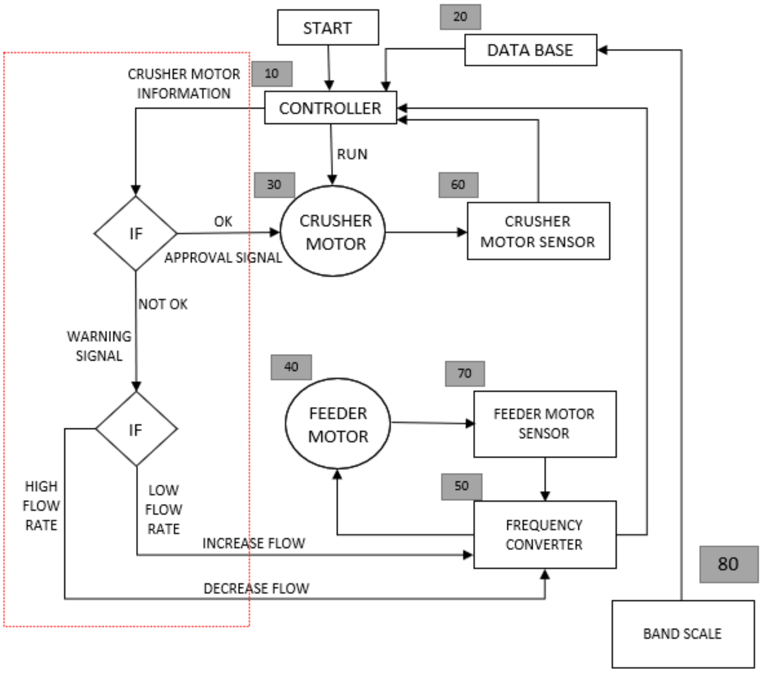

Figure 2. Algorithm

The implementation stages outlined in the work plan are below.

- The crusher group is initiated by sequentially activating the discharge conveyor motor, followed by the crusher motor, and finally the feeder motor, utilizing a programmable logic controller (PLC), provided that the sensor data is accurate and there are no safety switch emergencies.
- The panel displays information on warnings from level sensors, an open rope switch, a warning signal for a damaged motor, and the emergency stop button.
- The database stores information on the ampere (A) and power (kWh) ranges for breakers and feeder motors, as well as the range of values for belt scale (t/s).
- During operation, the breaker's motor sensor averages the amperage values over a period of 5–10 seconds.
- The belt scale calculates the value (t/h) as an average over the same time period.
- The user's text appears as a series of bullet points. If the mean current value obtained from the crusher motor and the mean value obtained from the belt scale fall outside the predetermined range in the database, the feeder speed is adjusted using a frequency converter. The feeder speed increases if the value falls below the limit. If the value surpasses the limit, the feeder speed reduces, thereby lowering the upper limit value. The feeder engine stops operating if the level surpasses a certain threshold.
- The research concludes with the reporting of energy consumption over time (in kilowatt-hours), production amount (in metric tons), hourly production rate (in metric tons per hour), and energy consumption per unit of output (in kilowatt-hours per metric ton). This approach enables the calculation of the mean capacity and energy consumption per unit of time.

An exemplar report about the topic will be incorporated into the field studies section. Implementation phases of the project were conducted at a pilot plant located in the Evri area of Kahramanmaraş (Figure 3.1- Figure 3.2).

3. RESULTS AND DISCUSSION

During the project's testing, we observed the current and energy consumption of each crusher in the system, as well as the total energy consumption of the entire system, when it was in idle operation without any material being fed into it. During the idle research, it was noted that the primary group jaw crusher functioned within the range of 80-90 amperes, the secondary impact crusher operated within the range of 190-200 amperes, and the tertiary vertical shaft crusher operated within the range of 180-185 amperes. The crushers utilize 61.40% of the total energy used by the plant while they are not in operation.

Under identical input conditions, including aggregate material, gradation, and volume, two separate tests were conducted comparing the existing situation with the algorithm management established as part of the project.

The initial test involved determining the distribution of aggregate gradation. This was done by considering the existing conditions and using the project algorithm. The results showed that 32% of the grain size was over 120 mm, while 68% was below 120 mm.

During the conventional crushing procedure, the energy consumption was measured to be 658.3 kWh while processing a crushing capacity of 540 tons per hour. Upon the project's installation, the hourly crushing capacity reached 720 tons, while the power consumption was recorded at 659.61 kWh. Upon comparing the data from Table 1 and Table 2, it was found that the use of unmanned industry 4.0 artificial intelligence technology management resulted in a 25% increase in energy efficiency per unit capacity. The test yielded a capacity increase of 33%.

Figure 3.1 Implementation field of the project

Figure 3.2 Implementation phases of the project

The second test involved doing an analysis of the overall distribution of particle sizes, taking into account the existing conditions and the approach used for the project. Specifically, 90% of the particles had a size more than 120 mm, while the remaining 10% had a size smaller than 120 mm.

During the conventional crushing procedure, the energy consumption was measured to be 624 kWh at a crushing capacity of 450 tons per hour. Upon the project's installation, the hourly crushing capacity reached 675 tons, while the energy consumption was assessed at 761 kWh. Upon comparing the data from Table 3 and Table 4, it was observed that the implementation of unmanned industry 4.0 artificial intelligence technology management resulted in a 20% increase in energy efficiency per unit capacity. The test resulted in a capacity increase of 50%.

Table1: Existing conditions of the plant

Facility's Operation/Production and Energy Report "Test Measurement"							
Gradation rate	KR01 Crusher Motor’s Current (A)	KR02 Crusher Motor’s Current (A)	KR03 Crusher Motor’s Current (A)	Total energy consumption in the entire facility (Active) (kWh)	Total energy consumption in the entire facility (Active+ Reactive) (kWh)	Capacity (t/h)	Energy consumption per unit mass (kWh/t)
%68 under 120 mm %32 over 120 mm	88	396	242	358	660	546	1.208791
	87	204	230	355	658	540	1.218519
	91	343	244	352	650	535	1.214953

Table2: When Industry 4.0 artificial intelligence technology management is active

Facility's Operation/Production and Energy Report "Test Measurement"							
Gradation rate	KR01 Crusher Motor’s Current (A)	KR02 Crusher Motor’s Current (A)	KR03 Crusher Motor’s Current (A)	Total energy consumption in the entire facility (Active) (kWh)	Total energy consumption in the entire facility (Active+ Reactive) (kWh)	Capacity (t/h)	Energy consumption per unit mass (kWh/t)
%68 under 120 mm %32 over 120 mm	103	396	216	348	648	715	0.906294
	110	314	324	340	659	720	0.915278
	115	335	278	337	660	722	0.914127

Table 3: Existing conditions of the plant

Facility's Operation/Production and Energy Report "Test Measurement"							
Gradation rate	KR01 Crusher Motor’s Current (A)	KR02 Crusher Motor’s Current (A)	KR03 Crusher Motor’s Current (A)	Total energy consumption in the entire facility (Active) (kWh)	Total energy consumption in the entire facility (Active+ Reactive) (kWh)	Capacity (t/h)	Energy consumption per unit mass (kWh/t)
%90 under 120 mm %10 over 120 mm	91	343	232	345	615	440	1.397727
	96	343	270	409	624	450	1.386667
	102	323	296	360	650	468	1.388889

Table 4: When Industry 4.0 artificial intelligence technology management is active

Facility's Operation/Production and Energy Report "Test Measurement"							
Gradation rate	KR01 Crusher Motor's Current (A)	KR02 Crusher Motor's Current (A)	KR03 Crusher Motor's Current (A)	Total energy consumption in the entire facility (Active) (kWh)	Total energy consumption in the entire facility (Active+ Reactive) (kWh)	Capacity (t/h)	Energy consumption per unit mass (kWh/t)
%90 under 120 mm %10 over 120 mm	132	322	254	348	756	680	1.111765
	140	372	236	495	761	675	1.127407
	143	391	220	495	773	685	1.128467

Table 5: Comparative Results

Project Results Report					
Grading rate	Condition	Average Capacity (t/h)	Results	Energy consumed per unit (kWh/t)	Results
%68 120mm under %32 120 mm over	Existing conditions of the plant	540	%33 capacity increase	1,218518	%25 efficiency increase
	After work	720		0,915277	
%90 120 mm over %10 120 mm under	Existing conditions of the plant	450	%50 capacity increase	1,386666	%20 efficiency increase
	After work	675		1,127407	

The calculation of facility energy consumption is determined by the apparent power.

The rock utilized as input in aggregate crushing and screening facilities is acquired through the process of blasting from natural sources and encompasses a diverse range of inorganic compounds within its composition. As you venture further into the blasting zone, you will notice alterations in the composition of the materials and their physical characteristics. However, the size distributions that are initiated in the facility differ as a result of the dimensions caused by blasting. In order to assess plant performance, field tests were conducted using various gradation densities. The average results of these tests were used to evaluate the overall performance. In addition to nutritional variety, there of the initiative, a single facility was able to achieve an annual energy efficiency of 771.150 kWh and avoid emitting 368609.7 kg of CO_2 (Figure 4).

4. CONCLUSIONS

A research was conducted to optimize the feeder flow rate during crushing using an algorithm powered by artificial intelligence. The program used may also be variations in main plant arrangement. For instance, in a primary group, it is possible to strategically install an extra front sieve (scalper) in front of the crusher to facilitate the cleaning process of the bunker, feeder, and crusher. Moreover, many orientations may be implemented if necessary. The method is designed to incorporate all these differences, allowing the user to modify the average crusher reference current value and filtering time as desired. Therefore, the algorithm may be readily adjusted to accommodate various types of mines and changes in primary group systems.

By comparing the data, it was discovered that unmanned Industry 4.0 artificial intelligence technology management reduced energy consumption per unit capacity by 22%. As a result production data from crusher facilities to keep the flow rate under continual control. The end result is an improved product quality because of this. The elimination of non-value-added activity and needless downtime caused by material anomalies is achieved.

The aggregate and mining sector has looked up to sector 4.0 as a model of best practices due to its smart production technology development and ease of application to the field. The initial step in incorporating natural resources into the industry is to execute energy-saving and maximally productive work using a widely applicable algorithm in the aggregate and mining industries.

On a nationwide scale, the project is anticipated to enhance capacity by more than 40% and improve energy consumption efficiency by 22% per unit tonnage. Based on the data from 2021, the mine production value is projected to rise from 814 million tons to 1017 million tons in 2022, thanks to the output of the 2915 crusher plant. As a result of this project, Turkey will be the leading exporter of aggregates and minerals.

Operator involvement is null and void in the AI-supported, totally autonomous system. The operator can now participate in procedures that are more productive.

In addition to incorporating digital transformation into the mining industry, the study's implementation offers a greener approach by reducing energy consumption, making better use of resources, and minimizing production-related environmental impacts. There has been a significant decrease in environmental effects in the mining and aggregate industry after implementing the twin transformation approach. Annually, 368609.7 kg of CO_2 emissions were avoided at only one plant.

This research has been an innovative study for the patents 2022/019220, " A system and method supported by artificial intelligence algorithms for use in mineral and aggregate crushing plants," [23] and 2023/019650, " An Algorithm Designed for the Total Optimization for Power Saving, Production Quantity and Quality by Modelling Operational Parameters in Aggregate Production Systems " [24].

The study seeks to enhance production efficiency and reduce investment costs by removing all procedures reliant on operator initiative in facility management and utilizing completely autonomous systems in the aggregate and mining sectors in the future. Consequently, it is anticipated that it will provide a working environment that will enhance resource efficiency and promote sustainability.

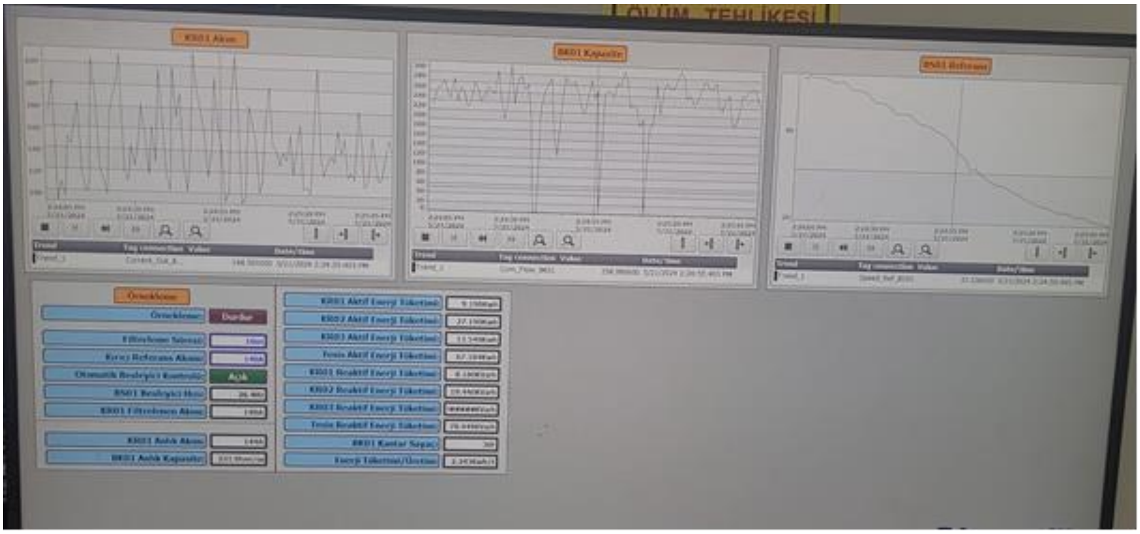

Figure 4. Monitoring of process parameters

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