

Energy Implications of Switching to Surfactant-Modified Concentrate in Iron Ore Pellet Induration

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Abstract. The article investigates energy consumption during the drying stage of iron ore pellets, a critical process in ensuring energy efficiency in mining and metallurgical production. Particular attention is given to the influence of charge material moisture content and the application of surfactants (SAS) on the specific consumption of energy resources, namely electricity and natural gas. Industrial trials were conducted at one of the leading mining and processing enterprises in the Kryvyi Rih region, focusing on the transition from the baseline (in-house) concentrate to raw material from another regional enterprise, pre-treated with non-ionic SAS. It was determined that the increased dispersity and hydrophilicity of the new raw material concentrate requires additional moistening of the charge, significantly affecting thermal regimes and energy expenditures during drying. Based on collected experimental data, regression models were developed to quantitatively predict the specific consumption of electricity and gas as a function of technological parameters. The primary factors influencing energy consumption were identified as the moisture content of the charge and the daily throughput of the drying unit. An increase in specific electricity consumption by 17.73% and natural gas consumption by 33.25% was recorded, accompanied by a simultaneous reduction in productivity by 9.55%. The findings are relevant for specialists in energy management, electrical engineering, and thermal analysis in metallurgy, particularly in the development of strategies for optimizing energy consumption under industrial conditions.

Introduction

Ensuring the energy efficiency of iron ore pellet production processes is a pressing challenge in the development of the mining and metallurgical industry, particularly in the context of global trends toward decarbonization and the transition to "green" metallurgy [1]. Efficient utilization of energy resources enhances the economic sustainability of enterprises and mitigates environmental impact by reducing greenhouse gas emissions. For instance, studies [2,3] highlight that the production of iron ore pellets, a critical intermediate product for metallurgical processing, is a priority area for implementing energy-saving solutions in the steel industry.

The pellet production process encompasses ore beneficiation and concentrate preparation, the formation of green pellets through pelletizing, and their subsequent drying [4, 5]. The primary sources

of energy consumption include electricity for operating mixers, pelletizers, draft and exhaust systems, conveyors, stackers, and other equipment, as well as thermal energy for moisture removal during drying. Given the complexity of the technological equipment, rigorous monitoring of its condition is essential to minimize operational risks [6, 7]. The efficiency of green pellet drying significantly depends on the physicochemical properties of the charge, including concentrate and green pellet moisture content, particle size distribution, binder content, and mixture rheological characteristics [8–11], which are determined at earlier stages. One such stage is the grinding of iron ore raw material, the efficiency of which is influenced, in particular, by the wear resistance of grinding media. As demonstrated in [12], enhancing the durability of grinding media stabilizes the particle size distribution and physicochemical properties of the concentrate, positively impacting the subsequent efficiency of pellet production. The rheological properties of wet concentrate significantly affect the formation, density, and strength of green pellets, as confirmed by studies [13], which determined a correlation between the surface activation moment of iron ore concentrate and the physicomechanical properties of green pellets. Additionally, researchers [14] determined that the rheological characteristics of iron ore suspensions depend on the solid particle content and particle size distribution, with the addition of fine fractions to coarse-grained pulp significantly reducing its viscosity.

According to [15], the specific heat energy consumption for drying mineral concentrates typically ranges from 800 to 1500 kcal per kilogram of removed water (0.93–1.74 kWh/kg), underscoring the significant impact of concentrate moisture content on the energy intensity of the process. In [16], it was determined that drying laterite ore in industrial flighted rotary dryers with high initial moisture content (~27%) results in substantial heat losses through the dryer casing, amounting to 3.5% of the expended fuel energy (5.8 GJ/h), driven by the specifics of heat transfer and the properties of the input raw material. To enhance drying efficiency and reduce energy consumption, novel technologies are being developed, such as microwave drying of iron ore pellets, which, as reported in [17], facilitates accelerated moisture removal by lowering the activation energy of the process and improving effective moisture diffusion compared to conventional convective methods [15, 18]. Energy consumption and heat losses in beneficiation processes are optimized similarly to metallurgical processes through the development of mathematical models, as demonstrated in [19] for metallurgical equipment. Temperature regimes and energy consumption are regulated using automated control systems and temperature monitoring technologies [20].

The moisture content of the charge and green pellets is a primary factor determining energy consumption during drying [4, 15, 21]: higher moisture levels require more heat for evaporation and extend drying times, leading to reduced equipment productivity and increased reject rates due to diminished green pellet strength. The particle size distribution of the charge also significantly affects energy consumption [4, 5, 9, 15]: finer fractions dry more quickly, but an excess of fine particles contributes to product losses. Larger pellets require prolonged drying, increasing energy expenditure and slowing production rates.

One way for improving iron ore pellet production technology involves the adoption of new concentrates treated with surfactants (SAS) [11, 21]. The effects of SAS application are multifaceted. On one hand, SAS modify the wettability and rheological properties of the concentrate, enhancing its pelletizing capability and reducing caking. As shown in [22], treatment with anionic and non-ionic SAS can reduce concentrate moisture content by 2–4% by altering particle surface properties. However, SAS treatment also increases charge moisture and modifies particle surface structure. Researchers in [23] found that the use of surface-active flotation reagents (e.g., Atrac) in iron ore concentrates increases porosity and reduces the strength of green pellets, adversely affecting their behavior during drying and potentially increasing energy consumption due to decreased bed permeability and dust formation. Elevated moisture levels complicate the drying process, elevate specific energy consumption, and may reduce the productivity of firing machines. Additionally, alterations in the formation of green pellet beds on conveyor machines can lead to process instability [4, 15]. Conversely, the SAS application improves concentrate dispersity and stabilizes the particle size distribution of green pellets. It also offers potential reductions in binder consumption, particularly

bentonite, which positively impacts green pellet strength [11, 24]. These changes requires a comprehensive evaluation when assessing the impact of the SAS on energy consumption and production process efficiency.

The issue of predicting energy consumption is particularly critical for mining and processing enterprises, including the ore beneficiation plants of the Kryvyi Rih region, which produce iron ore pellets for the metallurgical industry. These facilities face technological challenges related to increased concentrate moisture content, the need to optimize bentonite consumption to ensure the quality of green pellets, and the application of SAS. During the planned transition of the baseline “Enterprise A” to the concentrate produced by “Enterprise B,” alterations in the physicochemical properties of the charge material occur, leading to changes in the productivity of technological equipment and electricity consumption. Consequently, establishing quantitative relationships between raw material characteristics, energy consumption, and productivity parameters is a pressing task. In this article, the conditional designations “Enterprise A” and “Enterprise B” are used for confidentiality purposes and to maintain commercial neutrality, thereby avoiding unintentional promotion or disparagement of specific producers.

The objective of the study was to determine quantitative relationships between the physicochemical properties of the charge material (specifically moisture content, particle size distribution, and the use of the SAS) and the specific consumption of energy resources (electricity and natural gas), as well as the productivity of the firing machine (FM) firing unit under industrial conditions at Enterprise A during the transition from the baseline concentrate to a surfactant-modified concentrate produced by Enterprise B.

Materials and Methods

Description of the Test Facility. Prior to the commencement of trials, the equipment of the entire technological complex was prepared, including feeders, milling circuits, bowl pelletizers, a Metal7 three-product roller screen (with gap settings of 16.0 mm and 9.0 mm), a GST screen (self-balancing trajectory screen), exhaust fans, and the calibration and adjustment of weighing equipment.

Experimental studies were conducted on an industrial firing machine (FM) designed for the thermal processing of iron ore pellets. The installation is a continuous conveyor system equipped with a chain transporter and carts that move a pellet bed through drying, preheating, firing, recuperation, and cooling zones. The machine’s design (Fig. 1) incorporates injection burners, gas distribution chambers with gas-air distribution devices, a recycled heat carrier supply system, and an automated temperature regime control system. Heat recuperation enhances energy efficiency and reduces fuel consumption.

Key Technical Specifications of the Firing Machine (Enterprise A): Annual capacity — 2.4 million tonnes; current throughput — 300 t/h; specific productivity — 0.893 t·m²/h; operational dimensions: width — 4.0 m, length — 81/84 m; grate area — 324/336 m²; green pellet bed height — 300 mm; number of carts — 142; gas-air chambers — 28 (dimensions 4×3 m); cart movement speed — 0.6–2.5 m/min; cart weight — 10.3 t; zone distribution: drying, heating, firing, recuperation (largest zone — recuperation, 37.5%); maximum firing temperature — 1350°C; outlet heat carrier temperature — up to 550°C; specific heat consumption — 533.68 MJ/t; natural gas consumption — 17.9 m³/t; electricity consumption — 30.7 kWh/t; pellet outlet temperature — 100°C; drive power — 32 kW; total weight — 4600 t.

Input Materials and Test Conditions. Industrial trials were conducted due to the operational necessity of fully transitioning from the concentrate produced by Enterprise A to that of Enterprise B. Both concentrates exhibited high iron content (above 67%), but the concentrate from Enterprise B was characterized by increased dispersity (fraction –0.056 mm: 98.0–98.6%; fraction +0.056 mm (residue): 1.4–2.0%). Preliminary tests revealed that the enhanced dispersity of Enterprise B’s concentrate adversely affected the pelletizing ability of the charge material, leading to an increased volume of green return and reduced stability in pellet bed formation. To mitigate this issue, the concentrate from Enterprise B was pre-treated with the SAS Clearon S955, a non-ionic compound

based on ethoxylated isotridecanol, primarily used to improve filtration and dewatering of the concentrate post-beneficiation.

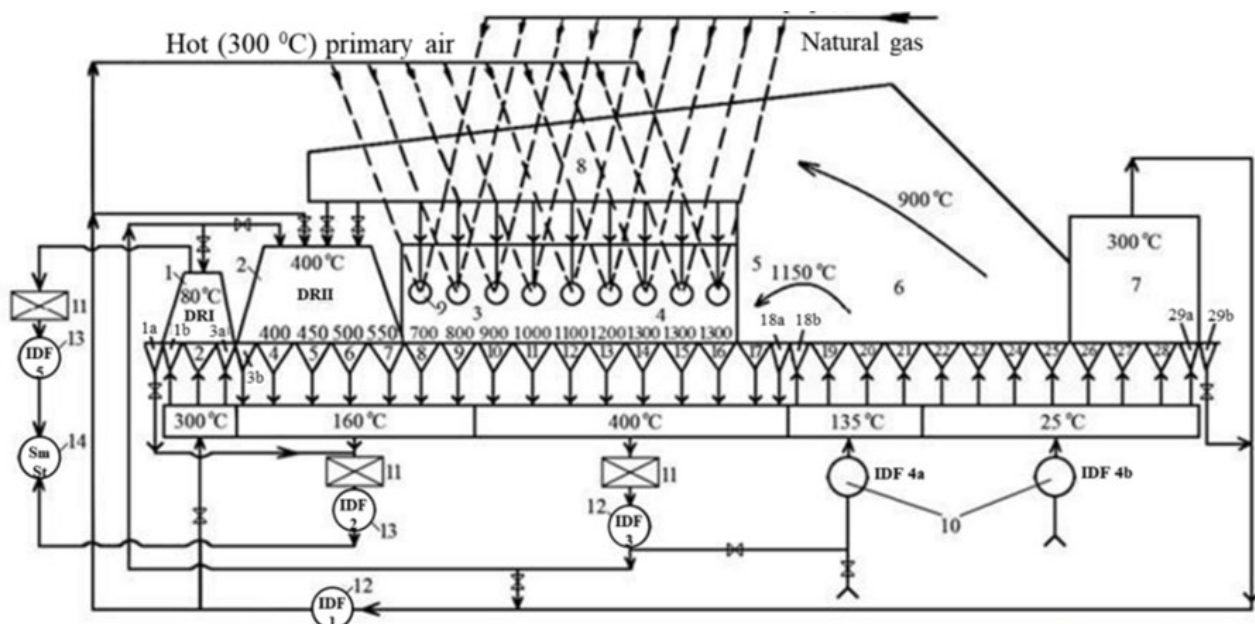


Fig. 1. Thermal diagram of the firing machine (Enterprise A): 1 – Drying I; 2 – Drying II; 3 – Heating; 4 – Induration; 5 – Heat recovery; 6 – Cooling I; 7 – Cooling II; 8 – Cross-flow manifold; 9 – Injection burners; 10 – Air fans; 11 – Dry dust collectors; 12 – High-temperature recuperative exhaust fans; 13 – Exhaust fans discharging gases to the stack; 14 – Chimney stack

In the studied case, the SAS also enhanced the wettability and aggregation of concentrate particles, facilitating the stabilization of the pelletizing process for the highly dispersed concentrate from Enterprise B. However, the reduced natural moisture content of the concentrate following dewatering required additional moistening in the mixer and pelletizer, ultimately increasing the overall moisture content of the charge. This, in turn, contributes to elevated energy consumption during pellet drying.

Charge materials (bentonite, limestone) were prepared and stored, and the transportation and stockpiling of Enterprise B's concentrate at Enterprise A's beneficiation plant storage facility were organized in compliance with requirements for batch purity and segregation. To stabilize the mechanical properties of green pellets, the bentonite consumption as a binder component was adjusted.

The trials were conducted over eight days. During the first two days, the FM firing machine operated using the baseline concentrate from Enterprise A to stabilize the technological regime and establish reference performance indicators. Starting at 21:00 on the second day, the concentrate from Enterprise B (pre-treated with the SAS) was fully introduced, loaded after emptying the bunkers, and used until the completion of the experiment. All key technological parameters (raw material consumption, gas and electricity usage, temperatures, and product characteristics) were recorded hourly, per shift, and averaged daily, enabling a comparative analysis of the impact of concentrate type on process efficiency.

Methods and Measurement Techniques. The moisture content of the concentrate was determined by weighing samples before and after drying in a BSL-1.0.3 oven (direct-flow, heat carrier: flue gases) at $105 \pm 5^\circ\text{C}$ until constant mass was achieved. The particle size distribution of green pellets was assessed using the sieve method (in accordance with DSTU 3210-95 / ISO 4701:2017) with an 8GV-3Ya vibratory screen equipped with a three-shaft vibration exciter (range: 5–20 mm). The compressive strength of green pellets (X6) was determined using the method in accordance with DSTU 3212-95 (similar to ISO 4700:2015), by applying compressive force to individual pellets until failure. Drop strength (X7) was assessed according to DSTU 3213-95 (analogous to ISO 3271:2015), by dropping pellets from a height of 0.5 m onto a steel plate and

counting the number of drops until breakage. The particle size distribution for the 10-14 mm class (X8) was evaluated in green pellets using the sieve method (DSTU 3210-95 / ISO 4701:2017), reflecting the efficiency of the granulation process and the stability of pellet formation. Productivity was measured using Schenck MULTIDOS belt scales (accuracy: 0.1–1.0%, up to 1000 t/h, belt speed: up to 0.2 m/s). Energy resource consumption was monitored as follows: natural gas consumption was recorded using Elster BK-G1000 meters at commercial metering nodes, while electricity consumption was measured with NIK 2303 AP3 industrial electricity meters (accuracy class: 1.0). Specific energy consumption was calculated based on variable product output, utilizing time tracking and daily accounting.

Determination of Influencing Factors. During the experimental-industrial trials, the following technological parameters were monitored hourly: machine productivity (t/h), cart movement speed (m/min), drying zone temperature (°C), pressure drop (daPa), quantity of green pellets at the screen (t/h), bentonite consumption (kg/t), consumption of fired return (t/h), moisture content of green pellets (%), specific electricity consumption (kWh/t), specific natural gas consumption (m³/t), and other parameters. The data were systematized in daily accounting tables (with averaged daily values) to identify changes in equipment performance during the transition from baseline raw material to the SAS-modified concentrate from Enterprise B. A classification of factors (see Table 1) affecting the outcomes, specifically machine productivity, electricity consumption, and natural gas consumption, was conducted.

The target functions focused on energy consumption (Y1 – specific electricity, Y2 – specific natural gas) and productivity (Y3), as the primary goal was to assess energy implications during the drying stage. The impact on fired pellet quality (e.g., strength) was not evaluated in this study, as preliminary checks confirmed compliance with standards, and the focus was on process efficiency rather than end-product metallurgy. Future work could extend to fired pellet properties.

Table 1. Classification of Influencing Factors

Machine	Material	Method	Measurement
FM pelletizing machine, injection burners, gas-air distribution system, Metal7 screen, GST screen, exhaust fans, BSL-1.0.3 drying oven, 8GV-3Ya vibrating screen	Bentonite (consumption, fraction, moisture, swelling), limestone, fired return, concentrate and green pellet moisture, fraction <0.056 mm, Fe, SiO ₂ , CaO+MgO content, Clearon S955 surfactant	Concentrate feeding sequence, dosing, parameter stabilization, use of temporary regime maps	Moisture determination (drying oven), sieve analysis (Ø200 mm sieves), Schenck belt scales, Elster BK-G1000 gas meters, NIK 2303 AP3 electricity meters
Man (Human Factor)	Management	Maintenance	Mother nature (Environment)
Trained personnel, manual/automated regime control, chronometric monitoring	Transportation and storage organization, regime map development, dosing and bunker verification	Preventive maintenance, equipment calibration, and technical servicing	Drying zone temperature, furnace and chamber vacuum, gas chamber pressure, and ambient humidity

Based on the observed effects, an Ishikawa cause-and-effect diagram (8M) was constructed to illustrate the impact of classified technological factors on the machine's productivity, electricity, and natural gas consumption (Figure 2).

To reduce the number of influencing factors, the expert judgment method was employed, which enabled the reduction of factors to 10 (or 11 when productivity was included as an influencing factor). The rationale for reducing the number of factors included mitigating the impact of technological factors whose values did not undergo significant changes during the transition from one raw material to another, implying that, under otherwise equal conditions, their influence is equivalent.

In Figure 2, the influencing factors considered in subsequent calculations (for the development of regression models) are highlighted in bold. During the derivation of regression equations using the Data Analysis methodology, the influence of each selected factor was further evaluated, allowing the identification of factors whose impact on the outcome was nullified, thereby facilitating additional reduction of the mathematical model's components.

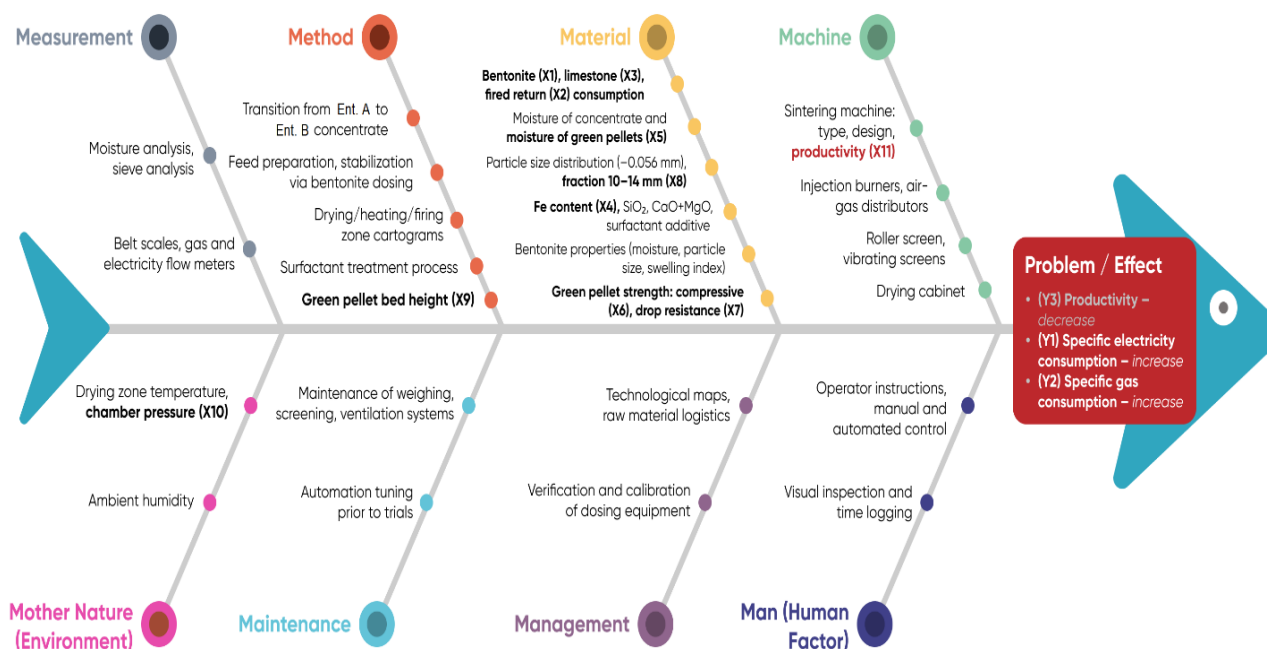


Fig. 2. Ishikawa Cause-and-Effect Diagram (8M) of Objective Factors Influencing FM Productivity, Electricity, and Natural Gas Consumption. Bold factors (including X6, X7, X8 for green pellets) were selected for regression modeling

Results

During the industrial trials, daily average values of technological parameters were collected and systematized, covering two periods: the use of the baseline concentrate from Enterprise A (days 1–2) and the transition to the surfactant-treated (the SAS) concentrate from Enterprise B (days 3–8). Table 2 presents the values of key influencing factors (X) and performance indicators (Y), including daily averages, the full range of fluctuations for each parameter (min...max), and aggregated averages for each stage.

The third day represented a transitional adaptation period during concentrate replacement, with extreme values due to regime adjustments. While included in averages for days 3–8 to reflect real industrial dynamics, sensitivity analysis excluding day 3 yielded similar trends: average productivity 269.6 t/h (vs. 269.5 t/h), electricity 37.3 kWh/t (vs. 40.44 kWh/t), gas 4.65 m³/t (vs. 5.57 m³/t). This confirms the robustness of results, though transitional effects amplify energy increases.

The data in Table 2 are structured in accordance with the regression analysis formulas (1) and (2), which form the basis of mathematical models describing the dependence of output parameters on key influencing factors. The change in raw material was accompanied by variations in the consumption of the main charge components, the physicochemical properties of the concentrate, the parameters of green pellet formation, and the efficiency of the firing process. Regarding the inclusion of productivity (Y3) as a factor in Formula (2) for Y1 and Y2 - while factors should ideally be independent, productivity here acts as a macro-parameter integrating multiple influences (*as shown by $R^2=0.99$ in Formula (1)*). It was included to explore ‘absorbed’ effects, acknowledging potential collinearity. This was mitigated by comparing models with and without Y3, and the statistical insignificance of some coefficients (e.g., b3–b6 in Formula (2)) confirms the approach’s validity without overfitting.

Table 2. Results of the industrial experiment on iron ore pellet production during the transition from Enterprise A's concentrate to Enterprise B's SAS-treated concentrate

Regression Equation Form		Formula No	Factor (X) or Parameter (Y)		Unit	Formula		Range (min...max)						
						(1)	(2)							
$Y_n(1) = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 + b_4 \cdot X_4 + b_5 \cdot X_5 + b_6 \cdot X_6 + b_7 \cdot X_7 + b_8 \cdot X_8 + b_9 \cdot X_9 + b_{10} \cdot X_{10}$		(1)	Bentonite Consumption	kg/t	X ₁	X ₁	14.55...15.88							
			Fired Return Consumption	t/h	X ₂	X ₂	13.5...16.54							
			Limestone Consumption	kg/t	X ₃	X ₃	5.3...8.96							
			Fe Content	%	X ₄	X ₄	67.81...69.86							
			Green Pellet Moisture	%	X ₅	X ₅	8.37...9.33							
			Compressive Strength	kg/pellet	X ₆	X ₆	1.3...1.48							
$Y_n(2) = b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 + b_4 \cdot X_4 + b_5 \cdot X_5 + b_6 \cdot X_6 + b_7 \cdot X_7 + b_8 \cdot X_8 + b_9 \cdot X_9 + b_{10} \cdot X_{10} + b_{11} \cdot X_{11}$		(2)	Drop Strength	times	X ₇	X ₇	3.83...4.18							
			10-14 mm Class	%	X ₈	X ₈	59.82...64.12							
			Green Pellet Bed Height	mm	X ₉	X ₉	315...357							
			Vacuum Chamber Pressure	daPa	X ₁₀	X ₁₀	271...482							
			Productivity (n = 3)	t/h	Y ₃ (1)	X ₁₁	243.6...298.0							
			Specific Electricity Consumption (n = 1)	kWh/t	Y ₁ (1)	Y ₁ (2)	33.99...56.35							
			Specific Gas Consumption (n = 2)	m³/t	Y ₂ (1)	Y ₂ (2)	4.14...10.7							
Feed stock	Day	Daily Averages												
		X ₁	X ₂	X ₃	X ₄	X ₅	X ₆	X ₇	X ₈	X ₉	X ₁₀	X ₁₁ / Y ₃ (1)	Y ₁ (1, 2)	Y ₂ (1, 2)
Ent. A	1	14,55	13,50	5,30	69,86	8,37	1,44	4,18	63,73	356	482	298	34,71	4,14
	2	14,55	15,88	5,30	69,86	8,38	1,48	4,13	64,12	357	472	298	33,99	4,22
Avg. Days 1–2		14,55	14,69	5,3	69,86	8,375	1,46	4,155	63,925	356,5	477	298	34,35	4,18
Ent. B (with Surfactant)	3	15,48	15,86	8,96	67,81	9,33	1,32	4,03	62,43	315	271	243,6	56,35	10,7
	4	15,88	15,58	8,96	67,81	8,70	1,30	3,83	59,82	329	284	272,6	36,71	4,59
	5	15,67	14,58	8,96	67,83	8,87	1,32	4,00	60,05	334	280	275,1	37,09	4,45
	6	15,00	13,71	8,96	67,82	8,80	1,31	3,98	59,82	337	282	275,3	36,78	4,56
	7	15,00	15,50	8,96	67,83	8,85	1,35	4,03	61,13	334	281	275,3	37,55	4,55
	8	15,00	16,54	8,96	67,87	8,80	1,34	4,02	60,03	334	287	275,3	38,18	4,59
Avg. Days 3–8		15,34	15,3	8,96	67,83	8,89	1,32	3,98	60,55	330,5	280,83	269,53	40,44	5,57

Figure 3 provides a graphical representation of the dynamics of three key indicators—productivity, specific electricity consumption, and natural gas consumption—over the eight-day period. The daily format enables tracking the technological system's response to the raw material change and highlights the transitional nature of the third day, which exhibited the most significant deviations. This information was considered when calculating the average values for each period.

Following the mathematical processing of the results presented in Table 2. Mathematical processing involved multiple linear regression using the least squares method. Models were evaluated for reliability: $R^2 > 0.99$ for all equations indicates excellent fit; F-statistic ($p < 0.01$) confirms overall significance; standard errors of coefficients were low (e.g., < 0.5 for key b_1 - b_{10}), with no multicollinearity issues ($VIF < 5$ for factors). Residual plots showed normality and homoscedasticity, supporting model accuracy. The coefficients for regression equations (1) and (2) were obtained, as shown in Table 3.

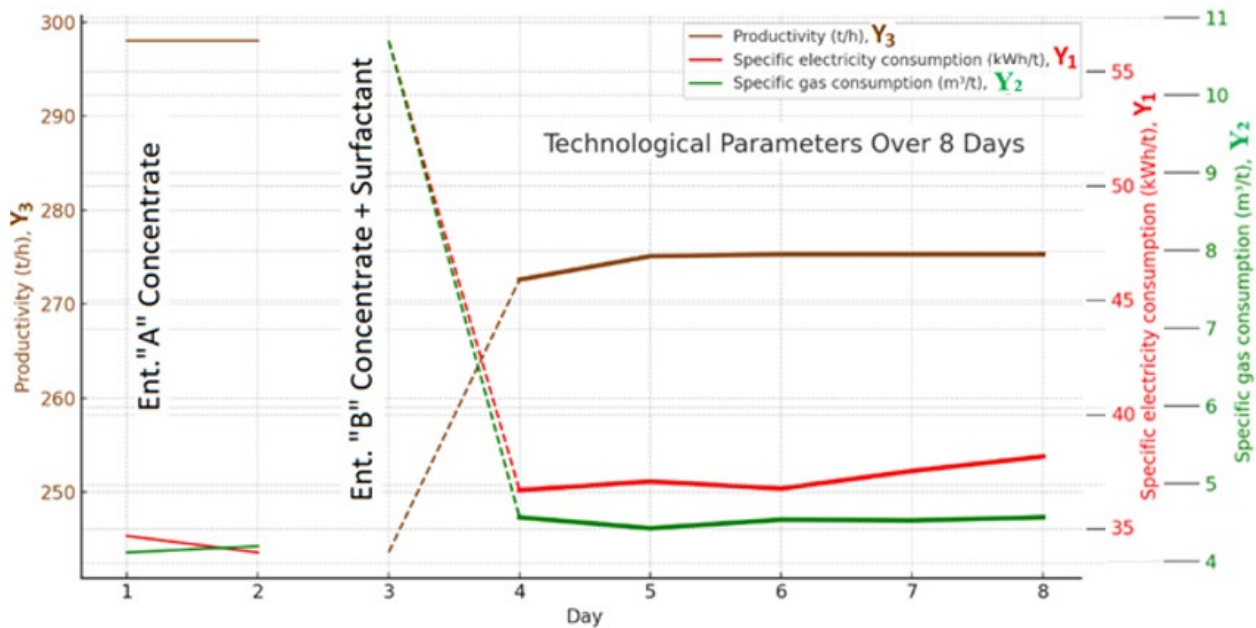


Fig. 3. Daily variation in productivity (Y_3), specific energy consumption (Y_1), and natural gas consumption (Y_2) during pellet production.

Table 3. Coefficients for regression equations (1) and (2) from Table 2 for predicting productivity and energy consumption.

Y	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}	b_{11}
Without Productivity as a Factor (Formula 1)												
$Y_1(1)$	383,256	-4,216	-0,03	-9,773	0	18,846	0	0	-1,763	-0,712	-0,056	-
$Y_2(1)$	218,84	-1,691	-0,086	-6,795	0	3,851	0	0	-0,736	-0,278	-0,081	-
$Y_3(1)$	-847,902	7,26	0,627	29,624	0	-12,953	0	0	3,519	1,552	0,429	-
With Productivity as a Factor (Formula 2)												
$Y_1(2)$	149,703	-0,2	0,23	0	0	0	0	13,821	-0,21	0,003	0,05	-0,619
$Y_2(2)$	27,135	0,073	0,061	0	0	0	0	0,835	0,095	0,09	0,015	-0,247

Analysis of Table 3 indicates that in the development of regression models (1) and (2) for predicting specific electricity consumption (Y_1), natural gas consumption (Y_2), and unit productivity (Y_3), certain factors were found to be statistically insignificant. This is evidenced by the zero values of the corresponding coefficients b in the regression equations.

Specifically, in model (1), which was constructed without accounting for productivity as a factor, the coefficients b_4 , b_6 , and b_7 for $Y_1(1)$, $Y_2(1)$, and $Y_3(1)$ are equal to zero. This suggests that the factors “Fe content” (X_4), “compressive strength” (X_6), and “drop strength” (X_7) did not significantly contribute to explaining variations in energy resource consumption under the studied conditions. It is likely that these parameters remained relatively stable within the experiment, or their influence was weaker compared to moisture content, bentonite consumption, or return material.

In model (2), which incorporated productivity as a factor (X_{11}), the influence of an even greater number of factors was nullified: specifically, for $Y_1(2)$ and $Y_2(2)$, the coefficients for X_3 , X_4 , X_5 , and X_6 became zero. This indicates that after accounting for productivity as a dominant macro-parameter, the residual contribution of factors such as “limestone consumption” (X_3), “Fe content” (X_4), “green pellet moisture content” (X_5), or “compressive strength” (X_6) became statistically insignificant. In other words, the effect of these factors was “absorbed” by productivity, which itself significantly influences energy consumption, either reducing or amplifying it through the mechanism of consistent background heat losses.

Thus, zero coefficients do not imply the absence of physical influence but rather the dominance of other, more significant factors within the specific experimental design. This is a typical outcome of multifactor analysis, where interrelationships between parameters may obscure or mask the influence of less impactful variables.

Discussion

During industrial trials, it was determined that the concentrate from Enterprise B exhibited a higher content of fine-dispersed fraction (-0.056 mm) compared to the baseline concentrate from Enterprise A. This change in particle size distribution led to reduced natural pelletizing ability of the charge material, complicating the formation of stable green pellets. To compensate for the poorer granulation properties, SAS were applied in combination with targeted additional moistening of the concentrate. The increase in bentonite consumption (from 14.55 to 15.34 kg/t) was required by the need to enhance the binding properties of the charge due to the lower natural pelletizing ability of Enterprise B's concentrate, caused by its higher dispersity and reduced particle aggregation.

As a result of these measures, the average moisture content of the concentrate increased from 9.4% to 9.9%, and consequently, in green pellets, from 8.38% to 8.89%. This indicates both the enhanced hydrophilicity of the treated concentrate and the technological necessity of ensuring a stable pelletizing process through moistening. However, the increased moisture content in the charge significantly complicated the subsequent drying stage.

Following the transition to Enterprise B's concentrate, a reduction in the average productivity of the firing machine by 9.6% was recorded, from 298 to 269.5 t/h. The lowest productivity (243.6 t/h) was observed on the third day of the experiment, during the adaptation of the thermal regime to the new conditions. During this period, peak energy consumption was noted: 56.35 kWh/t of electricity and 10.7 m³/t of natural gas. Subsequently, consumption stabilized but remained higher than baseline levels.

Overall, the average increase in specific electricity consumption was +17.7% (from 34.35 to 40.44 kWh/t), and natural gas consumption increased by +33.3% (from 4.18 to 5.57 m³/t). The primary reason for this is attributed to the need for prolonged drying due to elevated moisture content and reduced permeability of the green pellet bed formed from finer material. Additionally, changes in the rheological properties of the mixture and the lower initial mechanical strength of the pellets required the application of more cautious temperature regimes with extended heating cycles.

The dispersive properties of Enterprise B's concentrate, which differ from the baseline material, required its modification using the SAS. The generalized cause-and-effect relationships of this intervention on the pelletizing process and energy consumption are presented in the diagram in Fig. 4 ("Problem – Actions – Result").

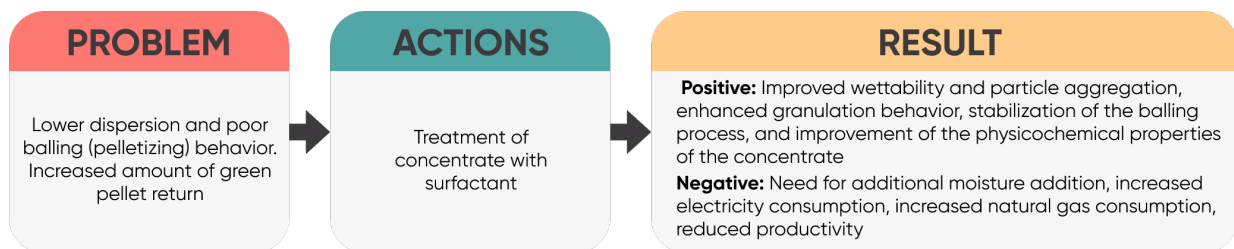


Fig. 4. Problem–Actions–Result Diagram

The analysis results are summarized in Table 4.

An additional factor contributing to increased energy consumption may have been the temporary instability of thermal regimes during the transition period. During this time, operators might have applied reduced temperatures or gas flow rates to prevent pellet degradation, which, combined with decreased productivity, led to an increase in specific energy consumption due to consistent background heat losses of the unit.

Thus, the application of the SAS in the processing technology of Enterprise B's concentrate improved particle wettability and aggregation. However, it simultaneously increased the moisture content of the mixture, deteriorated drying conditions, and elevated energy resource consumption during the transition period.

Table 4. Analysis of Industrial Experiment Results for Iron Ore Pellet Production During Transition from Enterprise A to Surfactant-Treated Enterprise B Concentrate

Parameter	Baseline Concentrate (Ent. A, No Surfactant)	Enterprise B Concentrate with Surfactant (Ent. B + Surfactant)	Δ (Absolute)	Δ [%]
Bentonite Consumption [kg/t]	14,55	15,34	↑ 0,79	↑ 5,43
Green Pellet Moisture [%]	8,375	8,89	↑ 0,515	↑ 6,15
Specific Electricity Consumption, [kWh/t]	34,35	40,44	↑ 6,09	↑ 17,73
Specific Natural Gas Consumption [m ³ /t]	4,18	5,57	↑ 1,39	↑ 33,25
Productivity [t/h]	298	269,53	↓ -28,47	↓ -9,55

Within the scope of the conducted trials, isolating the impact of the SAS on the results was challenging, as the change in concentrate was accompanied by simultaneous variations in multiple physicochemical and technological factors. Furthermore, the absence of laboratory data on the hydrophilicity of the concentrates limits the ability to quantitatively assess the wettability effect. Consequently, a promising direction for future research involves conducting targeted tests with controlled SAS dosing to precisely determine its impact on charge properties. Additionally, trials with concentrates of varying moisture content are necessary to clarify the role of moistening in the mechanism of energy consumption changes.

Conclusions

Industrial trials were conducted at Enterprise A to transition from its proprietary concentrate to the surfactant-treated (SAS) concentrate from Enterprise B. The experiments comprised two stages: days 1–2 utilized the baseline concentrate from Enterprise A, while days 3–8 employed the SAS-treated concentrate from Enterprise B. Compared to the baseline period, the new raw material altered the physicochemical properties of the charge, affecting the stability of pellet formation and drying. It was determined that the moisture content and dispersity of the concentrate significantly influence energy consumption.

Based on the data, qualitative and quantitative relationships between raw material characteristics (e.g., moisture, dispersity) and technological indicators (energy consumption, productivity) were identified. Regression models were developed to predict specific electricity and gas consumption, as well as productivity, highlighting the dominant roles of moisture content and productivity. Factors like Fe content and green pellet strength showed statistically insignificant impacts in the models, likely due to their stability or absorption by other variables. Variance analysis was not performed, but coefficient significance tests confirmed key influences.

The use of Enterprise B's the SAS-treated concentrate required additional moistening of the concentrate (moisture content increased on average from 9.4% to 9.9%, i.e., by +0.5%), resulting in an increase in specific electricity consumption from 34.35 to 40.44 kWh/t (+17.73%) and specific natural gas consumption from 4.18 to 5.57 m³/t (+33.25%). Correspondingly, a reduction in the average productivity of the firing machine was observed, from 298.0 to 269.5 t/h (−9.55%). Additionally, an increase in green pellet moisture content from 8.375% to 8.89% (+6.15%) and bentonite consumption from 14.55 to 15.34 kg/t (+5.43%) was recorded. These results indicate elevated energy expenditures and reduced process efficiency when using Enterprise B's concentrate, attributed to its higher dispersity and the need for additional moistening, which complicates drying and impacts the stability of thermal regimes.

Overall, the study highlights the necessity of tailored adjustments to drying regimes when transitioning to new concentrate types. Future research should focus on laboratory trials with varying the SAS concentrations and moisture levels to more accurately assess their impact on energy consumption and product quality. Particular attention should be given to stabilizing thermal regimes during transition periods, which could significantly enhance the energy efficiency of production.

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