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Modeling of Energy Consumption and Reduction of Pollutant Emissions in a Walking Beam Furnace Using the Expert Method—Case Study

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Abstract: This paper presents an algorithm for modeling electricity and natural gas consumption in a walking furnace with the use of artificial intelligence and simulation methods, depending on the length of the rolling campaign and the established rolling program. This algorithm is the basis for the development of a proposal for a set of minimum requirements characterizing the Best Available Techniques (BAT) for beam furnaces intended for hot rolling, taking into account the requirements set out in national regulations and the recommendations described in the BREF reference documents. This information should be taken into account when drawing up an application for an integrated permit, as well as when setting emission limit values. Based on the constructed algorithm, it was shown that depending on their type and technical specification, the analyzed projects will offer measurable economic benefits in the form of reducing the amount of energy consumed by 1,076,400 kWh during the implementation of 50 rolling campaigns to reduce gas by 14,625 GJ and environmental benefits in the form of reduction of pollutant emissions into the atmosphere 80–360 g/Mg. The constructed algorithm was validated in the Dosimis-3 program, based on a discrete event-driven simulation. Thanks to this representation of the model, its user can interactively participate in changes that take place in the model and thus evaluate its behavior. The model, verified in real conditions, can be the basic source of information for making effective operational technological decisions related to the preparation of production at the rolling mill as part of planning and long-term activities.

Keywords: hot rolling mill; steel; strip; steel industry; electricity and natural gas consumption; processing costs; BAT

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1. Introduction

To avoid catastrophic climate change, the world must achieve zero carbon emissions in all sectors of the economy by 2050. To this end, according to Directive 2009/28/EC [1], EU Member States should gradually increase the share of energy from their renewable sources, both in total energy consumption and in the transport sector. The problem related to CO_2 emissions in transport has been widely described in publications [2–7]. In Poland, despite the fact that the production of energy from renewable sources is growing every year, its main use is still conventional energy sources, which emit a large amount of pollutants into the atmosphere [8,9]. The overarching goal of the EU is to achieve 32% of energy from renewable sources by the end of 2030 and to reduce greenhouse gas emissions from 40% to 55%. These goals, set by EU member states, are highly ambitious, and will be impossible to achieve without a complete energy transformation in RES and the conventional economy sectors already operating. In addition, electricity prices are soaring across the board Europe. In August, the average price of MWh in Poland reached EUR 80. In Spain, it already costs over EUR 150—three times more than in 2020 [10,11]. In Germany, energy prices have increased by more than 60% this year. According to experts, this trend may continue in the coming months. This is the effect of, among others, more expensive European allowances for carbon dioxide emissions, or low production of energy from renewable sources. Energy companies pay record prices for the purchase of CO_2 emission permits—already over EUR 60 per ton, over 18% more than in mid-July 2021 [12,13]. There is a large number of studies on the potential of using renewable energy technologies in the global energy mix, but there are no studies on how to reduce CO_2 emissions to the atmosphere by plants with a diversified production method, i.e., metallurgy. In Poland, the steel industry is responsible for 14% of total CO_2 emissions to the atmosphere [14,15]. It is a branch of the economy that is still in the stage of intensive production and cannot be due to large energy demand for steel production to replace conventional energy, i.e., natural gas and electricity, with energy from renewable sources [16,17]. Therefore, solutions should be sought to optimize existing technologies [18], which will make it possible to reduce CO_2 emissions to the atmosphere, and thus pay production plants less for emission permits [19,20].

We propose to fill this research gap with this study. We aimed to build a model of energy consumption with a breakdown into electricity and natural gas in a walking beam furnace, depending on the length of the rolling campaign and the agreed rolling program [21,22]. The end result of our work is a model that allows the calculation of the energy costs of material processing depending on: steel grade and mass of the ingot, time soaking in the furnace, thickness, and bandwidth [23,24]. The results of this study can be widely used in projects to optimize energy consumption in hot rolling mills [25,26]. The presented algorithms make it possible to significantly reduce the emission of harmful compounds into the atmosphere [27,28], which will contribute to the fulfillment of Poland's emission obligations towards the EU [29,30].

2. Review of Current Research

Metallurgical production includes the processes of smelting and processing metals and their alloys into various rolled products. Almost half of the world's hot-rolled steel products are flat products, i.e., sheets and strips, and some of this production is further processed by cold rolling [31,32]. These products, in turn, are used for the production of numerous consumer goods, such as cars, household goods, packaging, etc. The constantly growing demand for flat-rolled products of increasingly higher quality, while striving to reduce the costs of their production [33], forces enterprises to look for new technological and structural solutions and is one with challenges for modern science [34,35]. For example, a modern rolling mill that produces steel strips must meet the following requirements: use the most economical COS feedstock, ensure high the reproducible quality of finished steel strips, provide high yield and efficiency, and consume limited energy and tools [36,37]. The energy used in production processes is of interest to managers of every enterprise, not only because of the cost of obtaining a given product. Important factors include the large-scale use of non-renewable fossil fuels and the need to achieve sustainable development. Therefore, increasing emphasis is placed on the efficient use of available energy and the optimization of production processes in terms of energy consumed [38,39]. The time taken to heat the charge in a walking beam furnace is a major factor in the increasing production costs in hot strip mills [40]. This problem is due to inadequate use of the furnace capacity [41,42]. As a result, the rolling mill incurs huge costs, mainly through the consumption of electricity and natural gas. These losses arise from the heating of the ingots in the different equalizing zones of the furnace. Heating the charge before plastic processing is one of the important steps in the production of final rolled products. In order to ensure proper operation of the technological line, it is necessary for the charge to reach the required temperature in the entire volume and to ensure the adequate uniformity of heating at the lowest possible cost. The efficiency of the furnace can be influenced by, among other methods correctly determining the heating time and temperature changes in the working space of the furnace [43,44]. The temperature distribution in the furnace space is limited by the design features of the furnace, the shape and dimensions of the charge and the physical properties of the heated material [45,46]. Incorrectly selected heating parameters may cause improper heating of the charge, disturbance of the furnace's operation, or an increase the heating time, which is tantamount to an increase in energy and gas consumption rates for furnace firing and reduces the furnace's efficiency [47,48]. Thus, the definition of the heating curve and the heating time is an important feature of the technology through which the required quality of the final product is obtained while minimizing manufacturing costs. Thermal stresses arise in the heated charge; they are caused by uneven temperature distribution and phase changes. If the material deformability limit is exceeded, they lead to local cracks, which results in a defect in the heated charge and, as a consequence, damage to the working surface of the roll barrel. These unfavorable phenomena, in addition to the start of the rolls, result in an unplanned stoppage of the rolling mill for the reconstruction of the rolls. This causes significant losses in utilities, mainly natural gas, for fueling the furnace and supplying the electricity needed to produce the final product; it also significantly interferes with the production planning process. Hot rolling installations feature one of the highest electricity consumption rates of any primary installation in the steel sector. Only electric steel plants are characterized by higher indexes. The production of an appropriate hot-rolled product requires the operation of many devices, the drive of which requires electricity. Significant electricity consumers are air fans and flue gas coolers from heating stoves. One of the problems associated with hot rolling is the emission of dust and gas pollutants to the atmosphere, especially nitrogen oxides NOx, sulfur oxides SOx, and aliphatic hydrocarbons. The main sources of air emissions from hot rolling mills are charge heating furnaces [49]. In hot rolling mills, a walking beam heating furnace is used; it is a device in which the metal charge is subject to the desired temperature changes over the appropriate period of time so that the metal achieves the required technological properties. For heating processes, it is important not only to achieve the desired temperature for the charge, but also the appropriate course of temperature changes in time and in the space of the working chamber, and to create the desired chemical composition of gases in it, i.e., the furnace atmosphere. In this type of furnace, the heated charge moves in steps from the input side to the discharge side, carried by the movable part of the hearth. This furnace works continuously. A batch for heating is loaded into the furnace in an axial manner, placing it on the stationary parts of the hearth. The movable part of the shaft, while lifting up, takes the load and moves it towards the discharge port; as it goes down, it rests on the fixed part again. Subsequently, the bottom part returns to its original position and the cycle begin again [50]. The heat of the exhaust gases from the working space of the furnace is used to heat the factors flowing for combustion. The walking-beam's heating furnace is fired with natural gas, with a production capacity of 450 Mg/h. The maximum heating temperature is 1250 $\pm$ 10 °C [51,52]. The working width of the furnace is 11 m, and the working length is 58.6 m. A total of 19,100 Nm^3/h is supplied, with heat consumption of approximately 1.25 GJ/Mg of steel and 92 kWh/Mg of electricity. The furnace features an automatic control system, with 12 fixed and 11 movable beams [53]. It enables uniform heating of the charge by automatically carrying out the heating process with flue gas control, continuous registration of heating temperatures, ingot exit temperature from the furnace, and precise identification of the material. Heat is supplied through burners located in the front wall of the furnace, directly above the hearth. The furnace's temperature is controlled continuously in zones. Ignition of the burners, flame control, gas and air supply control are carried out automatically in each of the zones [54,55]. The gas is supplied to the burners from the plant network, and the combustion air is supplied by a fan. The pressure in the furnace is regulated automatically. Each zone consists of several burners operating with the use of hot air heated in a central recuperator. All the burners are equipped with a set of safety and regulating devices. Gas from the plant network is reduced to an appropriate level in a pressure stabilization station and then directed through a set of electromagnetic valves to a collective manifold located on the furnace, and from there to the burners. The rolling mill features reduction gas stations equipped with security systems that operate automatically and cut off the gas supply in the event of power failure, combustion air, gas, and excessive gas pressure [56]. Moreover, the stations are equipped with a gas tightness control system. Additionally, each burner includes a reliable flame control system and a combustion air flow control system. The parameters of heating, rolling, and cooling the material are selected for the steel grade so as to guarantee the desired mechanical and technological properties of a given product.

3. Materials and Methods

The tests were carried out in a Polish hot-rolled steel strip mill (Figure 1). The rolling mill covers an area of approximately 10 ha, and its annual production capacity is around 2.4 million Mg. It features the following production characteristics:

- Charge: flat billets from a COS machine, 220–250 mm thick, 700–2100 mm wide, and 6–11 m long, weighing up to 35 Mg.
- Product: hot-rolled steel strip 1.4–25.4 mm thick, with a width of 750–2100 mm, in coils weighing up to 35 Mg.
- Rolled steels: structural unalloyed steels, including those for the automotive industry (DP) and pipes (X70), high-strength unalloyed steels (HSLA), and silicon steels (GO).

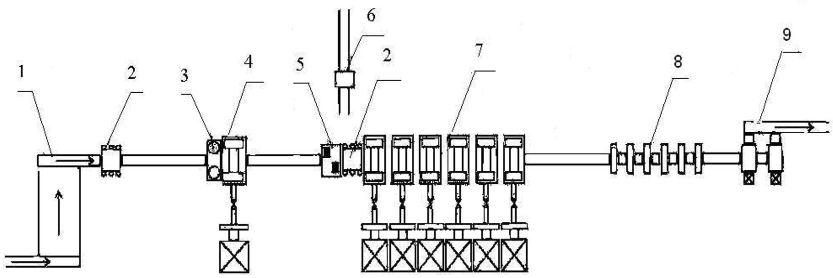

Figure 1. Schematic layout of equipment in the hot strip mill [56].

1—walking beam furnace, 2—hydraulic descaling device, 3—cage of the duo vertical rollers Ø1100, 4—area of the initial stand quarto Ø1250/1600, 5—drum shear, 6—roller conveyor, 7—finishing rolling mills unit, 8—laminar cooling tower, 9—coilers.

The study included the following tests:

- Using the artificial intelligence method on the basis of an expert system, forecasts of the heating time of the ingots to the desired rolling temperature in the walking beam furnace in its individual zones, along with the corresponding electricity consumption were made.

The results obtained with the use of expert methods were compared with the results of measurements performed in industrial conditions. The measurement of the obtained results is the following error: relative, mean, and mean square.

- A curve for heating and annealing ingots in a walking beam furnace was constructed, on the basis of which a model was built to calculate the energy costs of material processing depending on steel grade and mass, ingot soaking time, thickness, and bandwidth.
- Ways to prevent and reduce environmental impact were identified.

3.1. Forecasting the Heating Time of Flat Billets in a Walking Beam Furnace

Modeling the heating times of the ingots in the furnace to the desired rolling temperature is a complex issue. It concerns a very wide range of production in terms of the distinguished profile dimensions, as well as the steel grades used, from which the ingots are made. The basis for creating rational production plans is the precise knowledge of the heating times of the flat billets in the furnace in individual zones. The following methods were used to solve this problem: an expert system based on a machine learning algorithm (ID3) and linear and non-linear regression. Research using artificial intelligence methods is justified to solve this problem, among others, for the following reasons:

- For complex tasks, it is difficult to formulate directly defined, complete and correct algorithms for their solution. This is due to the fact that, as a rule, complex industrial environments are difficult to describe.
- Collections of available data from measurements, observations, documents, etc. are often too large and complicated to search for dependencies and classify them logically.

The problem of predicting the heating time of ingots in the furnace was reduced to the problem of classification in an expert system. The machine learning ID3 algorithm was used to develop the knowledge base of the rule-based expert system. The fundamentals of the system are the heating zones in the furnace and technological parameters of the rolling process. Through the SQL query language, the data describing the parameters and technological capabilities of the tools are taken from the created system module and added to the knowledge base of the expert system in the form of facts. The inferring module of the expert system, based on the production rules and information encoded in the knowledge base, uses "backwards" search strategies to determine the forecast heating times. The Nexpert artificial intelligence package by Neuron Data was used to build a prototype of this system. The expert skeleton system included in the package is the structure of the system. The program developed as part of the study k, in the PC-Shell system, consists of a set of instructions written in Sphinx. The system knowledge base was built as a declarative knowledge representation based on the principles of rational preparation of the production program and includes many decision rules. In a similar way, it is possible to increase the knowledge base with new criteria that significantly improve operational decisions at the production planning level. The following input data, available in the industrial conditions of the steelworks, were used to model the heating times of the billets in a walking beam furnace in its individual zones:

- Furnace heating time: $\mathrm{t_p^{(i)}}$

(0,1,2 ... n−1; n—the number of measurements of heating times in individual zones during one rolling campaign, taking into account a specific rolling program),

- Thickness and width of the strip: $\mathrm{b, h}$
- Strip length in the rolling campaign: l,
- Ingot heating temperature in individual zones: $\Delta\mathrm{h}$
- Rolling speed: v,
- Average unit pressure in the deformation zone: $\mathrm{p_{śr}}$,
- Rolling moment: $\mathrm{M_w}$,
- Nominal power of the drive motor: $\mathrm{N_n}$,
- Rolling temperature: $\mathrm{T_w}$,
- Random disturbances during rolling: $\mathrm{z_b}$.

The data set collected for the research covers measurements from two months; after filtering, it contains 1652 records. In order to estimate the quality of the results of forecasting the heating times of the ingots, the mean error E_L and the mean square error Φ_L were calculated in individual zones of the furnace according to the following formulas [53–55]:

$$E_L = \frac{\sum_{i=1}^{L}\left(\left|t_p^{(i)} - t_p^{(i)}\right|\right)}{L} \quad (1)$$

$$\varnothing_L = \sqrt{\frac{1}{L}\sum_{i=1}^{L}\left(\frac{\hat{t}_p^{(i)} - t_p^{(i)}}{t_p^{(i)}}\right)^2} \quad (2)$$

where:

L—number of heating measurements made,

$\hat{t}_p^{(i)}$—calculated heating time,

$t_p^{(i)}$—measured heating time.

The forecasting of ingot heating times was described on the basis of the multiple regression tool. The Statistica Package (StataCorp LLC) was used to build the regression models. The overall goal of statistical regression methods is to study the relationship between multiple independent (explanatory) variables and the dependent (response) variable. The computational problem to be solved is to fit the appropriate regression model to the set of points (empirical data) by estimating the parameters of the selected model and is described by the equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \quad (3)$$

where:
y—dependent variable,
$x_1 \ldots x_k$—independent variables,
$\beta_0 \ldots \beta_k$—model parameters,
ε—random component.

The least squares method was used to estimate the parameters, and the coefficient of determination R^2 was adopted as a measure of the quality of the linear regression model. It is a number from the range <0, 1>, where $R^2 = 1$ means a perfect match, while the value $R^2 = 0$ means no relationship between the variables.

The nonlinear regression model used to forecast the heating time of slabs in a walking beam furnace is presented in the following form:

$$y = C + exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k) \quad (4)$$

where:
y —dependent variable,
$x_1 \ldots x_k$—independent variables,
$C, \beta_0 \ldots \beta_k$—model parameters.

3.2. Modeling Energy Costs on the Basis of the Heating Curve

To build the feed curve, model tests of heat flow in a walking beam furnace were performed. The preparation of a new rolling technology by trial and error is costly, ineffective, and time-consuming. The continuous improvement of technology is an important factor guaranteeing high quality, sales, and competitiveness of production on the international market. A way to develop an effective production program in a metallurgical company is the use of computer support, which offers many valuable advantages. On the one hand, it does not require high financial outlays, and on the other hand, it makes it possible to quickly obtain satisfactory and reliable results, without the need for complex experimental research. Simulations are slowly becoming one of the most important techniques supporting the preparation of production, even in those industrial sectors in which unusual technological processes occur, such as in metallurgy, where there is a multiphase material flow. This is due to the fact that in the conditions of a market economy, enterprises must solve increasingly complex problems in a shorter time. The rapid development of computer technology and simulation programs makes it possible to use this technique in almost every design cell. On the basis of the existing production process and the knowledge of the flow characteristics in a given process, a model is built, which, when subjected to simulation tests, provides experimental results in the scope of the defined problem. The algorithm for the development of a simulation production model is shown in Figure 2.

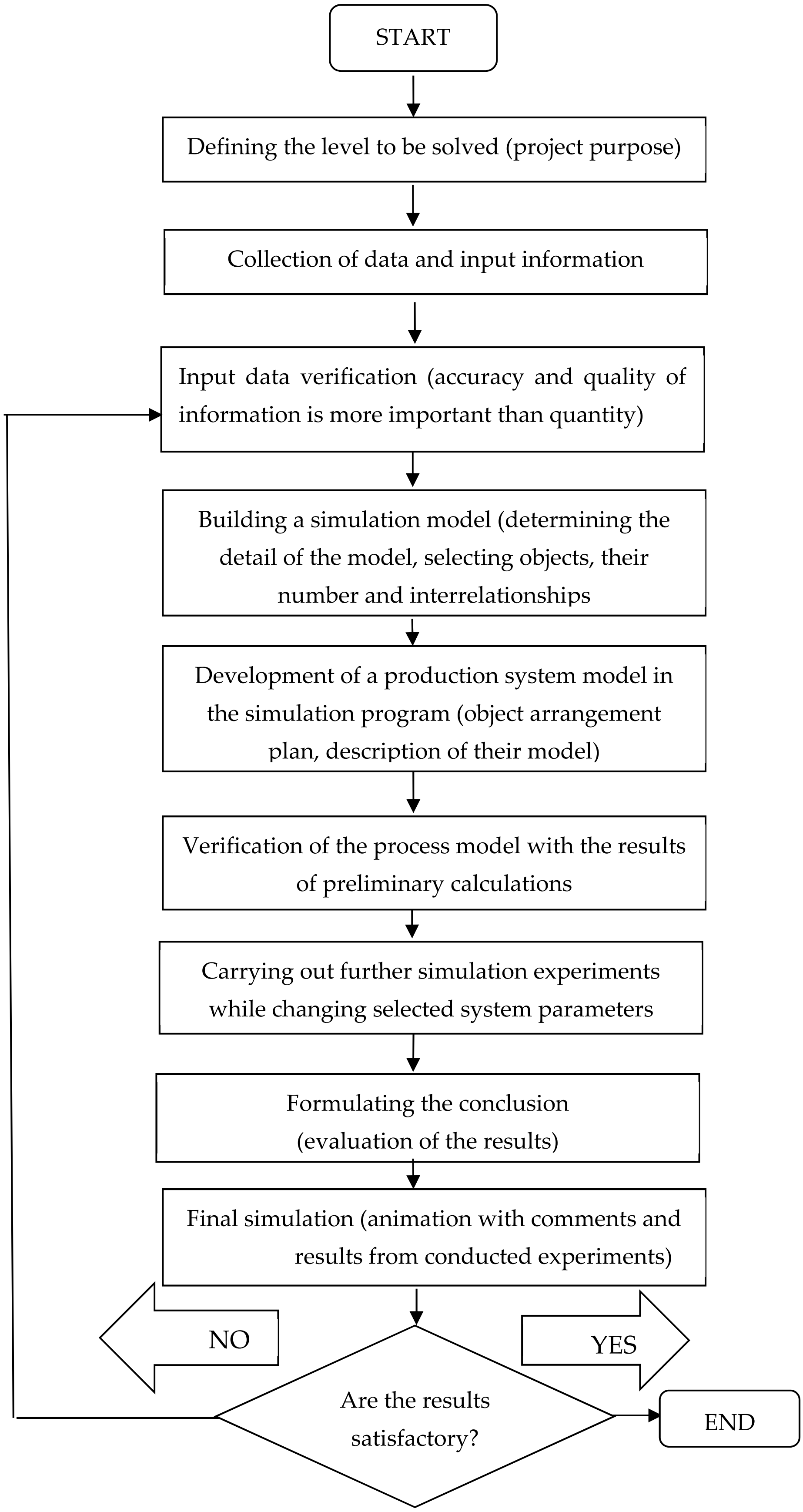

Figure 2. Procedure algorithm for the development of a simulation production model. Source: own study.

In walking beam furnaces, there is often underheating of the ingot from the furnace hearth. This problem is caused by several factors. The most important include: cooling from the sliding rails, the design of the furnace to raise the temperature of the furnace bottom in the heating zone, and the unheated hearth in the equalizing zone. These factors make it necessary to extend the heating time and the heating time of the ingots in the equalizing zone, which is associated with significant losses of media, mainly gas and electricity, which are needed to produce the final product. In order to improve the production planning process in a given strip mill, alternative variants should be sought. On the basis of measurements of the furnace atmosphere and simulation calculations of heating the ingot, we propose an optimal heating curve for a walking beam furnace in a steel strip mill, on the basis of which it is possible to calculate electricity consumption by the furnace and natural gas.

On the basis of the obtained model parameters, dependencies were built to describe the consumption of electricity and gas in the walking furnace, depending on three process parameters: the mass of the ingot, and the thickness and width of the rolled strip. The parameters of the described model for the first material group were used to build the remaining three models. Natural gas consumption per ton of production was determined by analyzing the effect of changes in the length of the ingot on the increase or reduction of energy losses in the furnace. As part of the study, it was assumed that the energy losses in the furnace would be proportional to changes in the length of the ingot. Based on this assumption, the relationship determining the level of changes in energy losses in the furnace can be determined as [56–58]:

$$\Delta G = 0.34 \cdot G_{sr} \cdot \Delta L \tag{5}$$

where:

0.34—percent of energy lost [58],

$G_{śr}$—average natural gas consumption (value equal to 1.29 GJ/Mg obtained from process data),

ΔL—ingot length change given by the formula:

$$\Delta L = \frac{L_{sr} - L}{L_{sr}} \tag{6}$$

where:

$L_{śr}$—the average length of the ingot is 9.19 m.

Natural gas consumption, calculated per ton of production, assuming changes in energy losses, given by the Equation (5), is equal to:

$$G = G_{sr} + \Delta G = G_{sr} + 0.34 \cdot G_{sr} \cdot \Delta L = G_{sr}(1 + 0.34\Delta L) \tag{7}$$

The second factor influencing the total consumption of natural gas is the heating time of the ingot in the furnace. This is conditioned by the steel grade. In the case of the tested rolling mill, all the grades of produced steel were classified into four heating groups (145, 160, 170 and 210 min). Taking into account the heating curve and statistical tests, the weighted average time spent in the furnace was determined (150.34 min), which in turn allowed the determination of energy consumption in each of the groups. By combining both factors influencing the consumption of natural gas, it is possible to determine the relationship between the length of the ingot and the steel grade and gas consumption. For this purpose, the previously calculated formula for gas consumption depending on the steel grade—and therefore the heating group—should be multiplied by the index corresponding to the weighted average time spent in the furnace. In this way, four linear equations were obtained, which form the sought model of natural gas consumption depending on the manufactured product range [59–61].

3.3. Verification and Validation of the Model in the Dosimis-3 Package

The Dosimis-3 package was used to verify the model. This package is a modularly oriented simulation tool that has been specifically adapted to the planning and modeling of systems logistics. Thanks to the modular approach to the modeling problem applied in the package, the user may quickly receive the results of experiment simulations; even for small ventures, it can be an effective tool for supporting decision-making processes. This package is an interactive graphical simulator, and the principle of the operation and organization of the calculations of this simulator is based on discrete driven events and enables the simulation of complex logistics systems, among other features. The calculations performed by the simulator are based on those occurring in the constructed model of events and the related passage of time, and the mathematical apparatus used in the simulation is based primarily on the finished automata theory. The package includes many built-in tools and correctness control mechanisms, model verification, and validation.

The verification and validation of the created models can be carried out, among others, by using the package of mechanisms as well as standard statistical tools: checking the completeness of the model, checking the correctness of the model, animating the waveforms, a mechanism for setting traps that allows users to track values of individual variables or their attributes, statistical evaluation of the observed waveforms generated by the program simulation, with dependencies coming from real data. The consistency and correctness feature checks that all parameters and connections are correct. This check is usually performed after each shift in model parameters. Selecting this functionality identifies all the items with errors; inconsistent parameters are selected and highlighted with one color.

The animation function turns out to be a very important and useful validation tool in simulation models. Additionally, it enables the presentation of the dynamic behavior model. With the help of the animation tool, it is possible to quickly spot errors in the model or, for example, blockages and damming in the modeled system. Variable states of objects flowing through the system are represented by appropriately colored elements graphics.

The animation of the flow of objects in the system can be performed in steps. The animation can be stopped at any time and the model view can be printed along with the states of the objects in the system. As the complexity and size of the model increases, so does the need for an efficient tool to find and track bugs in the model. This tool, which is especially useful in the process of the model validation, is a breakpoint mechanism. This mechanism was borrowed from the programming environments that use the so-called debugger (a program to detect errors in the code). Furthermore, the simulator includes a feature that allows the user to set break points for elements (e.g., when a specific event occurs), moving objects or table decision-making. Thanks to this feature, the modeler possesses the ability to stop the ongoing simulation, to trace parameters and fragments of the model that are of interest, and restart the simulation. The culmination of simulation studies is the analysis of the results and the possibility of making inferences based on them (in addition to the validation of the results). The results of the statistical analyses are segmented so that the user can quickly evaluate the transient behavior and, based on interval statistics, the stability of the tested system in individual time intervals streamlines the model validation process.

3.4. Ways of Preventing or Reducing the Impact on the Environment

Based on the analysis of hot rolling methods, the techniques, achievable emissions, and consumption levels corresponding to the application of the best available techniques are presented. The purpose of this part of the research is to provide information to industry, environmental protection authorities, and the public on achievable emission and consumption levels using specific techniques. Appropriate BAT techniques for walking beam furnaces and limit values have been established by taking into account local conditions, costs, and the associated environmental burden.

4. Results and Discussion

4.1. Forecasting the Heating Time of Flat Billets in a Walking Beam Furnace

Significant relationships between the analyzed variables in the industrial conditions of the steel plant are presented in Table 1. The Pearson correlation coefficient r (significance level 0.05) was adopted as the measure of the relationship. By analyzing the correlation matrix and scatter plots, it can be concluded that there is a strong relationship between the dependent variable $t_p^{(i)}$ heating time and the independent variables: b, h, l, Δh v, M_w, N_n, T_w, $p_{śr}$, and z_b; however, the nature of this relationship is non-linear. In the discussed case, it was assumed that the dependent variable is a function of the ingot heating time in all the zones of the furnace and other independent variables. Table 2 shows the correlation with the mean values and standard deviation of the key parameters of the analyzed rolling program. Sample data on the basis of which the correlation matrix was made is presented in Appendix A.

Table 1. Correlation matrix for the analyzed variables.

	$t_p^{(i)}$	h	b	l	Δh	v	$p_{śr}$	M_w	N_w	T_w
$t_p^{(i)}$	1.00	−0.34	0.36	0.12	0.61	0.06	0.87	0.20	0.02	−0.78
h	−0.34	1.00	−0.45	−0.09	−0.12	0.34	0.36	0.03	0.34	−0.23
b	0.36	−0.45	1.00	0.62	0.36	0.58	0.23	0.48	−0.24	0.36
l	0.12	−0.09	0.62	1.00	0.78	−0.12	−0.45	0.12	−0.45	−0.12
Δh	0.61	−0.12	0.36	0.78	1.00	−0.28	−0.32	0.47	0.14	0.84
v	0.06	0.34	0.58	−0.12	−0.28	1.00	0.78	0.56	0.09	0.11
$p_{śr}$	0.87	0.36	0.23	−0.45	−0.32	0.78	1.00	0.21	0.11	0.51
M_w	0.20	0.03	0.48	0.12	0.47	0.56	−0.21	1.00	−0.27	−0.65
N_n	0.02	0.34	−0.24	−0.45	0.14	0.09	0.11	−0.27	1.00	−0.42
T_w	−0.78	−0.23	0.36	−0.12	0.84	0.11	0.51	−0.65	−0.42	1.00

Source: own study.

Table 2. Correlations of key process parameters and electricity consumption per ton of production.

Mean	Standard Deviation	Average Thickness of the Tape, mm	Average Width of the Tape, mm	Average Weight of the Tape, Mg	Average Electricity Consumption, MWh/Mg
2.344	1.456	1.987	0.124	0.238	−0.654
1342.221	234.232	0.234	1.876	0.654	−0.762
15.562	3.345	0.321	0.908	1.000	−1.234
1.234	0.123	−0.765	−0.654	−0.834	1.000

Source: own study based on [56].

As part of testing the correctness of the model, the analysis of regression residuals was performed. Using an expert system based on a machine learning algorithm, the first obtained results in the field of forecasting heating times are more favorable than those currently obtained in industrial practice. These results demonstrate strong agreement with the measurement results (Figure 3), which proves the significant usefulness of expert systems for solving complex problems for which there are no precise mathematical models. The average E_L error of the heating times is, for example, 122 min for heating zone I, which is satisfactory from the point of view of short- and long-term production planning and reduces the heating time of the ingots by 23 min. As a result, the costs of media consumption for the production of the finished steel strip are reduced.

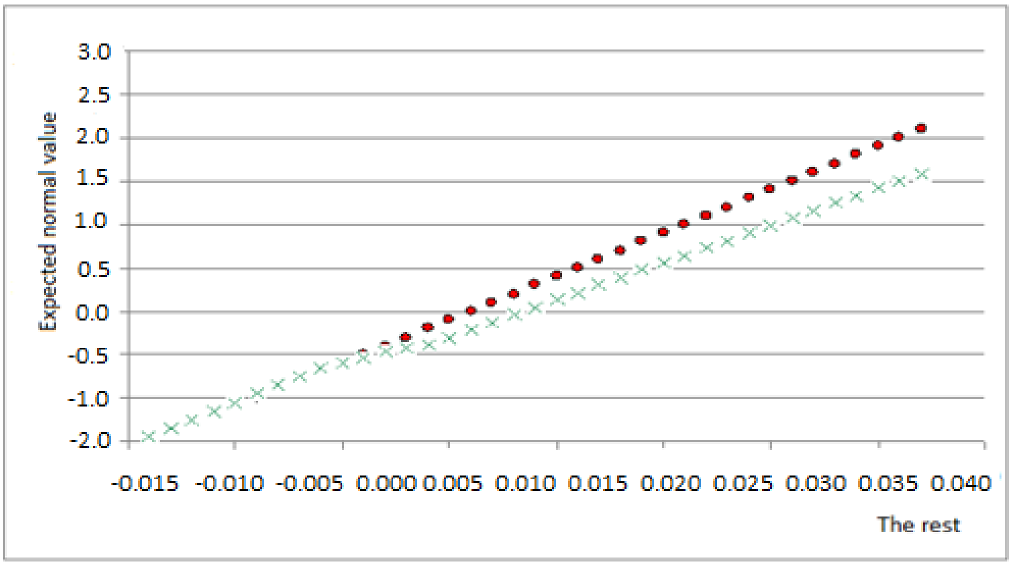

Figure 3. The plot of the normality of the residuals of the model. Source: own study.

The results obtained using traditional statistical methods, linear regression and non-linear regression, for industrial production planning conditions in a hot steel strip mill are unsuitable. They are characterized by a large discrepancy compared to the measurement results, as evidenced by the high values of the obtained errors, which are presented in Table 3.

Table 3. The results of the welding time prediction for the exemplary I heating group 145 °C.

Method	Error E_L, min	Mean Square Error Φ_L
Expert system (ID3)	122	0.17
Linear Regression	155	0.83
Non-linear regression	167	1.32

Source: own study.

The non-linear nature of the considered prognostic problem proves that the linear and non-linear regression method does not work well for forecasting the heating times of ingots in industrial conditions and does not make it possible to obtain satisfactory results. Artificial intelligence based on an expert system is most effective at forecasting heating times. The results obtained by models based on artificial intelligence qualify them for implementation in the industrial conditions of a steel mill, constituting a valuable source of information for the preparation of production, supporting operational technological decisions, and reducing the costs of producing a new product.

Analyzing the results obtained on the basis of the mean and mean square error in predicting the heating times of ingots as part of short- and long-term production planning, these methods based on artificial intelligence techniques turned out to be effective at solving the problem. Over 86% of the results are within the error limits of +/− 5%, while the results of the linear and non-linear regression predicted only 58% of the results, with an error of +/- 5%. It should be noted that artificial intelligence methods belong to the class of learning systems. In order to obtain even better compatibility of the results of the developed models with the measured data, it is possible to supplement the training data set with new cases from the course of the production process. This can contribute to the refinement of the models built and create the possibility of obtaining better results [55,56].

4.2. Modeling Energy Costs on the Basis of the Heating Curve

The heating curve for the calculation of energy costs was built on the basis of an algorithm based on the use of substitute heat transfer coefficients. The actual data from the furnace heating reports, taking into account the technical specifications of the device (Figure 4) and the data contained in Table 4, were used to build the heating curve.

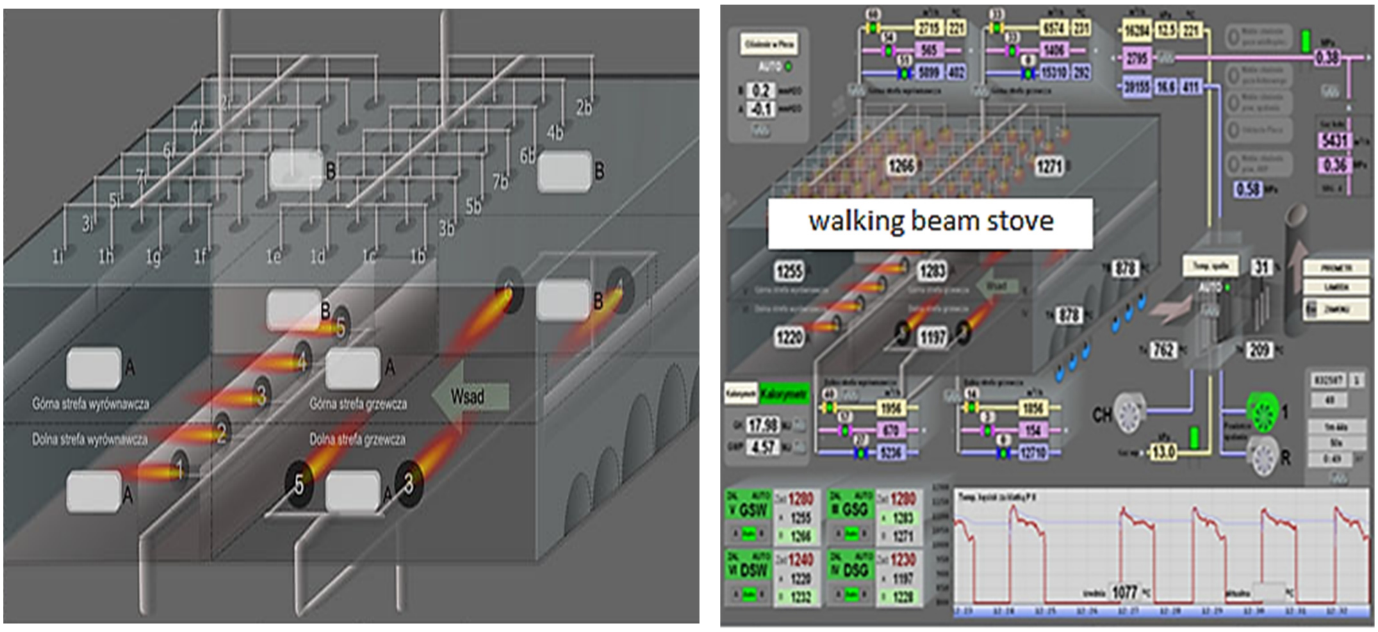

Figure 4. Walk-in furnace with different heating zones. Source: own study.

Table 4. Thermal capacity of walking beam furnace zones of the hot strip mill.

Zone Number	Location	Torch			Heat Input Zone, kJ/h
		Type	Number	Heat Input Zone, kJ/h	
1	Pre-heating	Side	14	1,800,000	25,200,000
2	Top, first heating	Side	6	2,400,000	14,400,000
3	Lower, first heating	Side	6	3,000,000	18,000,000
4	Top, second heating	Side	8	2,400,000	19,200,000
5	Lower, second heating	Side	8	3,000,000	24,000,000
6	Upper, third heating	Side	8	2,400,000	19,200,000
7	Lower, third heating	Side	8	3,00,0000	24,000,000
8	Top, preheat	Radiant vaulted	32	480,000	15,360,000
9	Lower, pre-heating	Side	6	3,000,000	18,000,000
10	Top right, soaking	Radiant vaulted	16	380,000	6,080,000
11	Top left, heating	Radiant vaulted	16	380,000	6,080,000
12	Bottom right, soaking	Front	6	1,500,000	9,000,000
13	Bottom left, heating	Front	5	1,500,000	7,500,000
The overall heat capacity of the upper zones					91,120,000
The overall heat capacity of the lower zones					114,900,000
The overall installed thermal power of the furnace					206,020,000

Source: own study.

The modeled heat transfer coefficients are shown in Figure 5, Figure 6, Figure 7. The author assumes a variant consisting in maintaining high temperatures, lying on the limit of the furnace's capabilities in the various zones of the furnace (Figure 5). As a result, there is a lack of symmetry of the furnace temperature above and below the charge (Figure 6). To achieve the required cold batch temperature field, it is necessary to raise the furnace temperature in zones III and V above the batch and to maintain high temperatures in zones IV and VI below the batch [58]. Based on the model values of the temperature distribution and with the use of substitute heat transfer coefficients proposed in individual zones (Figure 7), heating curves have been proposed (Figure 8).

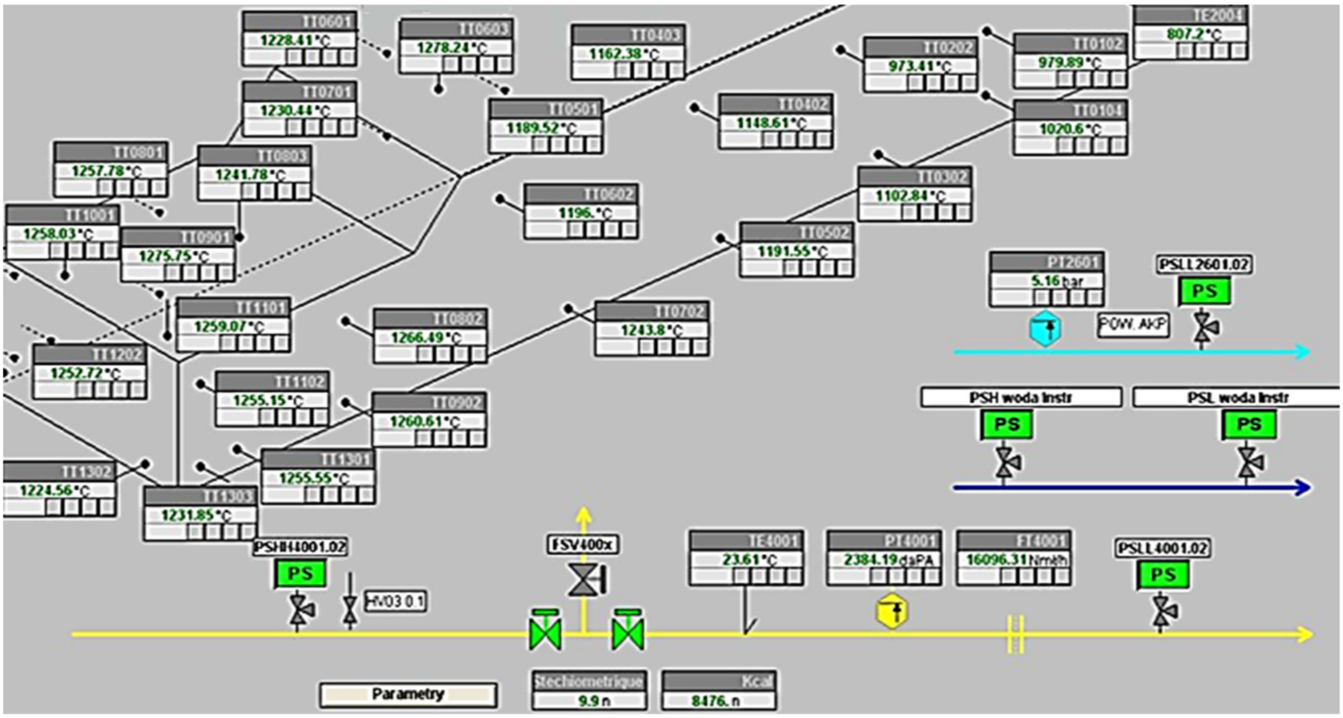

Figure 5. The furnace has a gradual distribution of heating temperatures. Source: own study.

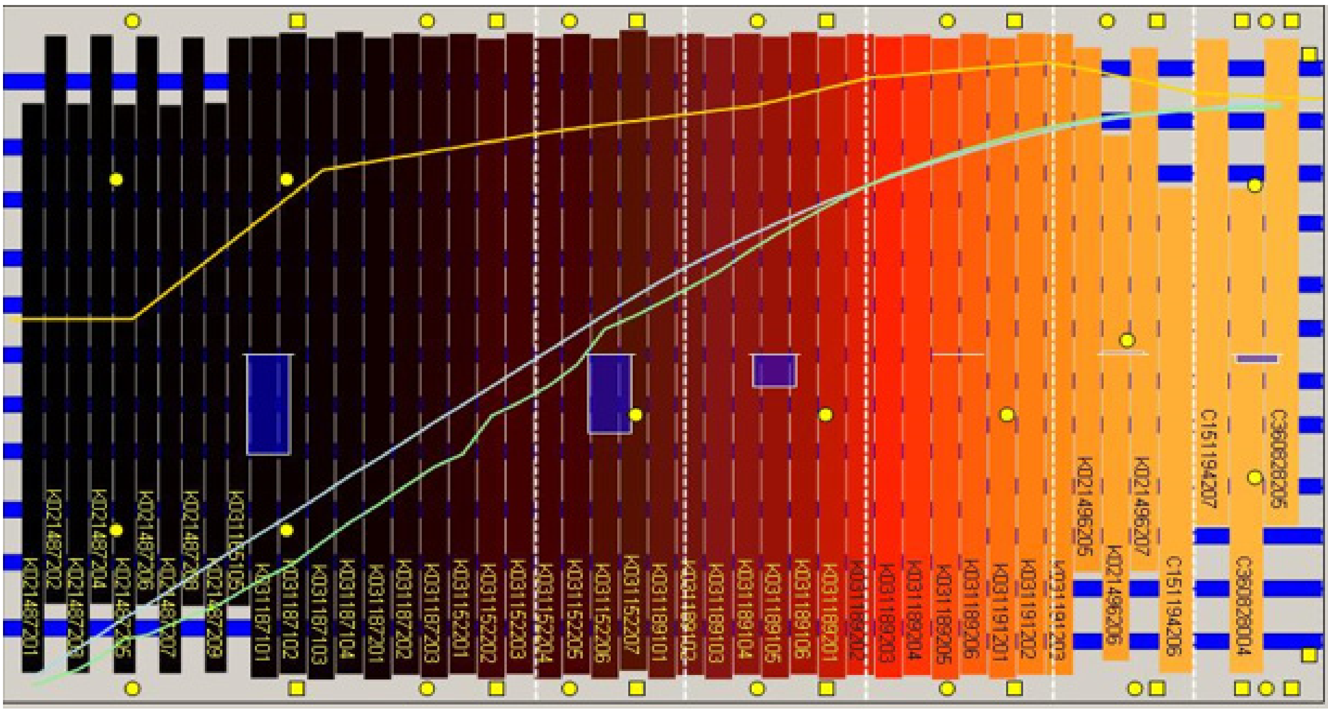

Figure 6. Bake the temperature distribution above and below the batch. Source: own study.

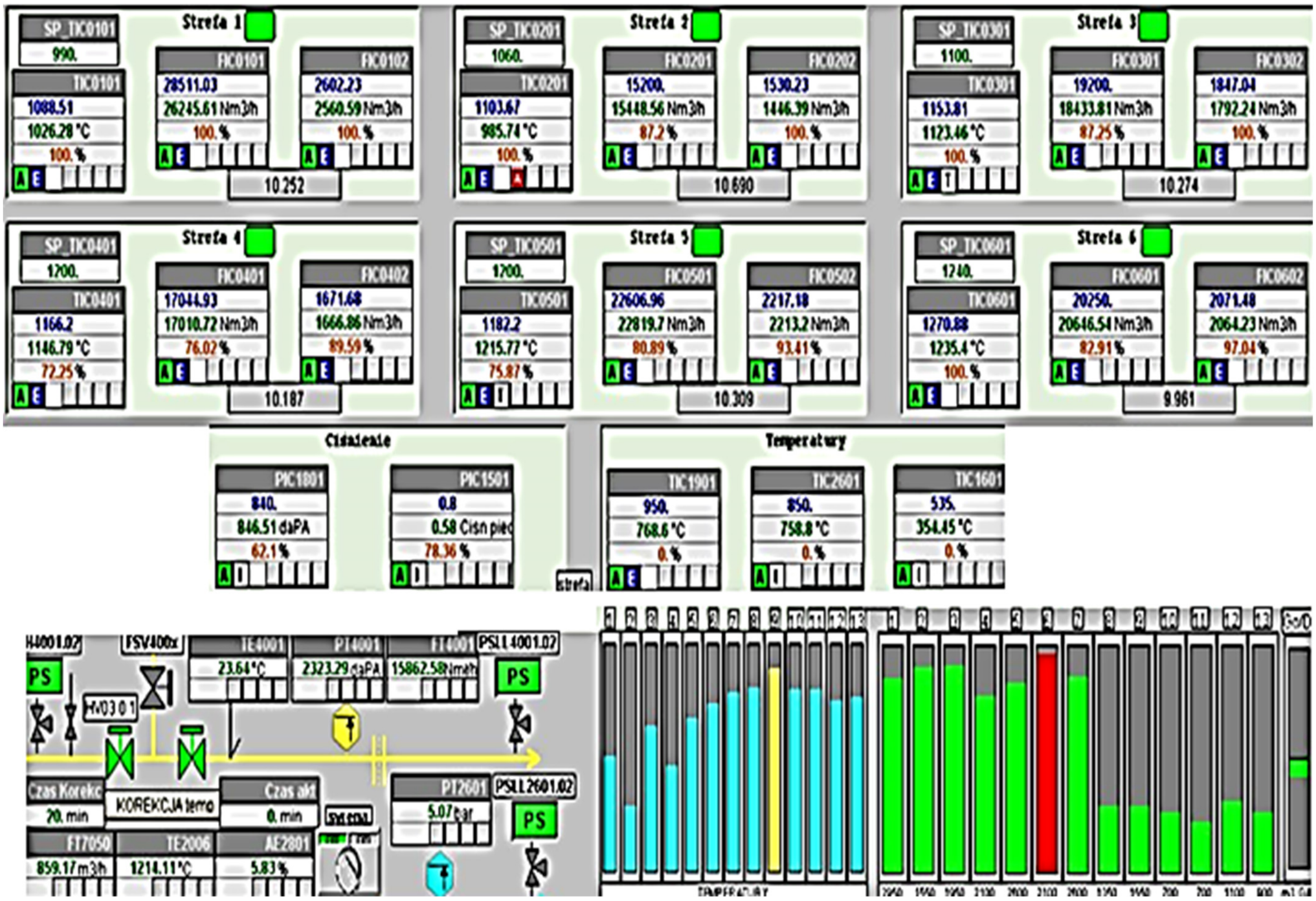

Figure 7. Walk-in furnace substitute heat transfer coefficients. Source: own study.

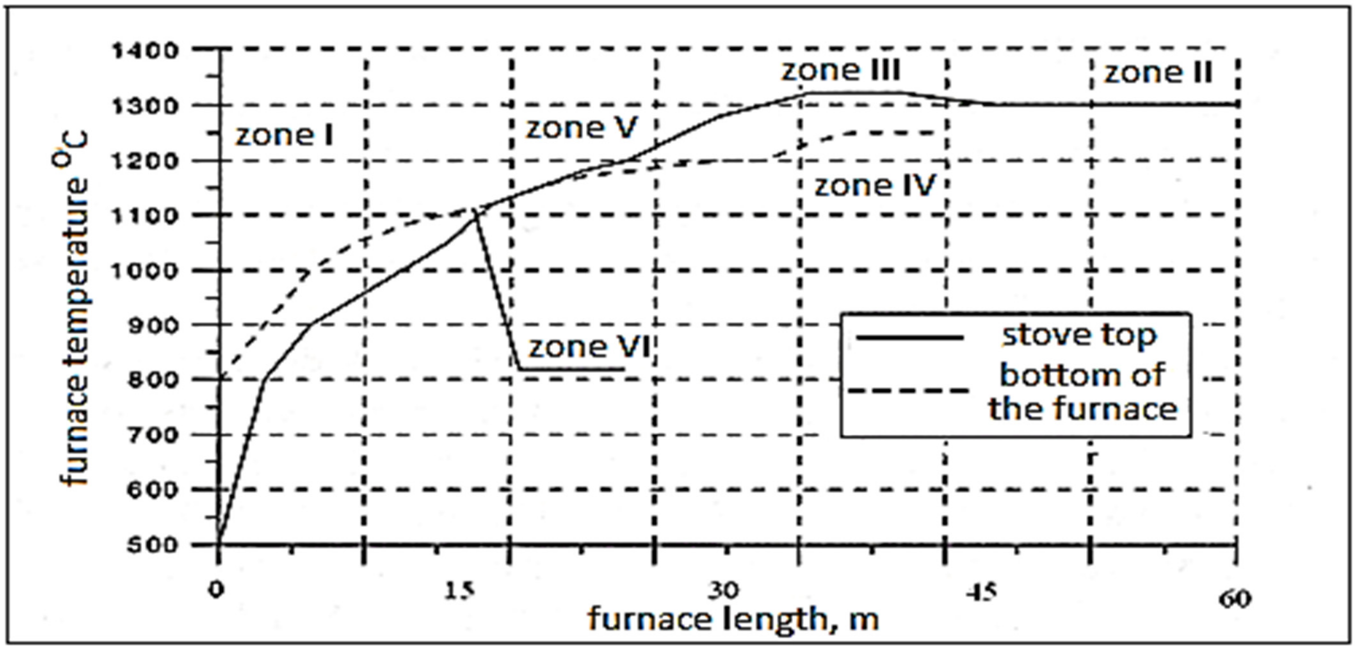

Figure 8. Ingot heating curves in the walking beam furnace of the hot strip mill for asymmetric distribution of the furnace temperature above the charge and under the charge. Source: own study.

For the proposed model, the time of heating the cold charge can then be shortened, e.g., in zone VI, from 220 min to 180 min (Figure 9), including heating on the fixed hearth to 45 min (Table 5).

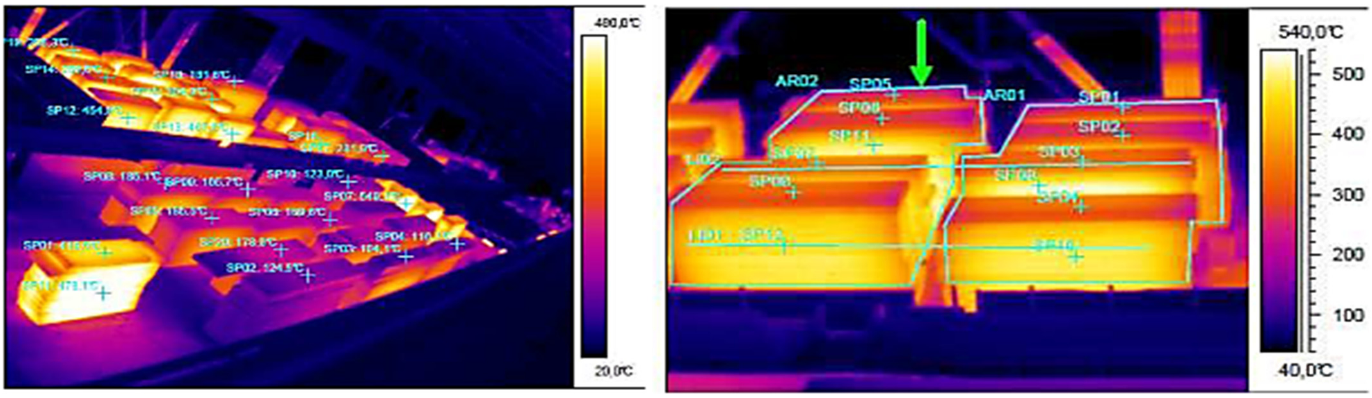

Figure 9. Thermograms of hot ingots. Source: own study based on [61].

Table 5. Ingot heating zones in walking beam furnace.

Heating Group Number	I	II	III	IV	V	VI
Total heating time minimum, minutes	100	145	160	180	200	220
Holding time in the equalization zone minimum, minutes	20	25	30	45	50	55

Source: own study.

The heating parameters are selected for the steel grade so as to guarantee the desired mechanical and technological properties, structure, and profile for the products in the form of coils and cut sheet metal. Based on the obtained model parameters, an algorithm for calculating electricity consumption, depending on the type of material, was proposed [56–58]:

$$EE_i = 9.7603 \cdot 10^{-1} - 2.5353 \cdot 10^{-2} \cdot g + 4.8474 \cdot 10^{-4} \cdot g^2 - 2.9422 \cdot 10^{-4} \cdot s + 6.0274 \cdot 10^{-8} \cdot s^2 + 1.4676 \cdot 10^2 \cdot w + 2.8632 \cdot 10^{-4} \cdot w^2 \quad (8)$$

where:

EEi—electricity consumption, depending on the type of material, kWh/Mg,
g—final sheet thickness, mm,
s—final width of the sheet, mm,
w—mass of the ingot, Mg.

On the basis of Equations (5), (7), and (8), Table 6 presents exemplary calculations of the consumption of natural gas and electric energy of a walking beam furnace for heating the slab billets to the desired rolling temperature, based on the production program and an exemplary completed rolling campaign.

Table 6. Examples of calculations of energy consumption depending on the implementation of the rolling program.

	b > 1500 h ≤ 3.0	b = 1500–1100 h ≤ 2.0	b = 1500–1100 h = 2–2.5	b = 1500–1100 h < 3.0	b < 1100 h < 3.0
Energy for heating the charge:					
MJ/t	1398.89	1388.34	1360.29	1381.06	1315.07
103 kcal/t	334.12	331.60	324.90	329.86	314.10
Electric energy usage, kWh	117.40	117.20	114.90	116.40	113.60

b—tape width, mm, h—tape thickness, mm. Source: own study.

The measurement data made it possible to determine the numerical relationships between the profile and type of sheet metal produced and energy consumption. An example may be the dependence of electricity consumption as a function of width with a breakdown into two thickness ranges in the second group of ingot hardness. A significant difference (over 25%) in electricity consumption can be observed between strips with a thickness of up to 2.99 mm and strips with a thickness in the range of 3 ÷ 5.99 mm and a width of up to 1000 mm. As the width of the produced sheets and strips increases, the energy expenditure necessary for their production becomes equal. As part of the study, the correctness of the constructed models of electricity and natural gas consumption was checked. The correctness of the electricity consumption model in comparison with the actual electricity measurements for the period of two months was 99.97% [56–58]. On the other hand, the correctness of the natural gas consumption model, compared to the actual measurements for the period of six months, was 99.76%. High compliance makes it possible to use the model in real conditions, taking into account the extension of its energy consumption and depending on the profile and type of hot-rolled sheets and strips.

4.3. Verification and Validation of the Model in the Dosimis-3 Package

The assessment of the model's adequacy consisted in comparing the indicators and parameters obtained during the tests and simulations with the indicators and parameters that could be determined as a result of the identification of the real object. The diagram of the verification model is presented in Figures 10 and 11.

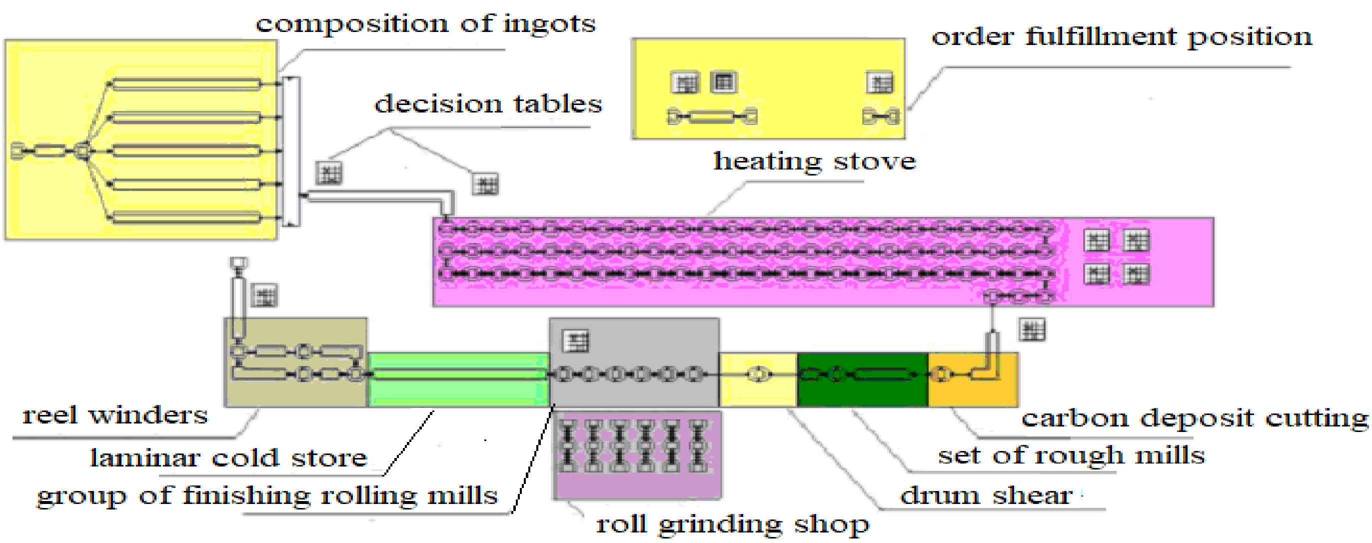

Figure 10. Validation model of the production system hot strip mills. Source: own study.

As simulation results for the analyzed cases, two indicators that are characteristic from the point of view of the production planning needs were taken into account:

- The ingot's heating time in the furnace, i.e., the time counted from the ingot entering the furnace chamber to the exit to the roller tables for the rolling process. This indicator aims to identify bottlenecks in the system.
- Soaking time, i.e., the time counted from reaching 800 °C by the ingot. According to the algorithm, this indicator makes it possible to control the zones of the furnace according to the heating curve in order to achieve the rolling temperature in an economically optimal manner.

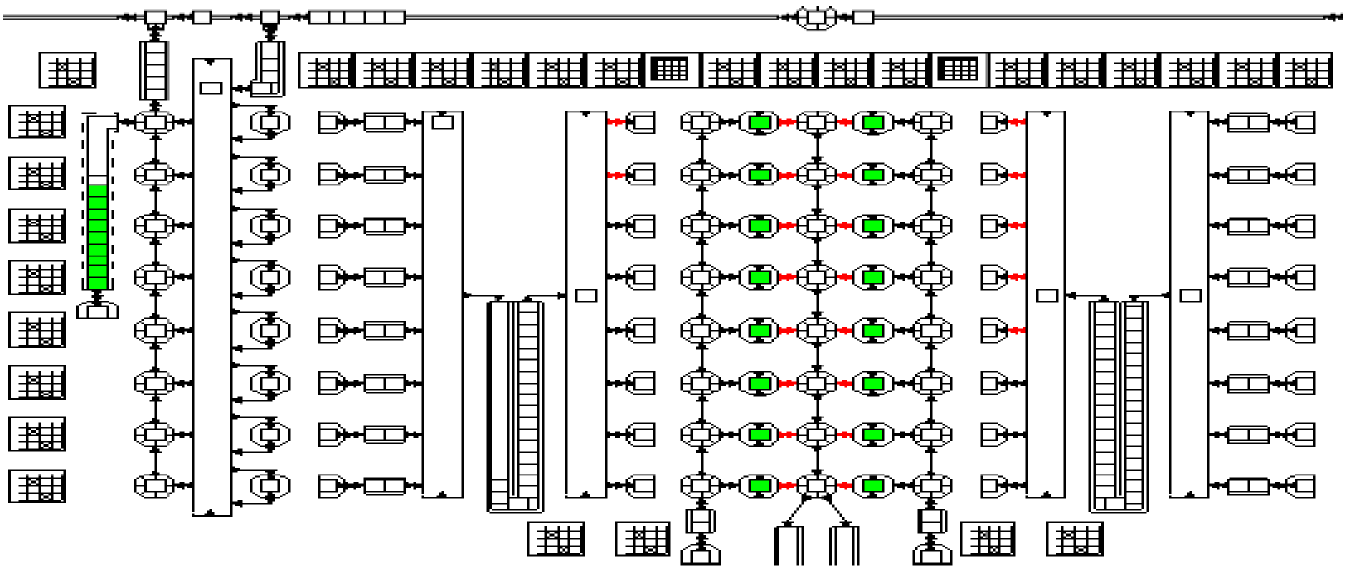

Figure 11. Animation-validation of flat billets flow in a walking beam furnace. Source: own study.

The diagrams presented in Figures 10 and 11 contain a list of the basic indicators analyzed during the simulation experiment, on the basis of which the following conclusions can be drawn:

1. The simulation shows that the actual technological system in a given rolling mill is designed with a large excess, which results in a sub-optimal use of the furnace capacity, at the level of 74–82%.
2. The rolling time is so long that, with the present number of heating zones operating in the furnace, it is difficult to achieve the desired rolling temperature.
3. The initial rolling campaign considered during the simulation were completed in less time than the subsequent campaigns. This is because the ingots of later campaigns were blocked in the furnace by waiting for them to move to a different heating zone.
4. As shown by the simulation, frequent reconstruction of the rolls increases the residence times of the billets in the furnace in the equalizing zone by an average of 330 min. This is connected with higher production costs. The increase in residence times was demonstrated by the consumption of 3093.75 GJ of gas and 227,700 kWh of electricity during the analyzed 2 month test period and 50 completed rolling campaigns.
5. During the performance of the 50 rolling campaigns, the rolling mill lost 2100 min on average for mandatory heating and heating with an incorrect heating curve. Considering that the rolling mill's efficiency is in the order of 450 Mg/h, and the heat consumption is approx. 1.25 GJ/Mg, it is possible to roll about 15,750 Mg of strip in 2100 min, and gas consumption by heating the billets in the furnace until the completion of the conversion and restarting the rolling process is in the order of 19,687.5 GJ.
6. The average duration of a single rolling campaign with the actual technological assumptions prevailing in a given rolling mill and with the use of production aggregates at the level of 60% is approximately 28 h.
7. The implementation of 50 campaigns for the actual rolling process demonstrated that the total process of their implementation lasted 1352 h 4 min. During this time, 608,400 Mg of strip was rolled, with the consumption of approximately 760,500 GJ of gas and 55,972,800 kWh of electricity.

It should be remembered that when designing a specific rolling program, a computer simulation should be performed in a wide range of analyzed parameters. This enables the selection of optimal parameters using the presented methodology and conditions for its implementation as part of both short-term and long-term production planning activities, taking into account the optimization of the production costs of the finished product.

4.4. Ways of Preventing or Reducing the Impact on the Environment

Based on the analysis of the hot rolling methods, achievable emissions and consumption levels corresponding to the application of the best available techniques are presented. The purpose of this part of the research is to provide information to industry, environmental protection authorities, and the public on achievable emission and consumption levels using specific techniques. Appropriate BAT techniques for walking beam furnaces and limit values were established by taking into account local conditions, costs and environmental burden.,

A reduction in the emission of harmful compounds, such as NOx, SOx, and dust, can be achieved through the use of high-methane natural gas, low-emission burners, and recuperators for heat recovery from flue gas. The furnace loading process should be carried out with the minimum opening and minimum dimensions of the charging window. The opening time of the charging windows should also be kept to a minimum. The above actions contribute to the optimization of gas consumption, the limitation of excess air, and thermal losses in the furnace. The quality of the gas used, the temperature of the combustion process, and the content of H_2S in the coke oven gas and the excess air should be constantly monitored. Gases from fire treatment should be discharged into the air through an electrostatic precipitator with a dedusting efficiency of 95%. To reduce the energy consumption of the furnaces, the heat of the rolled materials obtained in the previous process should be used. Low-emission swirl or flat-flame burners should be used, which should be characterized by the following emission level: NOx 380–100 g/Mg (reference data 80–360 g/Mg)/260 mgNm^3. The rolling mill should limit the air heating temperature through the automatic control of the furnace operation. Moreover, the thermal losses associated with the process should be reduced by minimizing the storage time of the hot charge and maximizing its rolling share. It is also essential to complete the charge in batches with a similar technological heating regime in order to maximize the use of the furnace's working space [58]. In both old and new plants, the charge should be changed from rolled ingots to slabs from the continuous casting of COS steel. The current regulations do not directly imply an obligation to measure air emissions from hot rolling processes. These obligations may result from the content of sectoral or integrated permits and may be imposed each time by individual arrangements with the environmental protection authority. Similar procedures are also used for noise monitoring. It is very important to monitor the emission of pollutants into the air on an ongoing basis and to record technological parameters: basic operating parameters and the actual efficiency of heating furnaces, the quantity and quality of the input used, electricity and natural gas consumption, and the level of pollutant emissions.

5. Conclusions

Summarizing the simulation of the performed tests, the following conclusions can be drawn:

1. The results obtained thanks to the use of artificial intelligence methods prove their effectiveness, and the accuracy of the solution regarding the best forecast of heating times is satisfactory both from the point of view of the needs of production planning as part of planning and long-term activities.
2. The comparison of the simulation model with the real model in industrial conditions demonstrated a clear improvement in the technological process, in which there were, among others:
    - A reduction in the residence time of the ingots in the furnace.

- A reduction in the duration of a single rolling campaign.
- A reduction in the residence time of the ingots throughout the technological process.

The result of this improvement was the total reduction of the implementation time of the 50 considered rolling campaigns by an average of 25 h and 38 min, thanks to which, among others:

- The rolling mill's efficiency increased by an average of 11,700 Mg tapes.
- There was a significant reduction in the production costs of the final product by saving 14,625 GJ of gas and 1,076,400 kWh of electricity,
- Under the optimization assumptions, the technological aggregates worked at full (100%) production capacity,
- The quality and technological conditions of the obtained tape did not change.

3. The implementation of 50 rolling campaigns with the applied improvements in the production system by reducing the heating time of flat slabs was shortened from the actual 58 to 52 days, which in the scale of the full year yields an additional 38 days. During this time, it is possible to:
   - Fulfill orders from an additional 36 rolling campaigns.
   - Use the additional days obtained for repairs and for the maintenance of production units, without reducing their productivity.
   - Save on utilities that can be used to modernize the plant or laboratory tests, which will improve the quality of the steel strip obtained, contributing to an improvement in the position of the plant on the metallurgical products market.
4. The benefits of this study include: its determination of the cost and energy relationships between individual profiles and steel grades in active production; the ability to track energy consumption and processing costs, depending on the currently produced assortment; and its verification of market prices for individual grades and profiles of steel.
5. The use of BAT techniques in the examined rolling mill for walking-beam furnaces will reduce CO_2 emissions by 56.7 thousand tons per year, which will allow a reduction in prices for the purchase of emission permits.

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Abbreviations

BAT	Best Available Techniques
BREF	Best Available Techniques Reference Document
b	Thickness of the strip, mm
h	Width of the strip, mm
$t_p^{(i)}$	Furnace heating time, min
l	Strip length in the rolling campaign, m
Δh	Ingot heating temperature in individual zones, mm
v	Rolling speed, m/s
$p_{śr}$	Average unit pressure in the deformation zone, MPa
M_w	Rolling moment, kNm
N_n	Nominal power of the drive motor, kW
T_w	Rolling temperature, °C
L	Number of heating measurements made, no.
y	Dependent variable
$x_1 \ldots x_k$	Independent variables
$\beta_0 \ldots \beta_k$	Model parameters
ε	Random component
E_L	Mean error, min
Φ_L	Mean square error
$\boldsymbol{G_{śr}}$	Average natural gas consumption (value equal to 1.29 GJ/Mg obtained From process data),
ΔL	Ingot length change, m
$L_{śr}$	The average length of the ingot is 9.19 m
EEi	Electricity consumption depending on the type of material, kWh/Mg
g	final sheet thickness, mm,
s	Final width of the sheet, mm
w	Mass of the ingot, Mg

Appendix A

Table A1. An example of selected data used to develop the model during the implementation of the first rolling campaign.

$t_p^{(i)}$	h	b	l	Δh	v	$p_{śr}$	M_w	N_w	T_w
656	220	1100	11.0	40	1.70	60.0	2100	5690	1250
780	180	1100	13.4	40	1.80	70.0	2060	5740	1225
871	140	1100	17.3	38	2.30	70.0	2250	7990	1220
953	102	1100	23.7	36	3.50	97.0	2380	13090	1213
1005	66	1100	36.7	26	4.40	112.0	2425	16200	1205
1060	40	1100	60.5	22	4.90	140.5	2280	16550	1190
1135	18	1100	134.4	9.9	0.80	239.5	2021	3537	975
1208	8.1	1100	298.8	4.3	1.80	360.6	1372	5324	955
1239	3.8	1100	636.8	1.7	3.85	454.0	842	6913	947
1268	2.1	1100	1152.4	0.6	6.99	550.0	464	7048	940
1288	1.5	1100	1613.3	0.4	9.81	620.0	151	3885	915
1310	1.2	1100	2016.7	0.2	12.27	610.5	75	2428	880

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