Les Cahiers du GERAD ISSN: 0711–2440

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G–2026–24

May 2026

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2026
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The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

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An improved approximation of metal accumulation in electric arc furnaces for ferrosilicon production

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May 2026
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Abstract : Accurate estimation of metal accumulation in electric arc furnaces (EAFs) is critical for maintaining stable ferrosilicon (FeSi) production and ensuring effective process monitoring. Direct measurement of accumulated metal is currently not feasible due to extreme operating temperatures and the uneven distribution of molten material at the bottom of the furnace. Consequently, accumulation must be estimated through theoretical calculations, which directly influence production planning and operational decisions. This study proposes an improved methodology for approximating metal accumulation based on an enhanced mass balance formulation. Several modifications were introduced to increase estimation accuracy and responsiveness to process dynamics. The proposed improvements result in a smoother and more stable moving average of metal accumulation. Additionally, comparisons with theoretical input–output balances demonstrate improved consistency with expected furnace behaviour. The methodology provides a reliable estimation tool that can support operational decision-making and enhance production control in industrial EAF processes.

Keywords: Ferrosilicon; metal accumulation; electric arc furnace; dust; mass-balance equation

Acknowledgements: The authors would like to thank Samuel Lemieux, the lead metallurgist at the ferrosilicon producer for his insight and help in building the test cases and analyzing the results, allowing to validate the proposed methodology.

1 Introduction

Ferrosilicon is an alloy used as an additive in steelmaking. It is produced in an EAF [8] with raw materials consisting of wood chips, quartz, scrap metal, and coal to a temperature of 2,000°C. This paper is concerned with a ferrosilicon producer in Canada. Once the raw materials are transformed into ferrosilicon, it is cast from the furnace as molted metal. The problem is that the metal is never completely removed from the furnace as a single cast, for various reasons. For example, some of the metal could be less liquid by the time the cast is completed, or there is an accumulation of metal in the furnace. The latter induces many difficulties in the transformation of ferrosilicon, since it changes the chemistry of the content of the furnace. As the percentage of silicon in the cast is important, a metal accumulation can increase or decrease this value, resulting in a scrap casting. Ideally, the exact quantity of metal accumulation would be known, but it is impossible to measure this accurately in practice. First, the heat of the furnace makes it impossible to use sensors. Second, as the size of the furnace is a few meters, the accumulation is uneven throughout the surface area. In the literature, most of the papers are concerned with the energy consumption of the electric arc furnaces [3, 7]. Another field of research is the modelling and simulation of the EAF, as seen in [4, 10].

The changing chemistry of castings changes the recipes, e.g. the quantity of each raw material to incorporate in the furnace, to obtain a desired percentage of silicon in the ferrosilicon. Therefore, the quantity of accumulated metal in the furnace must be approximated somehow. At a factory of ferrosilicon production in Canada, there is currently a function that approximates this accumulation, but it is missing important input parameters, leading to a poor approximation. The goal of this project is to refine this approximation to have a better control on the production of ferrosilicon.

The melting of raw materials in the EAF produces dust [5], which constitutes a by-product of the steelmaking process. It contains multiple metallic elements and is collected by a dust collector so it does not build up in the EAF. The mass balance equation of the EAF is directly linked to the dust produced during the process [6]. Without going into technical details and chemical equations, the silicon mass-balance must include input of raw material, as well as all the different areas where there is transformation of elements such as dust and accumulation. Therefore, considering metal accumulation and dust is crucial for a good mass-balance equation and currently, the mass-balance equation to approximate the metal accumulation in the EAF does not consider the dust production.

This project aims at improving the current approximation of metal accumulation in the EAF as well as the graphs that are used by the operators of the furnace to make operational decisions, without changing the whole system in place and without disrupting the way operations are currently handled.

The paper is organized as follows. Section 2 explains the EAF as well as the problems caused by the metal accumulation. The methodology to refine the approximation of metal accumulation is proposed in Section 3. Results are presented in Section 4 and final remarks in Section 5.

2 Electric Arc Furnace

This Sections explains briefly the ferrosilicon production and the metal accumulation in the furnace.

2.1 Ferrosilicon production

An Electric Arc Furnace consists of a molten bath, where the metal is in fusion and three electrodes, given it is powered by three phases, as shown on Fig.1. An electric current is induced in the electrodes, causing arcs, and hence melting the raw materials into ferrosilicon. During the process, dust [9] is created and contains multiple metallic elements, for example, lead, iron and zinc [2]. The ferrosilicon coming out of the EAF never has the same exact chemistry. It can also happen that the metal does not come out of the EAF, leading to metal accumulation. Once the metal is extracted from the furnace, additives are mixed in the molten metal to obtain the right chemistry. These quantities are evaluated by the previous casting's chemical analysis.

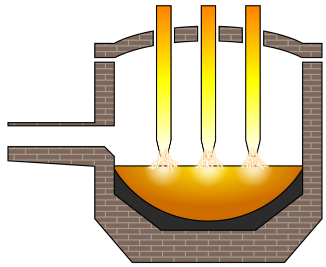

Figure 1: Electric Arc Furnace [1]

2.2 Metal accumulation

Ferrosilicon is produced by carbothermic reduction of silicon and iron oxide using carbon in an EAF [11]. When the reduction is not complete, it can cause the metal to accumulate in the EAF since it is not totally extracted from the furnace during the cast.

Metal accumulation in the EAF occurs when the sum of the metal cast with the dust is lower than the quantity of the raw material added to the furnace:

$$ACC = Si_{raw} - Si_{dust} - Si_{cast}, \tag{1}$$

where ACC is the accumulation of metal in the EAF in kg, Si_{raw} is the quantity of silicon in the raw material in kg, Si_{dust} is the quantity of silicon in the dust in kg and Si_{cast} is the quantity of silicon in the cast in kg.

When the cast is complete, elements like Magnesium are added to the ferrosilicon in fusion, and are named recipes. The quantity of metal accumulation in the EAF has a direct impact on the chemistry of an alloy recipe. For example, if there is more metal in fusion in the cast than expected, then the recipe is not exact and could cause a reduction of the percentage of silicon, for example, in the final product. Therefore, it is better to know as precisely as possible the quantity of metal accumulation in the EAF in order to tune the recipes.

2.3 Current metal approximation

Currently, at the ferrosilicon producer's factory, there is a system that approximates the metal accumulation in the EAF, as shown in Fig. 2. This is an actual snapshot of the computer system in place. The metal accumulation is the middle graph. The blue curve shows the current approximation of metal accumulation in the EAF. The x-axis presents 24 hours, whereas the left y-axis is the metal accumulation in tons. Eq. (1) is used to approximal the metal accumulation.

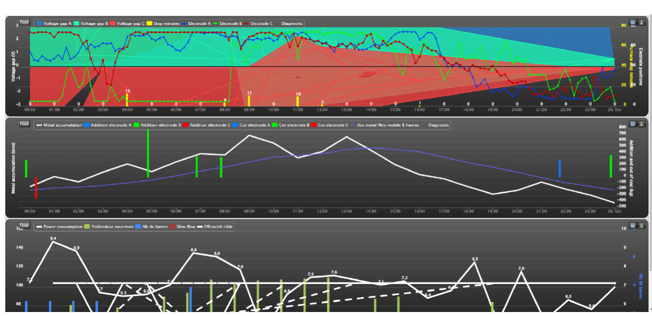

Figure 2: Current metal accumulation user interface

The goal of this project is to refine the approximation to have a better idea on the metal accumulation, in order to operate the EAF and recipes at their best.

3 Methodology

The current computer software in place cannot be changed, but it can be improved. As the graphics and calculations are used in all daily operations, the proposed methodology refines the calculations, without changing anything for the end-user.

The following modifications are proposed:

A) Approximate the metal accumulation when there is a cast, instead of per hour.
B) Add the iron Fe to the approximation.
C) Add the latency period of the raw materials addition.
D) Add the type of $FeSi$ currently in production.
E) Improve the user interface.

The followoing subsections detail the changes.

3.1 Approximate the metal accumulation when there is a cast, instead of per hour

The EAF in place produces a cast every 45 to 60 minutes. Therefore, there can be 0 to 2 casts every hour, depending on many factors such as the energetic consumption of the EAF. Using casts instead of hours will then give a more precise approximation of the metal accumulation, as the calculation will be updated at every cast.

3.2 Add the iron Fe to the approximation

In the actual calculation, only the quantity of Si is used, but iron is an important component as it is the second most present element in the $FeSi$. Therefore, incorporating this element in the approximation will lead to an increased approximation.

3.3 Add the latency period of raw materials additions

When raw materials are added to the EAF, they are not instantly consumed and there is a time delay before they start melting and integrate the metal in fusion. Currently, this time is not considered but is of upmost importance, since it takes a certain time in practice for the raw material to make it to the EAF. Therefore, the latency period of the raw materials is considered in the new approximation.

In Equations (3) to (5), parameter l_b specifies the latency period of the ferrosilicon type changes in production. When the type of ferrosilicon production changes, the latency period changes, since different weights of raw materials are added to the EAF (quart, wood chips, scrap metal, coal), given different types of ferrosilicon.

The actual calculation does not integrate this latency period and the raw materials are consumed within the hours in the calculation, but that is not the case.

The database of historical data was used to determine the latency periods when raw material is added to the EAF. Fig. 3 shows the latency times to consider, depending on the production changes on the y-axis. There are three types of ferrosilicon, 1, 2 and 3. When the type changes, for example 1 to 2, it is noted as 1-2 on the y-axis. These types represent different percentages of ferrosilicon as the final product.

One can notice that the latency times are between 3 and 5 hours (median), therefore there was a huge loss of information in the raw material consumption in the actual approximation of metal accumulation. This new latency period is added to the approximation.

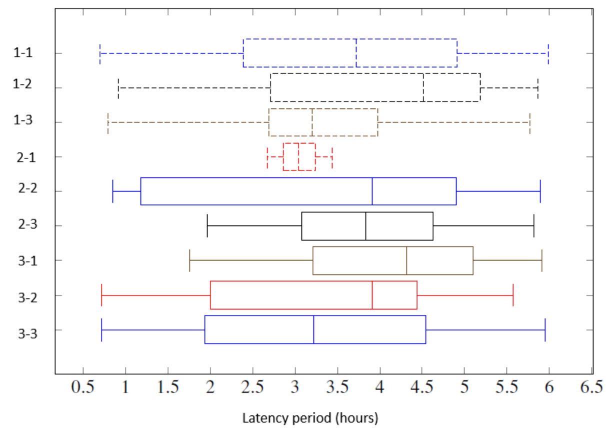

Figure 3: Production changes on the y-axis and latency period on the x-axis.

3.4 Add the type of $FeSi$ currently in production

The ferrosilicon producer produces different types of $FeSi$, more precisely three different percentages of Si in the alloy can be produced at the factory. Currently the calculation does not consider different products. The new calculation considers theses three possibilities, thus different values of Fe and Si in the raw materials incorporated to the EAF.

3.5 Improve the user interface

The current user interface, as seen on Fig. 2, shows the metal accumulation graph through other production graphs. The improvement to the interface is to create a separate graph, showing only the metal accumulation and making it easier for the operator to make decisions regarding the operation of the EAF.

3.6 New calculation of the metal accumulation

The following notation is used.

Sets are given by:

N = {1,2,...,n}	Type of raw material
B = {1,2,...,b}	Type of ferrosilicon in production
T = {1,2,...,t}	Hours

Parameters are given by:

x_{nt}	Weight (kg) of raw material of type n at time t
l_b	Latency period of the ferrosilicon in production
S_n	Percentage of Si in the raw material $n \in N$
F_n	Percentage of Fe in the raw material $n \in N$
y_t	Weight (kg) of the dust at time $t \in T$
z_t	Weight (kg) of the cast at time $t \in T$

The new metal accumulation calculation at time t is given by Eq. (2).

$$ACC_{new\,t} = SiMP_t - SiP_t - SiC_t, \tag{2}$$

where

$$SiMP_t = \sum_{i=t-l_b}^{t} \sum_{j=1}^{n} (S_j + F_j) x_{ij} \tag{3}$$

$$SiP_t = \sum_{i=t-l_b}^{t} (S_i + F_i) y_i \tag{4}$$

$$SiC_t = \sum_{i=t-l_b}^{t} (S_i + F_i) z_i \tag{5}$$

Eq. (3) provides the quantity of Fe and Si in the raw material. Eq. (4) provides the total quantity of Fe and Si in the dust and Eq. (5) the quantities of Fe and Si in the cast.

To calculate the total metal accumulation in the EAF and not only at time t, the approximation is added to the 23 previous casts, as shown in Eq. (6) to create a moving average.

$$ACC_{total} = \sum_{n=t-23}^{t} ACC_{new\,n} \tag{6}$$

4 Results

As it is impossible to actually measure the metal accumulation in the EAF, comparisons with known states of metal accumulation are used to validate the proposed approximation of metal accumulation. First, results are shown for known states of no accumulation. Second, results are shown for known states of accumulation.

The ferrosilicon producer gave access to the historical database for the years 2020 and 2021. The senior engineering metallurgist helped out by indicating dates that had no accumulations and others where it was certain.

4.1 No metal accumulation

4.1.1 January 12th 2020

The metallurgist searched through the database to extract days where the production was normal, with constant production and no accumulation in the EAF. Production day of January 12th 2020 was a normal production day.

The theoretical difference between the output versus the input taken from Table 1 gives a difference of 0.7 Tons, which means it is in normal operations. A difference value between -1 and 1 indicates there are little to no accumulation, which is the case for this day.

Table 1: Production statistics January 12th 2020.

Number of casts	27
Sum of S_i and F_e added in EAF	177.15 Tons
Sum of S_i and F_e output in EAF	177.85 Tons
Total weight of casts	176.56 Tons

Fig. 4 shows the comparison between the old and new approximation on a zero accumulation day. The red-dashed line is the old approximation and the red line is the new one. It is a lot smoother, and one can notice that the accumulation is either under 0 or very close to 0, which is representative of a no accumulation day. The old accumulation approximation gave an overestimation of the approximation. As for the moving average, the blue dashed-line is the old calculation with the 23 last hours and the blue line is the new calculation with the 23 last casts, giving again a value a lot closer to reality as the old calculation also over approximated the metal accumulation in the EAF.

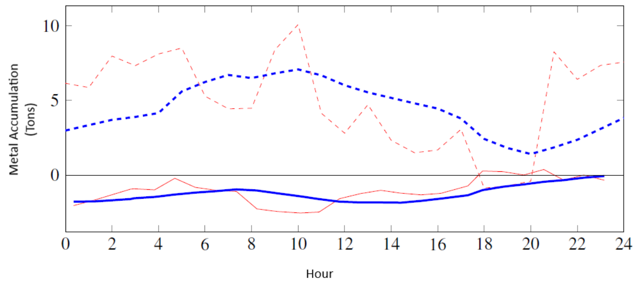

Figure 4: Zero accumulation day (Jan 12^{th}). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

4.1.2 March 15^{th} 2020

This day was also flagged as a normal production day with no accumulation. Productions statstics are shown in Table 2.

Table 2: Production statistics March 15^{th} 2020.

Number of casts	26
Sum of S_i and F_e added in EAF	108.55 Tons
Sum of S_i and F_e output in EAF	112.69 Tons
Total weight of casts	111.88 Tons

In this case, the difference between outputs and inputs is greater than 1, but the type of ferrosilicon in production changed, leading to these differences. The experience of the metallurgist is of upmost importance to give insight on these changes.

Fig. 5 presents the new calculations in the same fashion as previously. Again, the the moving average is a lot smoother and shows that there is no metal accumulation at the end of the day, which was not the case with the old calculations.

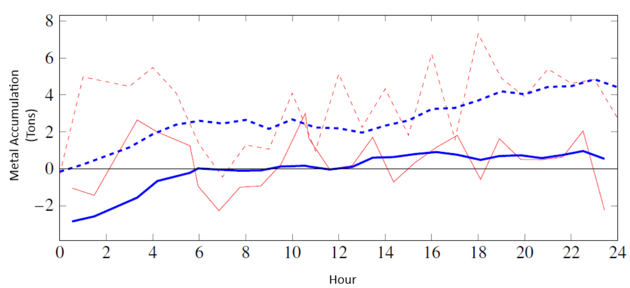

Figure 5: Zero accumulation day (March 15^{th}). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

4.2 Metal accumulation

4.2.1 December 4^{th} 2020

On the day of December 4^{th} 2020, the metallurgist flagged the day as a known accumulation of metal in the EAF, since it affected the production process. The hypothesis they based on was that on the day before, the production was under the target, whereas on the 4^{th}, they had a record production day.

Production statistics are shown in Table 3.

Table 3 shows that there is a theoretical accumulation in the EAF, given the input is higher than the output.

Table 3: Production statistics December 4th 2020.

Number of casts	23
Sum of S_i and F_e added in EAF	99.54 Tons
Sum of S_i and F_e output in EAF	96.07 Tons
Total weight of casts	93.455 Tons

Fig. 6 shows the comparison between the old approximation of accumulation in the EAF and the new approximation. First, the new calculation is a lot smoother. The moving average (blue line) is a lot smoother for the new approximation, since the 23 last casts are used in the moving average instead of the 23 last hours for the old approximation. As for the accumulation approximation, the red line show that the new approximation is higher than the old one, thus representing more precisely the metal accumulation in the EAF.

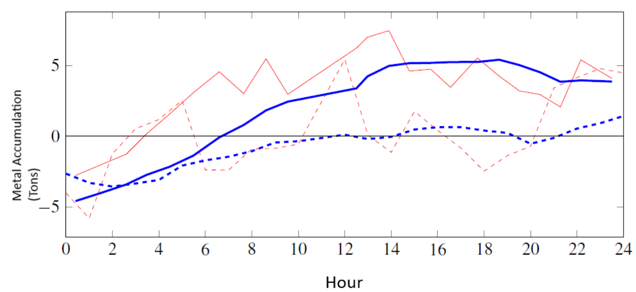

Figure 6: Accumulation day (December 4^{th}). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

4.2.2 June 1st 2021

This day was identified as an accumulation day. Production statistics are shown in Table 4.

Table 4: Production statistics June 1st 2021.

Number of casts	25
Sum of S_i and F_e added in EAF	108.98 Tons
Sum of S_i and F_e output in EAF	101.63 Tons
Total weight of casts	98.17 Tons

The theoretical difference is more than 7 Tons between the inputs-outputs, and the metallurgist also confirmed this accumulation day.

Fig. 7 presents the results and shows that the new calculation is close the the old calculation, but has a lower moving average at the end of the day, thus representing more accurately the actual quantity of metal in the EAF.

4.3 New user interface

Fig. 8 presents the new user interface. The advantage with this revised version is that a page is dedicated to the metal accumulation, whereas it was part of other graphs in the previous version,

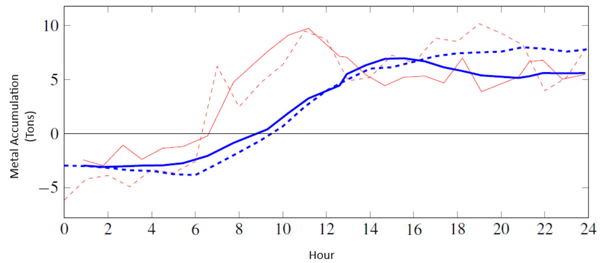

Figure 7: Accumulation day (June 1^{st}). The red dashed-line is the old accumulation approximation and the red line is the new accumulation approximation. The blue dashed-line is the old moving average and the blue line is the new moving average.

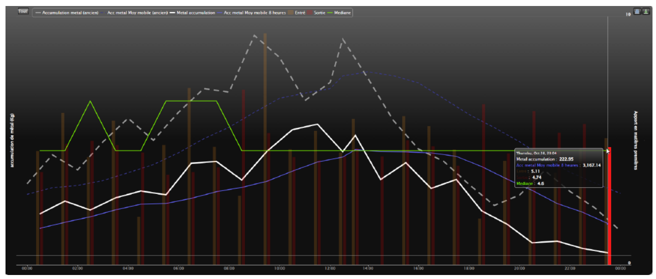

Figure 8: New user interface.

making it easier to analyze. The old approximation are kept on the graph as a transition period, the grey dashed-line is the old accumulation and the blue dashed-line the old moving average. As for the new calculations, they are visible with the white line for the accumulation and the blue line for the moving average. The median of accumulation is shown with the green line.

4.4 Discussion

The new user interface and new calculation of the metal accumulation was put in production at the ferrosilicon producer, allowing a precise calculation of the metal accumulation in the EAF and therefore allowing to take decisions to enhance the production process. It is also to be noted that a lot more results are available, but only a few were selected given the page limit.

5 Conclusion

This work presents a novel methodology to approximate metal accumulation in an EAF. Currently, direct measurement of metal accumulation is not feasible because of the extreme temperature conditions and the uneven distribution of molten metal at the bottom of the furnace. Consequently, accumulation must be estimated through theoretical calculations, as it significantly influences the production of FeSi. Several improvements have been introduced to the existing calculation framework. First, the approximation is now performed at each casting event rather than on an hourly basis, allowing for a more precise representation of process dynamics. Second, iron contributions have been incorporated into the theoretical mass balance. Third, the latency period associated with raw material additions has been integrated into the formulation. Finally, the methodology accounts for the specific FeSi grade currently being produced. These enhancements significantly improve the stability and reliability of the estimated accumulation. In particular, the resulting moving average is smoother and more consistent with operational behavior. Moreover, when theoretical input–output mass balance calculations are performed for the EAF, the proposed methodology provides results that more accurately reflect actual production condition. Future work based on this project would involve determining the quantities of raw material to add to the EAF in a blackbox optimization context.

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