

CHAPTER 3: THE COST OF EAF OPERATION.

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3.1. INTRODUCTION.

A number of control objectives were defined in Chapter 2, based on metallurgical requirements of EAF steelmaking. In some cases, improved control of a certain variable might have no economic benefits to the process. As the driving force behind the majority of control projects is an increase in profit, the control of any variable should be justified on both functional and economic bases. In this chapter the choice of controlled variables will be justified from an economic perspective, and the relative cost contribution of each controlled variable calculated to show their relative economic importance. The cost of the feed materials and energy inputs to the furnace will also be quantified, and their cost contributions relative to the total production cost and the cost advantages of controlling certain variables quantified.

3.2. COST COMPONENTS OF EAF OPERATION.

3.2.1. BACKGROUND.

In order to maximise profit of EAF operation, steel of the required quality needs to be produced in the shortest possible time, using the combination of feed materials resulting in the lowest cost. These three factors are to a certain extent conflicting, since throughput can for example be increased by using more expensive feed materials. An optimal point can however be found for which the cost of EAF operation is minimised.

The value of increased throughput will depend on the specific plant configuration. If the EAF is a bottleneck in the process, an increase in throughput will be a major cost consideration, whilst if the production capacity of the EAFs exceeds the demand of the casters or other downstream processes, throughput may not be critical [18]. For the process under consideration the EAF is a bottleneck [18], and any increase in throughput will increase the production of the plant in total.

Research has been done to determine the optimal feed additions to a furnace. De Vos [7] reported on the optimisation of flux additions to an EAF and reported reduction in production cost in excess of 3%. As in many other optimisation projects, a static furnace model was used, and the efficiency of the strategy during furnace operation could not be quantified accurately.

Very often the economic optimisation and the functional control objectives of a process are seen as separate objectives, and are handled by different systems [24]. By integrating the economic and functional control objectives, a controller can be designed that satisfies the functional control objectives and the economic goals set for the process simultaneously.

The first step in quantifying the cost of an EAF tap is to determine the factors contributing to EAF cost, as discussed in the next section.

3.3. COST COMPONENTS OF EAF OPERATION.

3.3.1. Operational cost considerations.

Taylor [5] identified the cost components, and their relative contribution to the total cost of producing steel with an EAF, as shown in Table 3.1. The analysis is however based on 1977 data, and the cost contribution of DRI is for example not included in the analysis. Discussions with a South African steel producer [18] resulted in a revised cost table, based on a 50:50 ratio of DRI and scrap charging (85 ton each). Ferroalloy additions are omitted from the revised cost estimate since these are typically added after the tap. The revised table is shown in Table 3.2.

Cost component	Percentage
Labour	1.2%
Investment	1.8%
Oxygen	0.7%
Crucible	0.1%

Table 3.1. Operational costs as a fraction of total EAF operational cost (1977) [5].

Cost component	Percentage
Scrap.	58.2 %
Maintenance and other costs.	14.0 %
Electric power.	10.5 %
Electrodes.	6.2 %
Ferrous alloys.	3.6 %
Labour.	1.9 %
Flux.	1.7 %
Refractories.	1.6 %
Investment.	1.6 %
Oxygen.	0.7 %

Table 3.2. Revised table: Operational costs as a fraction of total EAF operational cost (2000) [18].

Cost component	Percentage
Scrap.	29.7 %
DRI.	22.3 %
Electric power.	14.9 %
Maintenance and other costs.	14.0 %
Electrodes.	7.5 %
Refractories.	3.7 %
Flux.	3.6 %
Labour.	1.9 %
Investment.	1.6 %
Oxygen.	0.7 %
Graphite.	0.1 %

The percentages shown in Tables 3.1 and 3.2 describe the contribution to the total cost of an EAF tap for typical inputs. For control purposes, it is convenient to express the cost components in terms of the manipulated variables and the units typically used to describe their addition rates. Table 3.3 shows the quantities of the cost components typically consumed during a tap, and also the relative cost per unit, where the measurement unit is defined in column 5. Unmodelled components (electrode and refractory consumption) and indirect costs, not influenced significantly by the controller (maintenance, labour and investment) were omitted from Table 3.3.

Table 3.3. Table showing the per unit consumption during a typical tap.

Cost component	Percentage of total cost	Consumption	Per unit percentage	Unit
Scrap.	18.7 %	53.5 ton	0.35 %	/ton
Hot metal.	24.1 %	65 ton	0.37 %	/ton
DRI.	9.2 %	35 ton	0.26 %	/ton
Arc power.	14.32 %	70605 kWh	0.211 %	/MWh
Flux.	3.6 %	4.5 ton	0.8 %	/ton
Oxygen.	0.7 %	4220 Nm ³	0.129 %	/ton
Off-gas fan.	0.58 %	2760 kWh	0.21 %	/MWh
Graphite.	0.1 %	100 kg	1.0 %	/ton

The energy consumption of the off-gas fan was calculated using typical off-gas power inputs. The percentage for electric power indicated in Table 3.2, was subdivided into the power consumed by the arc and the power consumed by the off-gas fan, as indicated separately in Table 3.3.

In the model described by Bekker [13] hot metal is also charged to the EAF in addition to scrap and DRI. The scrap and DRI consumption required for a 50:50 charge ratio [18] was therefore reduced to account for the consumption of liquid metal, scrap and DRI as described by Bekker [13]. The percentage contribution of DRI and scrap to the cost of a tap was reduced proportional to the reduction in DRI and scrap consumption. The percentage contribution of the hot metal was chosen to keep the cost of the iron additions

(scrap, DRI and hot metal) equal to that described in Table 3.2 (52 %). Although this assumption probably underestimates the cost of hot metal, the per-unit cost of hot metal as shown in Table 3.3 is already significantly higher than the cost of DRI and also higher than the cost of scrap. This explains why hot metal charging is being phased out [18].

The per-unit percentages are not affected by the configuration described by Bekker [13], as the consumption and percentages were reduced in the same proportions. As controller tuning is based on the per-unit percentages (see Chapter 5), the same controller tuning parameters could thus be used for the manipulated variables, whether hot metal is charged or not. Hot metal charging or the lack thereof would however influence the setpoints and control objectives significantly.

The data contained in Table 3.3 can be used by an operator or implemented in a controller, to ensure that the most economical options will be used to reach control objectives. The relative cost implication of reaching or not reaching certain control objectives will be discussed in the following section.

3.3.2. Cost implication of controlled variables.

The following controlled variables were defined:

- Percentage carbon in the steel melt.
- Steel temperature.
- Steel mass.
- CO emission.
- Relative furnace pressure.
- Off-gas temperature.
- Slag foam depth.

The cost implication of each one of these controlled variables will be discussed in turn.

3.3.2.1. Percentage carbon in the steel melt.

The carbon content of the steel melt has very little influence on the cost of the tap at any time during the tap. When the steel is tapped, however, the carbon content should meet the specifications the melt was intended for. The tolerances on carbon content vary for the different types of steel produced, but in general the allowable variations have a range of approximately 20 %. Since it is more likely that the carbon content would be too high than too low, it is often aimed at producing steel close to the lower end of the carbon specification. The 20 % range would thus not be divided symmetrically (+/- 10 %), but in a range of -5 % to +15 %. If the carbon specification is completely off target (more than +/- 50 % from specification), the melt might be scrapped, implying that the melt cost would more than double.

If the specification on carbon content is not met, some form of corrective action needs to be taken, unless the melt is scrapped. This corrective action includes switching on the arc for an additional time period, blowing more oxygen, or making some additions to the melt. The cost of these corrective actions is in general small compared to the cost of the melt. To blow oxygen for another 5 minutes would for example have a small impact on the total cost of a tap. Oxygen consumption contributes approximately 0.7 % to the total operational cost, and to blow oxygen at the maximum feed rate for an additional 5 minutes would thus increase the production cost with less than 0.1 %.

In many processes the EAF is a bottleneck in the process, which means that a caster or another downstream process is consistently waiting for steel from the EAF, or would have to slow down production if the steel melt from the EAF is delayed. Another matter of concern is that a delay of approximately 5 minutes exists between taking a steel sample and the availability of a result. If a corrective action adds 5 minutes to the melting time [18], 10 minutes would thus pass (time of corrective action added to the delay between sampling and the availability of a result) before the final composition is known and tapping may commence. If it is assumed that the typical production time of a tap is 100 minutes [13], the reasoning above shows that a production loss of 10 % would occur due to a too large deviation in carbon content. Although some losses are not accounted for using this

approach (e.g. stopping and restarting the continuous caster) [18], the cost due to production losses account for the biggest part of cost due to variations in carbon content [18].

The cost of not meeting carbon specifications as a percentage of the cost of a tap, is shown in Figure 3.1 for a general case. The cost between 15 % and 50 % or -5 % and -50 % deviation from the desired carbon content is equal, since the cost of additions are negligible compared to the cost of lost production, as described above.

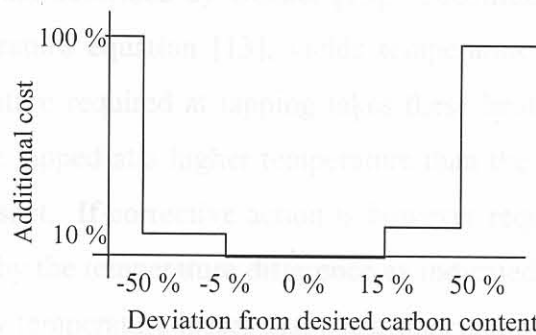


Figure 3.1. Additional cost due to deviation from the desired carbon content.

3.3.2.2. Steel temperature.

The steel temperature should be high enough to ensure proper tapping of the melt and also to contain sufficient heat as required by secondary metallurgical processes. A too high temperature may lead to unwanted reactions with the steel melt, more inclusions in the steel, and increasing EAF lining wear. Since none of the factors due to a too high temperature are modelled, the cost will be based on a too low temperature, and it will be assumed that a symmetrical cost distribution exists.

The tapping temperature may vary by approximately +/-10 K before corrective action is required [18]. Similar to the assumption for carbon content, the throughput would be a determining factor in the additional cost due to a too low temperature. If the temperature is too low, electrical energy (arc) or chemical energy (oxygen) will be added to increase the temperature, depending on the steel composition. The cost of the additions (oxygen or

electrical energy) is once again small compared to the cost of lost production, but may become significant for large temperature differences. Temperature measurement delays typically vary between 3 and 5 minutes [18], and an average delay of 4 minutes will be used in this analysis, corresponding to a 4% increase in tapping time. The heat losses that occur during the time it takes to make a measurement are however significant, and need to be taken into account.

The heat losses can be calculated using the equation describing the temperature rate of change in the EAF model described by Bekker [13]. Substituting typical steel and slag masses into the temperature equation [13], yields temperature losses of approximately 0.26 K/s. The temperature required at tapping takes these heat losses into account, and steel would typically be tapped at a higher temperature than the actual requirement, since the delay is always present. If corrective action is however required, the steel would not only have to be heated by the temperature difference as indicated by the measurement, but additional to this also by temperature losses that occur during the measurement delay. Due to this fact and limitations on the maximum power input to the EAF, the tapping time would not only be increased by the measurement delay corresponding to 4 % of the tapping time, but also with another 4 % in recovering energy losses during the measurement delay. For steel temperatures more than 10 K lower than the specification, the additional time added to the tap is given by Equation 3.1, where ΔT is the difference between the measured and specified temperature.

$$\Delta \text{Time} = 8 \% + 0.063 \%(\Delta T - 10) \quad (3.1)$$

Since it is assumed that throughput is the determining cost factor, any increase in tapping time corresponds to an increase in EAF operational cost. The additional cost of a tap due to not reaching the required tapping temperature is shown in Figure 3.2. It is assumed that the tapping temperature is never far below the required temperature, since this might cause the melt to solidify inside the EAF. The cost of a frozen melt will thus not be considered.

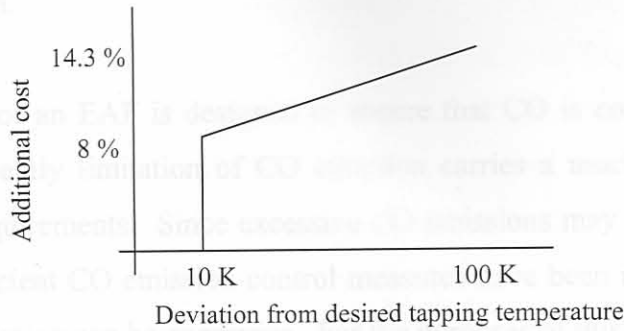


Figure 3.2. Additional cost due to deviation from the steel tapping temperature setpoint.

3.3.2.3. Steel mass.

The required steel mass is determined by the production capacity of the processes downstream from the EAF, or by the maximum capacity of the EAF, depending on where the bottleneck occurs. If it is assumed that the EAF is the bottleneck, any tap not utilising the maximum capacity of the EAF would translate into a production loss. A steel mass of 5 % below the required mass thus corresponds to a production loss of 5 %, equivalent to a cost increase of 5 %. Exceeding the capacity of the EAF might cause some problems that will not be considered. For the purpose of this analysis it will be assumed that exceeding the capacity of the EAF has no advantages, nor disadvantages. The total cost of a tap with a too high steel mass will however be higher due to increased feed and energy consumption. The additional cost due to variations in the steel mass from the desired mass is shown in Figure 3.3.

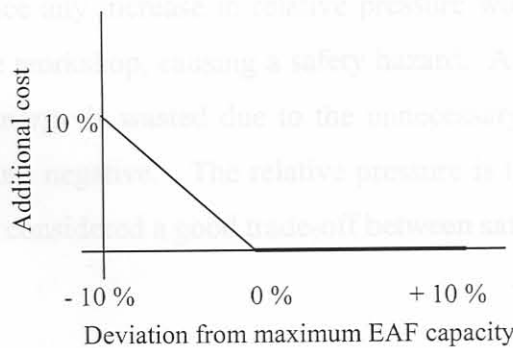


Figure 3.3. Additional cost due to deviation from specified steel mass.

3.3.2.4. CO emission.

The off-gas system of an EAF is designed to ensure that CO is combusted in sufficient quantities, but frequently limitation of CO emission carries a much lower priority than other operational requirements. Since excessive CO emissions may lead to a forced plant shutdown until sufficient CO emission control measures have been implemented, the cost of excessive CO emission can be enormous. For the purposes of this analysis, the cost of a forced plant shutdown will be approximated by the cost of 10 taps (1000 % additional cost). Although this is probably an underestimation, the cost is partly offset by the fact that CO emissions are typically averaged over a defined time period, and one peak CO emission of a short duration would thus not lead to legislative action against the plant. Different specifications exist for average CO emissions over different time periods, and the average CO emissions over a defined timeframe would thus have to be analysed.

The off gas system is designed to ensure adequate CO combustion with a large safety margin. It is thus unlikely that a plant would run the risk of a forced shutdown due to too high CO emissions. With regulations getting as low as 0.009 % CO (mass/mass) [5], it might be worth the effort of continuously monitoring and limiting CO emissions.

3.3.2.5. Relative furnace pressure.

The cost of not controlling relative furnace pressure efficiently, is easily underestimated by steel producers. Ideally the relative furnace pressure should be controlled at 0 Pa. This is however infeasible, since any increase in relative pressure would lead to the emission of dust and fumes into the workshop, causing a safety hazard. A too low relative pressure is also infeasible, since energy is wasted due to the unnecessary extraction of hot gases to keep the relative pressure negative. The relative pressure is typically controlled at -5 Pa [13] or lower, as this is considered a good trade-off between safety and efficiency.

Substitution of typical values into the EAF model [13], shows that the additional energy extracted with the hot gases is approximately 337 kW/Pa. Controlling the relative pressure at -5 Pa instead of the ideal 0 Pa, thus causes additional energy usage of approximately 1.7 MW, accounting for almost 4 % of the total EAF electrical input. Jones *et al.* [27] estimated that losses in the off-gas stream accounts for approximately 20 % of the energy input into an EAF. The value of 20 % is however an estimate of the total energy losses in the off-gas stream, including the energy required to keep the relative pressure at 0 Pa. The calculation of 4 % is based only on the additional cost contribution due to a relative pressure 5 Pa below the optimum value of 0 Pa. Significant savings in energy consumption are thus possible by improved relative pressure control, or in utilising the energy contained in the off-gas stream efficiently.

The cost of inefficient relative pressure control can be expressed as a fraction of the total cost of an EAF tap. As indicated in the preceding paragraph, a significant portion of the EAF electrical energy consumption can be attributed to inefficient relative pressure control. Electrical energy as a percentage of total EAF operational cost is approximately 14.9 %, and the cost of not regulating the pressure effectively can thus be calculated as 0.1255 %/Pa for negative relative pressure.

The analysis for positive relative pressure is much more complex, since the influence on the health of a number of workers needs to be taken into account. The duration of the positive relative pressure would thus be of importance in this analysis and the fume evacuation system in the workshop would also have to be considered [5]. This analysis of the cost of inefficient relative pressure regulation will focus only on negative relative pressure, and the cost impact of negative relative pressure is shown in Figure 3.4. It is assumed that a positive relative pressure of a short duration will not have a significant impact on the health of the workers, and that the relative pressure setpoint would be chosen adequately low to prevent frequent positive relative pressures. Improved regulation would thus enable specification of a higher relative pressure setpoint without compromising the health and safety of workers.

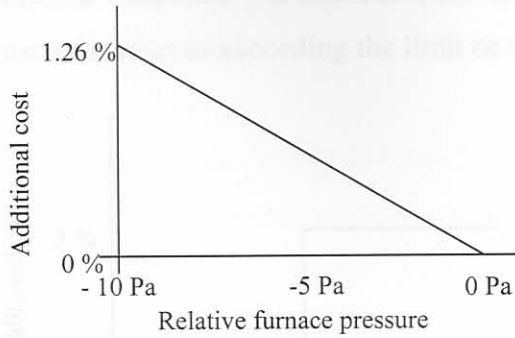


Figure 3.4. Additional cost due to deviation from 0 Pa relative furnace pressure.

3.3.2.6. Off-gas temperature.

Off-gas temperature needs to be limited to prevent the bag-house from exploding [13]. All possible steps are taken by steel producers to prevent bag house explosions, due to the severe impact of such an explosion. For the EAF under consideration, a trip switch ensures that the EAF operation is halted if a danger of bag-house explosion is detected, based on an off-gas temperature measurement. The time between the EAF being switched off and switched on again translates into a production loss, similar to the losses due to variations in carbon content and tapping temperature. For the purpose of this analysis it will be assumed that 3 minutes of production time is wasted [18] for each time the off-gas temperature exceeds a predefined limit of 773 K. The cooling losses during this period is approximately 0.2 % of the total cost of an EAF tap, that is once again insignificant compared to the cost of the lost production. Exceeding the specified off-gas temperature would thus lead to an increase in production cost of approximately 3 %, since the duration of a tap is approximately 100 minutes. The temperature-measurement of the off-gas is real time and no additional delay is associated with such a shutdown.

There is no advantage, nor disadvantage to a low off-gas temperature. Although variations in off-gas temperatures would be influenced by variations in the off-gas fan power consumption, this will be accounted for in a separate model. The cost as a function of exceeding a predefined temperature is shown in Figure 3.5. Since the EAF would be

halted as soon as the predefined temperature is exceeded, the cost is not a function of the off-gas temperature, but just a function of exceeding the limit or not.

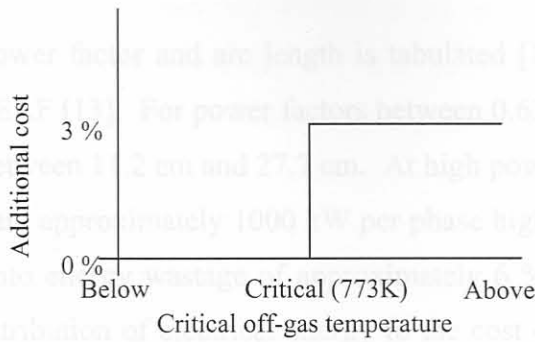


Figure 3.5. Additional cost due to exceeding the maximum off-gas temperature.

3.3.2.7. Slag foam depth.

Several advantages are attributed to foamy slags. These include decreased heat losses to the side-walls, improved heat transfer from the arcs to the steel (allowing higher power input), reduced power and voltage fluctuations, reduced audible noise, increased arc length without increased heat losses, and also reduced electrode and furnace lining consumption. Efficiencies of 60 – 90 % with foamy slags compared to 40 % with conventional slags have been reported [27]. The rate of energy loss in the EAF is also halved by using a foamy slag compared to a conventional slag [27]. The influence of the slag foam depth is however not quantified in any of the above-mentioned references, but just advantages of using a foamy slag layer.

The aim of foaming the slag layer is to ensure that the arc is covered in a slag layer, thus preventing radiation to the sidewalls and ensuring maximum energy transfer to the bath. Although some steel producers aim for a slag layer 3 times the depth of the arc length [18], a slag layer of at least the same depth as the arc length [17] seems to be a more reasonable aim. A slag foam depth much higher than the arc length has no advantages nor disadvantages, except for increased feed consumption in achieving the foam depth. It might however have operational disadvantages since a very large slag volume will have to be tapped into a vessel designed for a much smaller slag volume. A slag foam depth too

low to cover the arc has a negative cost implication, since it will cause inefficient power transfer to the bath and increased heat losses.

The cost contributions of the feed materials relative to the total cost of an EAF tap were

The relation between power factor and arc length is tabulated [17] for a 60 MVA EAF, similar to the modelled EAF [13]. For power factors between 0.63 and 0.88, the arc length varies logarithmically between 11.2 cm and 27.7 cm. At high power factors the heat losses for a conventional slag are approximately 1000 kW per phase higher than for a foamy slag layer. This translates into energy wastage of approximately 6 %. Multiplication of this percentage with the contribution of electrical energy to the cost of EAF operation, yields an additional cost component of 0.9 %. For the purpose of this analysis it will be assumed that a linear relationship exists between heat losses and slag foam depth. For a slag foam depth of 0 cm the additional cost contribution would thus be 0.9 %, and for a slag foam depth of 30 cm or higher, the additional contribution would be zero. The additional cost as a function of slag foam depth is shown in Figure 3.6.

Heat losses due to inadequate slag foaming are not accounted for in Table 3.2 or 3.3, and are not modelled explicitly either. An analysis of the EAF under manual control however revealed that sufficient slag foaming was maintained throughout the tap. To ensure that a comparison of the EAF under manual and MPC control is done under similar conditions, the slag foam depth was included in the simulation study.

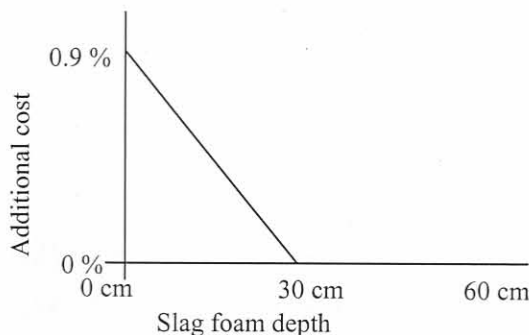


Figure 3.6. Additional cost attributable to slag foaming depth.

3.4. CONCLUSION.

The cost contributions of the feed materials relative to the total cost of an EAF tap were quantified. The relative costs of achieving the defined control objectives were also quantified using typical EAF operational practices as a framework. An addition of all the defined cost components for a specific EAF configuration, would give the total cost of a tap as a percentage, relative to the typical cost of a tap (100 %). The defined cost contribution can be used to determine the efficiency of new EAF operational practices, and also to design controllers minimising EAF cost.

- **Robustness:** All of the basic MPC components can be realized in the domain of a particular plant.
- **Practicality:** It is often the resolution of problems such as achieving control of a nonlinear process, which determines the utility of a controller.
- **Flexibility:** It is widely used, as shown by many real applications in industry, where MPC is commonly and profitably employed [26].

At present MPC is the most widely used multivariable control algorithm in the chemical process industry and in other areas [21]. While MPC is suitable for almost any control problem, it displays its main strength when applied to problems with:

- A large number of manipulated and controlled variables.
- Constraints imposed on both the manipulated and controlled variables.
- Changing control objectives and/or equipment (operator/operator) failure.
- Time delays.

The furnace model used for simulation purposes [13] consists of 13 states and 7 u_i (manipulated variables (MVs) and disturbances). Constraints exist on the controlled variables (CVs) of the EAF due to physical constraints and control objectives. The MVs have limited ranges. MPC will therefore be used as the automatic control strategy to be compared to manual control as is currently used.

The remainder of this chapter will provide the theoretical background on MPC controller design and implementation.