An Optimization Model for Making Alloy Additions During Steelmaking at SSAB Iowa

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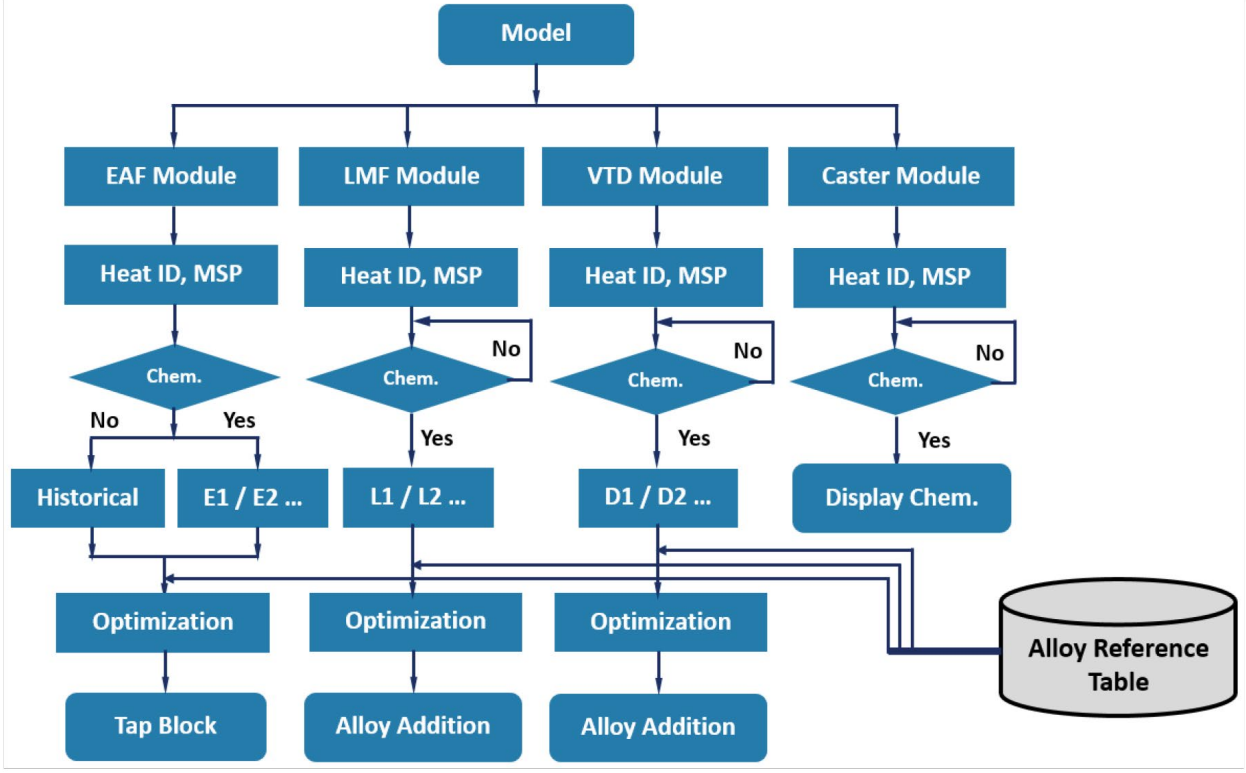
During steelmaking, different alloying agents are added to liquid steel at various stages to ensure the steel chemistry meets customer specifications.[1] At SSAB Iowa, alloys are generally added to liquid steel in different processing steps until the specification requirements are met:

- Tapping from the electric arc furnace (EAF): Bulk alloys are added into the ladle during tapping. The stirring power of the tap stream helps to quickly homogenize the alloying elements in the ladle, which minimizes subsequent treatment time during the refining process. Therefore, to utilize the advantage offered by adding alloys at tap, mill metallurgists strive to maximize the amounts of alloys added at tap in order to achieve concentrations of dissolved elements as close as possible to the minimum required by the specifications. However, the amounts of alloys added are dependent on the variation of tap chemistry due to the scrap mix. If the addition amounts are overestimated, the specified customer chemistry can be exceeded, resulting in production delays since the heat will have to be diluted or diverted.
- Secondary refining at the ladle metallurgy furnace (LMF): Alloys are trimmed at the LMF to the final specification levels. From a quality point of view, to avoid steel downgrades or diversions to alternate products with lower profit margins, the incremental additions of alloys are conducted cautiously until the required concentrations of various elements are achieved. Along with alloy additions, the steel must be completely deoxidized, desulfurized, homogenized and the bath heated to the required temperature before the ladle is shipped to the vacuum tank degasser (VTD) or caster. On-time processing of heats at the LMF is very critical to maintaining the continuity of casting, and hence productivity. The steel has to be refined, alloyed to the required chemistry and heated on time to deliver the ladles to the caster to maintain the expected productivity per the schedule. The time available to the LMF operators to adjust the heat within specification is even shorter when casting wider products because of the higher casting throughput. In addition, some of the heats tapped from the EAF may require longer processing time at the LMF due to non-optimal quality as a result of slag carryover. These conditions may complicate the judgment of the operators, and hence cause the chemistry of the steel to deviate from customer specifications. The choice of an optimal combination of alloys for trim additions in the ladle is based on operator judgment, which creates a challenge in itself to consistently maintain an optimal and cost-effective operation.
- Vacuum treatment in vacuum tank degasser (VTD): Depending on the steel

Figure 1



Alloy addition model structure (E1/E2, L1/L2, and D1/D2 represent the chemistry sample identification at the electric arc furnace (EAF), ladle metallurgy furnace (LMF) and vacuum tank degasser (VTD)).

specification, some steels may require final alloy trims after vacuum degassing. As a final stage, any miscalculations in alloy trims will be very costly.

To minimize the occurrence of deviations of steel chemistry from specifications, and to produce steel with optimal quality and optimize alloy additions with the purpose of ensuring cost savings, SSAB Iowa initiated a project to develop a comprehensive alloy addition model in 2017. In addition to cost savings, the model was intended to improve liquid steel yield and increase productivity. This paper discusses features of the new alloy addition model and its applications at the mill.

Model Development

Model Structure — The model was designed to interface with all of the liquid steel processing units, which includes EAF tapping, refining in the ladle and casting, in real time. Utilizing the power of linear programming,[2,3] the optimal types and amounts of alloys are automatically recommended by the model to ensure both quality and cost-effective choices are made by the operators. To address the issues at different steelmaking units, the model was broken down into four separate modules: (1) EAF Module, (2) LMF Module, (3) VTD Module and (4) Caster Module, as illustrated in Fig. 1.

The designs of individual modules are similar to each other. Once the model calculation is initiated, the model begins to communicate with the mill level 2 system to retrieve the information from each process unit, such as heat identification and steel composition specification. The model automatically verifies or updates these items every minute to ensure the information is available in real time.

For the EAF Module, if the steel chemical analyses are available, the model preferentially takes the latest analysis results as an initial condition for the EAF tap bulk alloy optimization. However, it is unnecessary to delay the model calculation since the tap chemistry test may not be available by the time additions need to be made. This is because post-tap chemistry tests usually take a priority over tap tests. To ensure the bulk alloys are prepared on time, an algorithm was developed to estimate the steel composition in the EAF. As presented in Eq. 1, the model essentially considers the

effects of steel grade, scrap recipe and steel chemistry from previous heats.

$$C_i = f\left(S,\quad R,\quad \sum_{m=0}^{N} C_i^m / N\right) \qquad \text{(Eq. 1)}$$

where

C_i = the estimated element concentration, wt.%,
S = a parameter related to steel grade,
R = a parameter related to scrap recipe, wt.%,
C_i^m = the measured element concentration after EAF melting and
N = the total number of EAF chemical analyses.

Several chemistry tests are typically required at the LMF and VTD as alloy additions are being gradually performed to adjust the steel to within specification. To ensure the accuracy of additions, the optimization program only recommends the next alloy trim amounts once it receives chemistry input from the current test. During the holding period, the optimization program idles, which saves a significant amount of computational resources. The design of the caster module was used to display the chemistry results in the tundish only at this stage. However, the caster module can be extended if any alloys would be added in the tundish in the future.

Alloy Database — The alloy costs, chemistries (including both major and residual elements) and relative concentrations of elements for the grade being made are important variables in the optimization program.

Table 1

Alloy Reference Table (element recovery rate is in wt.%)

Alloy	EAF	LMF	VTD	Cost	C	Mn	P	Si	Al	N	Cu	Ni	Cr	Mo	Cb	V	Ti	B
LarpingCarbon	N	Y	Y	0.xx	9x.x													
ChargeCarbon	Y	N	N	0.xx	8x.x					1.xx								
InjectCarbon	Y	N	N	0.xx	8x.x					0.xx								
Graphite	Y	N	N	0.xx	6x.x													
Al Cones	Y	Y	N	0.xx					9x.x									
Al Shred	Y	N	N	0.xx					9x.x									
Al Shot	N	N	Y	0.xx					9x.x									
LCFeMn	Y	Y	Y	1.xx	0.xx	8x.x	0.x	0.x		0.x								
FeMn	Y	Y	N	0.xx	6.xx	7x.x	0.x	0.x										
LCSiMn	Y	N	N	1.xx	0.x	6x.x	0.x	2x.x										0.x
FeSi	Y	N	N	0.xx	0.xx			6x.x	1.xx									
SiMn	Y	N	N	0.xx	1.xx	6x.x	0.x	1x.x										0.x
ElectroMn	Y	N	N	1.xx	0.xx	9x.x	0.xx	0.xx										
NitridedMn	N	N	Y	1.xx		8x.x				7.x								
LCFeCr	Y	Y	N	2.xx	0.xx		0.xx	0.xx					6x.x					
MCFeCr	N	Y	N	1.xx	3.xx	0.xx	0.xx				0.xx		6x.x	0.xx		0.xx	0.xx	0.x
FeMo	N	Y	N	8.xx	0.xx			0.xx			0.xx			6x.x				
MoOxide	Y	N	N	7.xx							0.xx			9x.x				
NitroVan	Y	Y	Y	1x.x	3.xx					1x.x						9x.x		
FeCb	N	Y	N	1x.x	0.xx	0.xx	0.xx	1.xx	1.xx						6x.x			
FeV	N	Y	Y	1x.x	0.xx		0.xx	0.xx	1.xx							8x.x		
FeTi	N	Y	Y	1.xx	0.xx			0.xx	6.xx								6x.x	
FeB	N	N	Y	1.xx	0.xx													1x
Cu	N	Y	N	3.xx							100							
Ni	N	Y	N	4.xx								9x						

At SSAB Iowa, a large number of alloys are added at different steelmaking units. In addition, new types of alloy are continuously being trialed. To manage the alloys efficiently for the model, a reference table was developed, including the alloy information for the applicable station, unit cost and recovery rates for different elements, as listed in Table 1. To facilitate the optimization, the table was implemented in the mill database, which can be directly referenced during the calculation.

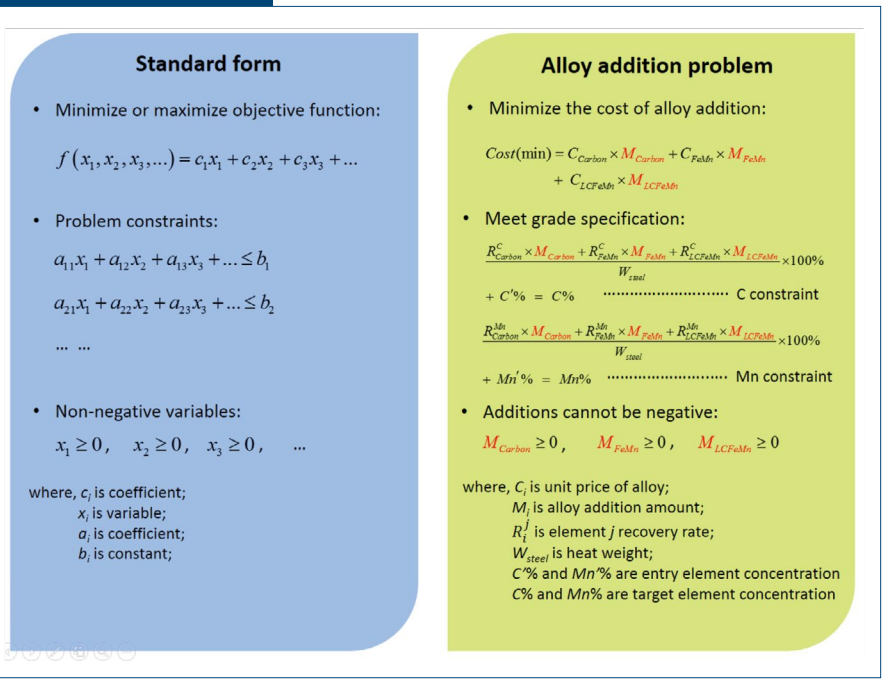
In the alloy reference table, the recovery rates of alloys are maintained by the mill metallurgists. The recovery rate of a given alloy can be dynamically adapted according to historical data, which improves the accuracy of the prediction. In addition, it is easy to add any new alloys or remove the existing alloys from the reference table. The unit price of alloys is provided by the SSAB Purchasing Department.

Alloy Addition Optimization — The core of optimization is based on the algorithm of linear programming. In past decades, models based on linear programming were often used to optimize the material and energy flows in steel plants.[4–6] Steel mills usually have a choice over the use of various materials and production processes. For example, linear programming is used to analyze the value in the use of materials due to the frequent fluctuations in their prices.[7] The use of linear programming for determining the best combination of alloys to achieve the chemistry specification for a given steel grade is also becoming popular in the steel industry.[8–11]

Generally, the alloy addition problem is formulated as a cost-minimizing linear programming model. Following the standard form of linear programming, the objective function of the problem is to minimize the cost of alloy additions. A constraint of the problem is that the concentration of each element after the alloy addition meets the grade specification. As a simplified example, to trim the steel with manganese, linear programming is used to determine the combined addition of ferromanganese and low-carbon ferromanganese required. To avoid a significant increase in carbon content, low-carbon ferromanganese is typically used for some steel grades to trim the manganese content. However, the unit price of low-carbon ferromanganese is about twice that of the ferromanganese. For those heats with low entry carbon, a combination of carbon, ferromanganese and low-carbon ferromanganese are used to minimize the alloy costs while ensuring that the grade specifications for both carbon and manganese content are met. Additionally, the addition of individual alloys cannot be negative numbers. To solve the problem, the objective function and constraints can be formulated using the standard linear programming form, as given in Fig. 2.

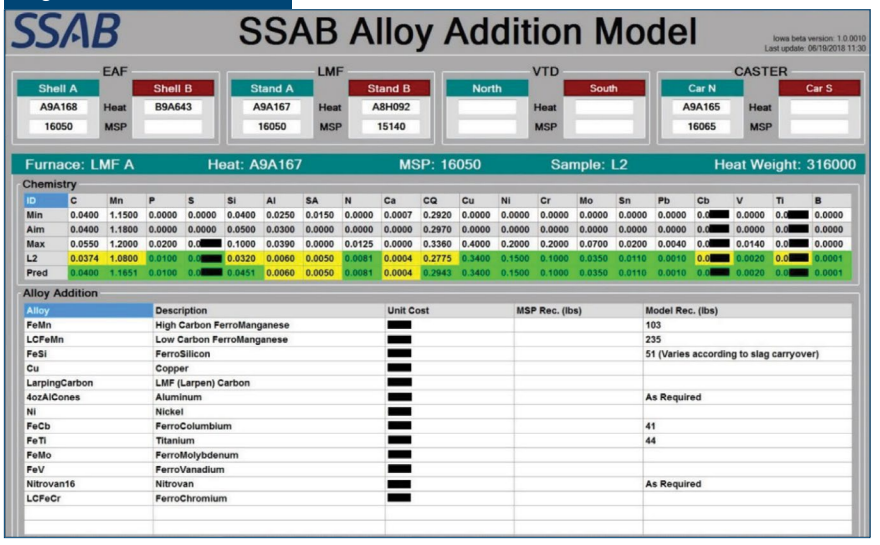
To solve the alloy addition problem, the unit price and recovery rate of each alloy can be referenced from Table 1. Each element entry concentration is based on the heat chemical analysis. Since this is a multiple-step optimization problem, the definition of target element concentration relies on the processing stage. For example, the minimum values required by the specification are used for the EAF tap alloy target, and the aim specification is used for the addition of alloys at the LMF and VTD. For some heats with high sulfur entry content, the model aims for an average value between the minimum and target values of the specification, allowing sulfur removal before the heat is trimmed to the final composition. In addition, the silicon content in steel can be affected by carryover slag from the EAF tapping; therefore, the operators have to determine the charge amount, although a reference amount is recommended by the model. To accelerate the calculation, the algorithm of Simplex

Figure 2



Linear programming problem formulation.

Figure 3



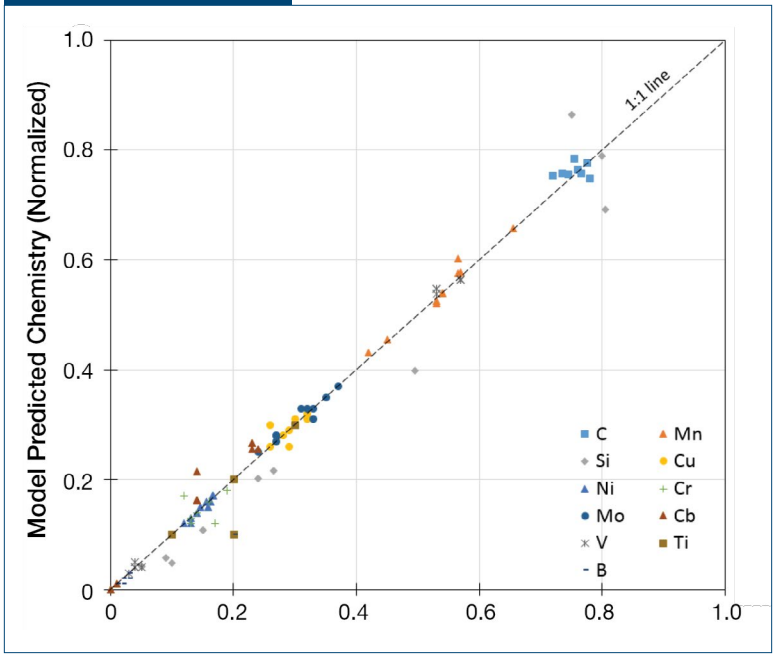
Model interface design.

Model Interface Design — The model was designed for the applications at the meltshop with minimal human interaction. As a comprehensive alloy addition optimization model, the model interface includes all of the modules presented earlier. As shown in Fig. 3, the heat number and mill practice are available for the heats being processed at a metallurgical vessel. To track the status at different units, the operators only need to select the unit, for example, Stand A at the LMF, then the model is able to automatically display the relevant information for the heat at this unit, including chemistry sample identification number, heat weight, chemistry range required by specification, chemistry testing results, recommended alloy additions and predicted steel chemistry after the additions. To capture any changes in the process, the model checks for updates every minute.

was employed, which involves determining slack variables, setting up tables, checking optimality, identifying pivot variables and optimizing the solution. The detailed procedure of the algorithm can be found in literature.[12,13] Usually, it takes less than a second to obtain the optimization results.

Model Validation — To validate the model calculation, the predicted chemistry results are compared with the measured results. The comparison considers carbon, manganese, silicon, copper, nickel, chromium, vanadium, niobium, molybdenum and titanium contents of the steel. The normalized concentrations of different elements are plotted in Fig. 4. The results verify that the model calculations are in good agreement with the measurements. The few wider deviations in silicon content are probably due to slag carryover from the EAF during tapping.

Figure 4



Model validation.

Model Applications

Model Implementation — The model was successfully deployed to the shop floor (LMF), as shown in Fig. 5. As a touch-free tool, the model automatically interacts with the level 2 system to capture the information and trigger the calculation.

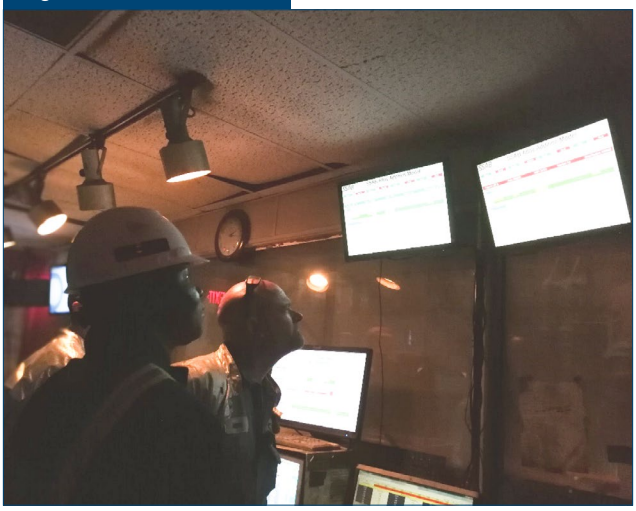
Model Performance — Cost savings were realized due to the implementation of the model. As examples of the model cost savings, several cases observed from the operation are reviewed, as listed in Table 2. The first scenario is making low-/

medium-carbon steel grades. Due to the tight range of carbon in some grade specifications and potential carbon pickup from other alloys, operators usually hesitate to add alloys with high residual carbon levels. The typical approach is to add low-carbon-containing alloys at the beginning, for example, low-carbon ferromanganese. After the chemical analysis, additional carbon might be charged to further trim the carbon to the specification. The problem with this approach is that the low-carbon alloys are generally much more expensive than regular alloys. In addition, the carbon recovery from carbon-containing alloys could result in additional cost savings. An advantage of the model is considering how much carbon can be recovered from the carbon-containing alloys when their additions are maximized. With this approach, the cost saving is maximized using less-expensive alloys and avoiding trimming with carbon. In addition to cost savings due to carbon recovery from the alloys, such an approach can lead to reduced processing time since an additional chemistry test will not be required, as would have been necessary if the heat was separately trimmed with carbon.

The second scenario is the use of MoO_2 and FeMo for alloying. Due to the difference in unit price and element recovery rate, the model prefers to recommend adding more MoO_2 at tap instead of using FeMo for a trim addition at the refining stage. In this case, up to US$1,262 per heat cost savings can be achieved, as shown in Table 2. Another advantage is that the EAF tap provides excellent conditions for homogenizing the alloys; therefore, a significant amount of treatment time can be saved in the refining stage.

The third scenario is making a steel grade containing silicon and manganese. One option is using ferromanganese and ferrosilicon exclusively for the alloying, and the second option is maximizing the use of silicomanganese before considering how much ferromanganese and ferrosilicon to trim the steel with. Since the manganese contents in common SSAB steel grades are typically much higher than the silicon contents, the only limitation in Option II is in achieving the maximum allowable silicon content from silicomanganese. As presented in Table 2, a considerable cost savings is expected based on Option II. Hence, taking advantage of the model, the additions of silicomanganese and ferromanganese are usually maximized at tap while ferromanganese and ferrosilicon are recommended for trim additions.

Figure 5



Model installation at LMF pulpit.

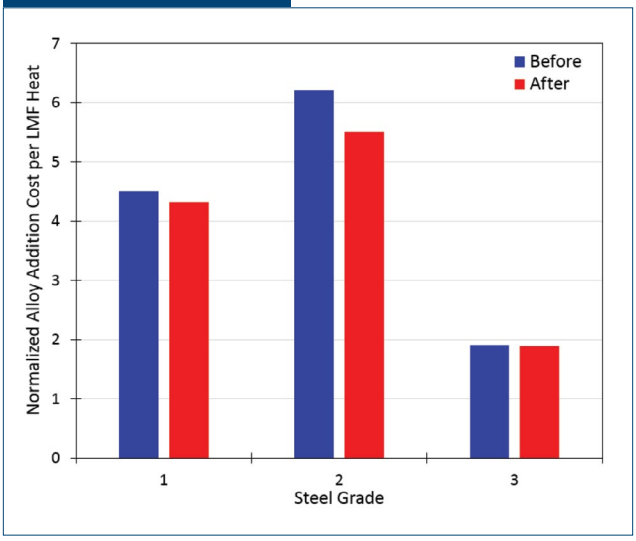
The LMF alloy costs for three different steel grades have been tracked since the model was implemented on-line in July 2018. Compared to the historical data (January 2017 to July 2018), the average LMF alloy costs per heat has dropped by about US$20 to US$700, as shown in Fig. 6. In addition, the number of LMF chemical tests has decreased. After the model implementation, the percentage of LMF heats requiring more than three chemical tests was reduced by 1% (13.5% after versus 14.5% before), as illustrated in Fig. 7. The reduction of the number of chemical tests helps to minimize process delays.

Table 2

Model Case Study

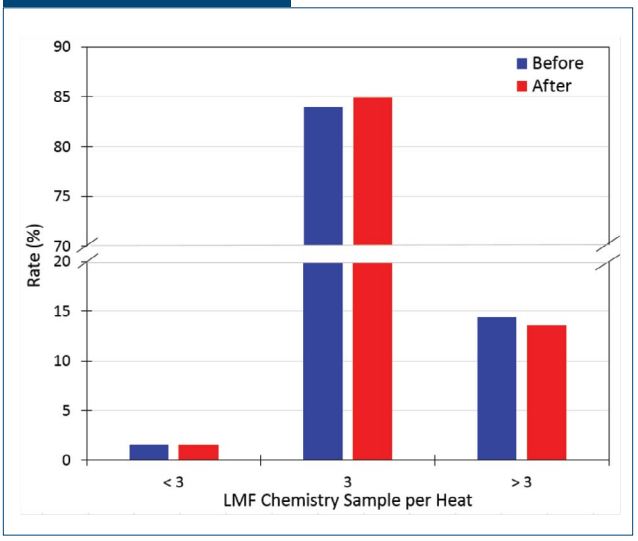
Scenario	Option I	Option II	Cost saving per 160-ton heat
I	LCFeMn: US$1.098.80 Carbon: US$17.80	LCFeMn: US$303.20 FeMn: US$500.50	Total: US$312.90
II	FeMo: US$10,915.60	MoO_2: US$9,653.60	Total: US$1,262.00
III	LCFeMn: US$3,044.70 FeSi: US$972.20	SiMn: US$3,564.00	Total: US$452.90

Figure 6



Average alloy cost per heat.

Figure 7



Number of chemistry tests per heat at the LMF.

Conclusions

A comprehensive alloy addition model has been developed for application to steelmaking at SSAB Iowa Inc. The model communicates with the mill level 2 system from EAF tapping to casting, and automatically recommends the amounts and types of alloys to add using a linear optimization algorithm. Implementation of this model has resulted in a significant alloy cost savings along with an improvement in operational accuracy and efficiency.

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