Coal Supply Chain Management and Economic Efficiency of using High-Ash Coking Coal in Ferroalloy Manufacturing

Bura Akhmetzhanov#1, Kashamida Tazhibekova#2, Aigerim Shametova#3 Abay Urazbekov#4

1,2,3,4 *Department Economics and Management of Enterprise, Karaganda State Technical University, Karaganda, Kazakhstan*

1,2,4 tkashamida@yahoo.com
3 ashametova.74@mail.ru

Abstract **– In the global competitive environment, metallurgical industries reach progress through cuts in production costs. In this light, the priorities to boost ferroalloy manufacturing include the effective innovative material- and energy-saving technologies, which are applied to alternative carbonaceous reducing agents used in ferroalloy production. Additionally to a regression model for predicting the average annual world prices for steel, this article assesses the economic efficiency of using weak coking coals in ferroalloy manufacturing. This study also explores the relationship between supply chain management and production cost considered a key factor in supply chain management. The factors influencing price behaviour are the capacity of the world metallurgical plants and the price for coking coal. The economic efficiency of using high-ash coking coal to produce ferroalloys was studied on the ferrosilicoaluminium (FeSiAl) FS55A20 against the ferrosilicon FS75. The comparative analysis was performed using economic-mathematical modelling. The commercial efficiency of investment projects was studied using statistical (payback period) and dynamic (net present value) methods. Based on these factors, the steel price forecast was made for 2019–2023. In ferroalloy manufacturing, the shift from ferrosilicon FS75 to ferrosilicoaluminium FS55A20 will bring a profit of USD 2.1 million annually. The average payback period for investments in the project was 2 years. The calculated net present value of the project was USD 2.4 million.**

The analysis resulted in the outline of the main factors to consider when choosing a strategy of supply chain management.

Keywords *– world prices, regression model, high-ash coking coals, ferroalloys, supply chain management, production cost, high ash coal.*

1. Introduction

The main coal consumers are the energy production industry and manufacturing industry, where the ferrous metallurgy accounts for a lion's share of coal consumption [1]. The demand for ferrous metallurgy has recently grown, as evidenced by the significant excess of the steel production capacity over the global market demand. The experts expect this gap to increase in the near future due to a slowdown in China’s economy and a decrease in demand for steel in some industries [2]. Today, world companies are targeted at reducing production costs and searching for sources to finance enterprise modernization programs [3, 4]. The right strategy of supply chain management is crucial for accomplishing the objectives from earlier. The supply chain management (SCM) in the industry development, market survival, rate of production vibrant communication among and customers [5]. The structure of coal logistics is determined by the locations of economic coal seams and the industrial and population centres where the coal is consumed [6].

In the metallurgical industry, supply chain management is a specific practice due to various reasons and specifically due to the nature of production systems they contain [7]. Unlike the assembly production, supply chain practices in metallurgy are associated with energy-intensive physical-and-chemical processes [8]. The products may differ in qualities because they consist of elements of a certain shape, size and structure, with certain physical, chemical and other properties that determine their value in use [9].

On the other hand, metallurgists traditionally strive to minimize the cost of raw materials by optimizing the coal charge with cheaper brands [10].

Electrometallurgy and sectors associated with a direct reduction of iron, due to rising prices for natural gas and electricity, use coking coal to produce high-quality steel but they cannot completely shift from the blast furnace process [11]. Ferroalloys (ferronickel, ferroniobium, ferrovanadium, alloys containing iron, ferro aluminium) are well-known agents used to bring steel to the intended chemical composition [12]. In the production of steels for various purposes, deoxidation is usually carried out by secondary aluminium. However, some materials used as alloy components in steel production are usually used in combination with iron (ferroalloy). These materials are manganese, silicon, titanium, niobium, vanadium, etc. Their

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International Journal of Supply Chain Management
IJSCM, ISSN: 2050-7399 (Online), 2051-3771 (Print)

combination with iron in an alloy (ferroalloy) creates the best conditions for steel production [13]. In recent years, steel deoxidation has been carried out by adding ferroaluminium and silico-manganese to reduce the consumption of aluminium [14]. The critical raw materials used in the steel production are iron ore, coking coal, processed metal and limestone [15]. The world steel production accounts for 12% of world coal consumption (approx. of 761 million tons of coking coal annually). Coal reserves exist in almost every country around the world, but only 70 countries have proven reserves [16, 17]. Therefore, coking and steam coal markets are largely interconnected, and this makes supply chain management logically organized [18, 19]. In recent decades, facilities producing coke for global steel production have gradually moved from European to Asian countries for environmental reasons. With them, the coking coal consumption centres have also moved to developing countries [20, 21]. This is why the choice of a supply chain strategy becomes more challenging [22].

The main regions producing coking coal are Asia (particularly China), Australia, North America (the USA and Canada) and the CIS countries (Russia, Ukraine and Kazakhstan) [23].

It draws attention to how China and Australia gradually occupies a greater space in world production. China is increasing production to meet domestic needs, while Australia is consolidating its position as the world's leading exporter [24]. Australia is the first largest coking coal exporter. Other major coking coal exporters are Canada and the United States. These countries account for about two-thirds of the world trade [25]. So far, coke produced at the corresponding affiliated plants accounts for more than 90% of the world's coke consumption. The remaining 5-10% of coke is purchased. It seems clear that the coke that goes on sale is more interesting from the perspective of analysis [26]. Russia with its current export turnover is also not yet able to compete with the leading global manufacturers. The remoteness of the major production basins from consumers is both a distinctive feature and a problem of the coal industry in Russia [27].

Many studies are focused on factors that used to influence the use of energy in steel production to quantify their possible influence in the future [28, 29]. Long-term price forecasts are crucial to the manufacturing industry. The long-term investment decisions in any industry, including ferrous metallurgy, are based on an understanding of price behaviour at the implementation and payback stages of the project [30]. In the metallurgical industry, for example, price forecasts may embrace the period over 10 years. The tendency of price for the final product necessarily must be comparable with the expected cost dynamics. In this way, it will allow making more reliable profitability forecasts, and so the payback forecasts. In price forecasting (in virtually every industry), there are two approaches to modelling [31]:

1. decomposition of price time series data: trend detection, autocorrelation, seasonal and random components;
2. factor analysis based on a regression model: allocation of essential price factors, quantitative assessment of their impact on the regression, exogenous factors, and price forecast construction.

Factor analysis is based on choosing significant factors that influence prices and assessing their influence. The forecast specifies the most likely dynamics of factors influencing price change. Prices in the forecast are calculated using the regression equation [32]. Factors influencing steel prices are export prices used to forecast internal prices, allocation of rolled products production volumes in consuming industries, and global capacity utilization [33]. The most commonly used approach is the econometric analysis, which regards the steel demand to be a function of the gross domestic product (GDP) or per capita GDP [34, 35].

The literature analysis showed that coking coal is the main source of energy in the production of ferroalloys for steel making. Additionally to high cost and scarcity, coke production is associated with the use of high-quality coking coals, which are a limited resource. The coking technology itself is associated with the need to solve a number of complex environmental problems. Thus, it is advisable to consider the comprehensive use of high-ash coking coal to produce items that are in demand in other industries, including the metallurgical industry.

Therefore, **the purpose of this study** is to forecast global steel prices using a regression model, determine the strategy of supply chain management and evaluate the economic efficiency of using high-ash coking coals in the production of ferrosilicoaluminium (FeSiAl) FS55A20.

2. Methods

The prices for high-ash coking coal were considered the main factor in steel price forecasting.

A regression model was built to study the behaviour of steel prices. The assumption was that the cast iron price P_t, steel utilization rate and the cost of raw materials RMC_t are linearly related. Other factors influencing the price (technical progress in steelmaking, shift to developing countries, etc.) were recorded via trend time series. Margin steel producers are located in Asia (Japan and China), where top steel consumers and raw materials buyers live. The contract prices for raw materials (coking coal + slag) served a good reference to approximate cost dynamics for marginal steel producers. The transportations from Australia to Japan were not considered in the model because they correlate well with the prices for raw materials. For the same reason, the model does not involve the ferrous scrap. The raw material cost index was measured at the current US dollar rate, and therefore, accounts for the inflation. Thus, the equation is as follows:

$$Pt = \alpha CUt + \beta RMt + \gamma t + \varpi \tag{1}$$

Where: *t* – time trend variable (or the time index), equals 0 in 2018 and increases/decreases by 1 unit in each interval of the given year; α, β, γ, and ω – regression coefficients calculated from 2008-2018 records.

The average world price for steel P_t and high-ash coking coal is calculated as the arithmetic mean of four variables: FOB US price for hot-rolled coil, European hot-rolled coil price, Chinese hot-rolled coil price, and price for exports from Russia (data from Steel Business Briefing Ltd (SBB) and Commodities Research Unit (CRU)). Prices were taken as the annual average.

The coefficient of the raw-material cost is estimated as a weighted sum of prices for coking coal and iron ore:

$$RMCt = 0.6 \times \text{Coking coal price}_t + 1.6 \times \text{Iron ore price}_t \tag{2}$$

The weighted total was determined from the expert estimates of raw material consumption per ton of hot-rolled sheet. The Australian export price was chosen as the representative price for coking coal. Data were from CRU and WSD.

In order to reconcile the shifts of supply and demand curves, a dimensionless parameter –capacity utilization CU_t – was used. At equilibrium time *t*, capacity utilization can be found by:

$$CUt = Qt / Capacities\,t \tag{3}$$

Where: *Qt* is equal to steel production volumes.

Thus, capacity utilization and steel production cost are considered two major factors influencing the equilibrium steel price.

The capacity coefficient estimation was based on data from the World Steel Association.

Based on annual data from 2008 to 2018, the calculation formula (1) is as follows:

$$Pt = 13.45CUt + 3RMCt - 5.2t - 972 \tag{4}$$

The model coefficients are all significant. The determination coefficient R^2 equals 90%; in other words, the model cannot explain 10% of changes in average world steel prices. The calculated values are close to actual prices. This makes the forecast 67% precise.

The ARIMA model was used to autocorrelate the prices in dynamics.

The economic efficiency of using high-ash coking coals in steel production was assessed coals from the Borlinskoe and Kuuchekinskoe deposits. Numerous studies conducted by research institutes, laboratory and industrial tests showed that those coals are high-ash.

2.1. Economic assessment of production using economic-mathematical modelling

The economic efficiency was assessed by analyzing steel cost when using high-ash, weakly coking coal in ferroalloy manufacturing. The integral effect (commercial + socio-economic efficiency) was determined according to guidelines for evaluating the effectiveness of investment projects [36]. To determine the role of ferroalloys from ferrosilicoaluminum (FeSiAl) FS55A20, an optimization model was formed, the objective function of which is to maximize the company's profit margin (*M*). The controllable variables for problem-solving and limitation recording were the following:

○ an expected output x_j^s of *j* products produced through technological process *s*;

○ zi_j^s volume of raw materials *i* required to produce *j* products;

○ selling price p_j of *j* products; selling price p_i of raw materials *i*;

○ raw-material cost Z;

○ money *C* for resources;

○ a_j volume of contractual obligations relating to *j* products;

○ b_i volume of available raw materials;

○ available production capacity x_j^s max for producing x_j^s

Constraints of the optimization problem are as follows:

$$M = f(x1, x2..., xn) \rightarrow \max \tag{5}$$

$$x_j^s \geq 0 \text{ and } zi_j^s \geq o \tag{6}$$

$$Z \leq C \tag{7}$$

$$xj \geq a_j \tag{8}$$

2.2. Economic assessment of investment projects

The commercial efficiency of investment projects was studied using statistical (payback period) and dynamic (net present value) methods.

The Net Present Value (NPV) is calculated by:

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{9}$$

Where: B – benefits over a year t;

C – costs over a year t;

t – a given year (1,2,3, …n);
i – discount rate, in per cent).

The payback period (PP) for investments is associated with liquidity. This short-term method considers the period during which the invested amount will be repaid.

The payback period is estimated with the formula below:

$$PP = I_o / CF_{cr} \qquad (10)$$

Where: *PP* – payback period in years;
I_o – the total sum invested, USD;
CF_{cr} – annual cash inflow, RUB.

According to PP, the faster a project can pay back the initial investment, the better. The PP focuses on cash inflows and on the rate of these inflows, rather than on profitability or total profit. When using this criterion, an acceptable payback period should be determined as a measure for assessing capital investments. The higher is the liquidity needed, the shorter the PP should be. The PP method has two major drawbacks. Firstly, it does not take into account those inflows that come after the payback period.

Hence, this method is for short-term forecasting. Therefore, PP cannot be used as a tool for decision-making in projects with a long payback period. Instead, it is applicable to those projects that provide a quick return of invested resources, even if the inflows are modest and short-lived.

Based on research results, an analysis was carried out to study major factors influencing supply chain management.

Table. 1. Data on resources involved when using hard-ash coal

Parameter	**Volume/Price**
Volume of available raw materials;	1.6 mln tons of waste per year
FS55A20 production output	16 mln tons per year
Marginal profit	30%
Product selling price per ton	FeSiAl: from USD 1200 per ton
Raw material selling price	
FS55A20 price per ton	FeSiAl: from USD 1200 per ton
Annual revenue from product sales	USD 19200 thousand
Total sum invested	USD 30000 thousand
Sales proceeds	USD 19200 thousand
Energy costs;	30%
Wages and taxes	8%

3. Results and discussion

Let us put the regression model into context. A 1% increase in capacity utilization leads to an increase in rolled product prices by USD 14.35 per ton. Accordingly, when capacity utilization moves up 6.9%, then the steel price will increase by 100 US dollars. A 1-dollar increase in the cost of raw materials leads to an increase in rolled product prices by 4 US dollars, of which 1 dollar is directly related to the increase in prices for coking coal. The remaining 3 dollars will come from the rise in prices for other cost items (steel scrap, ferroalloys, freight, energy and labour), which tend to change in the same direction as prices for coking coal and slag. Prices tend to reduce 5.2 US dollars every year due to emerging regional industrial innovation with low production costs.

Figure 1 shows the input data used to estimate the regression model.

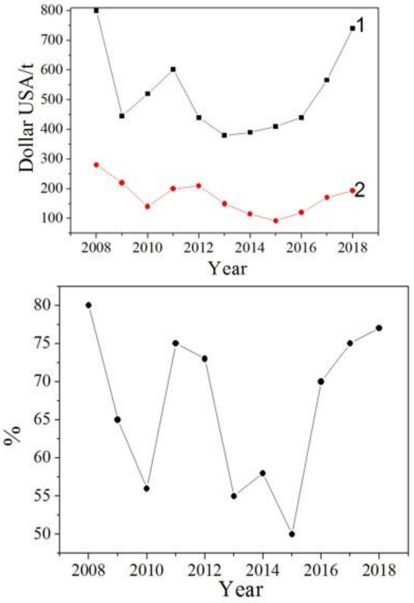

Figure 1. Input data*:* (a) 1 – average world prices for hot-rolled coil; 2 – coking coal price; (b) capacity utilization.

Figure 1 shows that despite the global crisis in the world from 2012 to 2016, prices for raw materials dropped so did the prices for the hot rolled coil (Fusco, 2016.).

Figure 2 displays actual rolled product prices against calculated prices.

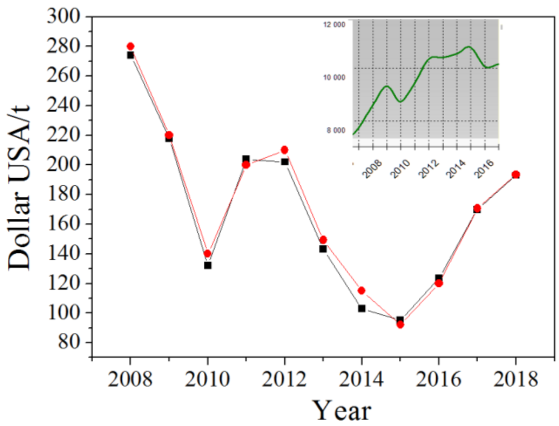

Figure 2. Average world prices for hot-rolled coil: *1 – estimates based on regression; 2 – actual price*. Insertion**:** world GDP per capita in 2008/2016, current USD.

The calculated values were exactly close to the actual prices. The only mismatch was observed in the time interval between 2012 and 2014 when the strengthening of the US dollar contributed to a decline in world steel prices. This conflict between calculated and actual prices is also associated with the global crisis when the GDP shrank (see inset in Figure 2). In addition, the regression model overestimated the actual increase in steel prices in 2010, 2012, and 2014. However, speculative factors did their job in 2014 and brought the actual and calculated values back in tune in 2015.

3.1. Model sensitivity analysis

This is a standard stage of modelling which allows estimating the price sensitivity to changes in the market environment. Based on the regression model, an analysis was carried out to estimate steel price sensitivity to changes in the raw materials market (raw-material cost) and demand (capacity utilization) (Table 2).

Table 2. The sensitivity of prospective rolled steel prices to changes in capacity utilization and raw material costs, relative to 2018

Capacity utilization, %	Raw material costs (increase rate relative to 2018), USD/t					
	–50%	–25%	0%	25%	50%	100%
77-4	157.4	361.4	569.1	776.8	984.5	1399.8
77-8	233.4	436.2	643.8	851.5	1059.2	1474.6
77	310.0	510.9	720.0	927.7	1134.0	1549.4
77+5	409.0	603.7	811.4	1019.1	1226.8	1642.2
77+10	503.0	697.8	905.5	1113.2	1320.9	1736.3
77+15	597.0	790.6	998.3	1206.0	1413.7	1829.1
77+20	691.6	884.8	109.5	1300.2	1507.8	1923.2

Sensitivity analysis shows the world steelmaking capacity utilization rate of 77%, indicating an excess reaching about 583 million tons. Steel prices are sensitive to changes in costs: with a 25 per cent increase in the cost of raw materials, the steel price will rise from 740 to 927 USD/t (28%). The increase in capacity utilization by 10% causes the prices to rise from 740 to 905 USD/t (13%).

Table 3. The global rolled steel price forecast for 2019-2023

Attriburte	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
						Forecast				
World steelmaking capacity utilization, %	58	50	70	75	77	79	80	82	83	85
Raw material costs: Coking coal price (Australia), FOB), USD/t	115	92	120	171	193	196	218	230	235	234
%	68	57	145	100	136	142	127			
Time trend	4	3	2	-1	0	1	2	3	4	5
The average world price for hot-rolled sheet, USD/t	390	410	440	566	574	590	615	665	684	713

The capacity utilization and raw-material cost index are equally essential when it comes to historical steel prices. After 2009, the raw-material cost significantly decreased due to a significant increase in imports to China. The global price cuts in 2009 can be explained by a decrease in capacity utilization and raw material costs [37].

3.2. The World Steel Price Forecast for 2019/2023

The regression model requires an independent forecast factor: capacity utilization and the coking coal price behaviour (raw material cost index). The global investment banks and specialized metallurgical agencies regularly update their forecasts for steel production, world steel output and prices for coal and iron ore. Based on these updates, a consensus forecast is made (Table 3).

According to the forecast, in 2023, the rolled product prices will amount to 713 USD/t, 123 dollars higher from 2018. In the same year, the cost of raw materials will increase by 41 USD per ton. According to the regression model, the raw material cost has a threefold effect on prices, so such an increase will cause steel prices to rise by 123 US dollars per ton. This is the proportion in which prices increase in the regression forecast. Thus, the forecast is based on the estimated cost of steel production. The consensus forecast of external experts does not take into account the growing steelmaking capacities and is based on the cost of raw materials. According to the correlation analysis, there is a positive correlation (+0.95) between the steel price and the coking coal price.

Therefore, producers need cheap raw materials, such as high-ash coal. Below is an assessment of the economic efficiency of using high-ash coal in ferroalloy manufacturing.

3.3. Calculating economic efficiency of using high-ash coal in FeSiAl FS55A20 production

The FeSiAl alloy was made using various types of charging materials [38, 39]. Coal is one of such materials, which has been recently in common use because it contains all the components necessary for making FeSiAl alloy (silicon oxide, aluminium, iron and carbon). The use of coal allows solving cost and environmental problems. Items containing FeSiAl is cheaper to make than items containing electrolytic aluminium because FeSiAl is cheaper than pure aluminium. In addition, the deoxidizing ability of silicon and aluminium is stronger if they are combined.

The first stage of the study was a comparative analysis of expenses that go into the production of ferrosilicon (FS75) cost and FeSiAl (FS55A200). The variables used in the calculation were the *specific consumption of raw materials* and the *specific consumption of electricity* used to make FeSiAl in an electric furnace using 12 MW for an hour.

Alloy composition, wt%: FS75: Fe – 25, Si – 75; FS55A20: Fe – 10, Si – 65, Al – 25. The FS55A20 was produced using coal wastes.

The alloy production cost and alloy cost were calculated at prices of 2009. Calculation results are shown in Table 1. Calculations can be made corrected after the stabilization of gas prices.

The FeSiAl alloy is made from coal, quartzite, and steel chip.

Table 4 shows that a shift from FS75 to FS55A20 takes much less raw materials, so the total cost of the alloy decreases from 20% to 8%, while the electricity costs more, by contrast, 61% from 53%. As a result, the plant will receive an annual profit of USD 2.1 million. The NPV of the project is 2.4 million US dollars.

At the same time, the profit from selling 1 ton of alloy increases from 12% (FS75) to 21.5% (FS55A20) (Table 4) because the price for FS55A20 includes the cost of aluminium, 1.7 US dollars per kilogram. When using coal waste, the cost of FS55A20 will be USD 1200 per ton.

Given the 6.9% depreciation of fixed assets (Table 4), the payback period for investments will be 2 years on average. With the turnout of 50 thousand tons of FS55A20 alloy per year, the annual profit will amount to USD 10 million. Additionally to that, each ton of FS55A20 alloy may take 0.6 tons of methanol or 30 thousand tons per year.

Table 4. FS75 and FS55A20 production costs

	Expenses per 1 ton		Price, USD per ton	Product cost, USD per ton		Annual benefit, in thousand USD per 16 tons
	FS75	FS55A200		Ferrosilicon	FeSiAl	
1. Raw materials:						
- quartzite	2.35	0.65	6	14.10	3.9	163
- high-ash coal	0	3.08	120	0	369	-5904
- coke	0.86	0	700	602	0	9632
- steel chips	0.21	0.12	500	105	60	720
Total	3.42	3.85		721	432.9	4611

Conversion costs, Electric power, thousand kWh - anode paste, ton - electrodes	9.65 0.06 0.01	12.5 0.08 0.01	29,4449.8 350	283.71 273.5	367.5 363.5	1345 -1440
Wages	-	-	-	30	39	0
Depreciation of fixed assets (6,9 %)				43.7	57.25	0
Works general expenses				21.6	28.3	0
Other expenses				17.9	23.5	0
Total cost				534	604.6	-1101
Market product				1000	1200	

As a result, each ton of deoxidized steel offers an economic benefit of 0.7 US dollars. With this sum as the minimum value taken for 5 kg of FS55A20 per ton of steel, we will get the total economic benefit from using one ton of FS55A20 of at least 140 US dollars per ton. When producing 16 thousand tons of FS55A20 alloy per year, metallurgists will get an economic benefit of at least USD 2.3 million annually. Considering the needs of metallurgical plants (300 thousand tons a year), the economic benefit will be about USD 42 million per year.

3.4. Essential factors to consider when choosing a strategy of supply chain management

Based on the assessment, this section identifies the major factors that should be considered when choosing the strategy for managing a supply chain in ferroalloy production with high-ash coal. The first common factor is globalization. In the metallurgical industry, the globalization trend is significant. Large companies take control of several manufacturing enterprises mainly through acquisitions and mergers. This allows them to enter new market areas. The growing complexity of supply chains and business instability in some countries like Asian countries lead to increased internal and external logistical risks. In specialized manufacturing plants, supply chains contain many specialized products (for example, high-ash coal in the production of ferroalloys) and technologies, which are hard to replace. Another factor is demand volatility. Unstable demand is specific to most industries today, including the metallurgical industry. This situation is being aggravated by the global economic crisis, which has hit the metallurgical industry most hard. Technological innovations are also a factor. The use of cheap raw materials (high-ash coal), according to our calculations, is a cost-effective practice, but the quality of output may pose a threat in metallurgy. These factors must be all harmonized in the current innovative planning technology so that companies and supply chains were profitable but not in a strong competition.

4. Conclusion

The regression model explains the behaviour of average world prices for hot-rolled steel based on two external factors: the world steel production ratio and the cost of producing coking coal as a raw material for steel. Data analysis showed that capacity utilization and the steel production cost influence the steel price. During 2008–2018, the capacity utilization played an important role. However, after 2014, steel prices become rising. According to our forecast, steel prices will increase by 123 USD per ton by 2023 compared to 2018. There is a correlation between the steel price and the coking coal price (r = 0.95%). The advantage of this regression model is that it is easy to use when making an economic forecast and the strategic development plan for supply chain management in a large metallurgical company. The calculated net present value of the project is 2.4 million US dollars. The economic efficiency of using high-ash coals in ferroalloy production was assessed. According to the assessment, the total economic benefit of using 5 kg of FS55A20 per ton of steel is not less than 140 US dollars per ton. Earlier in the text, this assessment was analyzed to identify the major factors that should be considered when choosing the strategy for managing a supply chain in ferroalloy production with high-ash coal.

5. Acknowledgement

This article was financed within the framework of a project "Assessment of technical-and-economic efficiency and a technological possibility of using Kazakhstan weakly coking coal in ferroalloy production and as smokeless fuel for household needs", under the subprogramme 1 of the Agreement No. 209 of March 19, 2018. Registration card No. 01.01-22/161 dated April 13, 2018. State registration number No. 0118PK00698.

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