



## Using New and Novel Techniques to Develop a Process Diagnostic System in Basic Oxygen Steelmaking

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## Glossary

BAP	Bath Agitation Process, method of stirring the liquid steel within the BOS vessel using argon or nitrogen gas
BF	Blast Furnace, where liquid iron is made
Blow	Part of the BOS process where oxygen is blown into the vessel
Blowing hard	Affect caused by blowing in the BOS vessel, with the lance too low
Blowing soft	Affect caused by blowing in the BOS vessel, with the lance too high
BOS	Basic Oxygen Steelmaking, process used to convert liquid iron to liquid steel
CBM	Charge Balance Model, used to calculate the required mix of scrap, fluxes and liquid iron for the BOS process
Charging	Process of loading inputs (scrap steel, liquid iron) into the BOS vessel
EB	End Blow, end of BOS process
EBM	End Blow Model, used to estimate oxygen and coolant requirements to get from the IB point to the EB target carbon and temperature
FIS	Fuzzy Inference System, implementation of Fuzzy Logic, within this thesis this is associated with Matlab's Fuzzy Logic Toolbox
FL	Fuzzy Logic, method used to apply language based logic to data processing
Fluxes	Materials charged to form the slag layer in the process
Harsco	Contractor employed by Tata to handle scrap on site, including loading scrap boxes for BOS process
IB	In Blow, approximately 70-80% point in BOS process when steel is sampled
QA	Quality Assurance, set of standards used to ensure quality and consistency within the steel plant
Slag	Mixture of predominantly limestone and silica, used to remove impurities from the steel such as phosphorus
Standage	Term used to describe when large volumes of liquid iron stored in torpedo ladles awaiting BOS process build up
T	Temperature
Tapping	Process of emptying the BOS vessel, by rotating the vessel to pour the steel out through a hole in the side of the vessel.
TF	Trickle Feed (Bunker) used for small additions to the BOS vessel during the Blow
WOBS	Waste Oxide Briquettes, coolant made from waste materials generated at steel works

# 1 Introduction

## 1.1 Process Diagnostic Research

The thesis will outline work done on developing an expert diagnostic system within the Basic Oxygen Steelmaking (BOS) at Tata Steel's Port Talbot integrated steel works. The site in Port Talbot specialises in strip products, where this describes sheet steel for applications in car bodies, tin cans and a wide array of consumer white goods and construction. The flow chart below outlines the chapters of this thesis, briefly describing the main focus of each chapter, and how these sections relate to the BOS process stages.

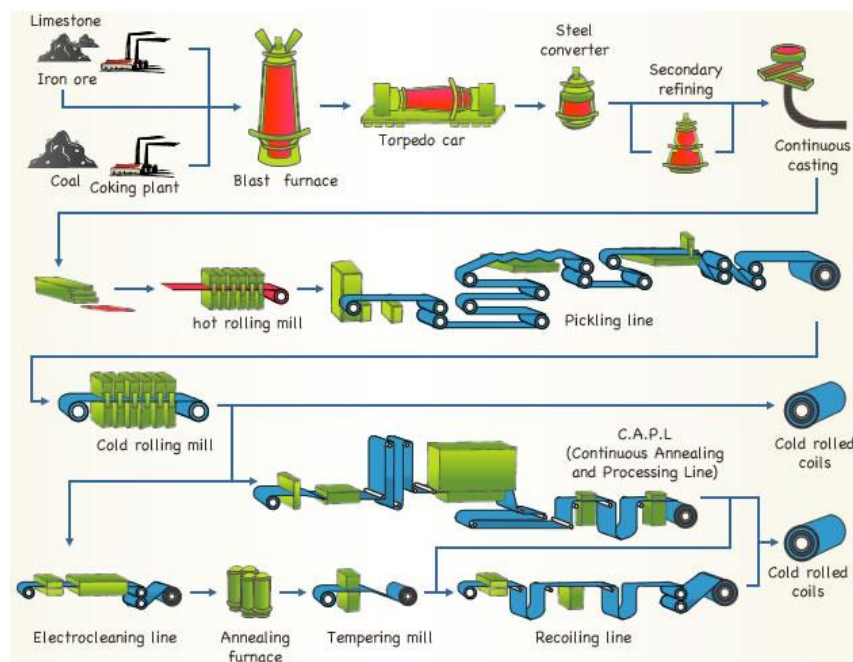
**Table 1.1 - Thesis Chapter Overview**

<b>Chapter 1 Process Introduction</b>	This chapter will outline the process of steel making, briefly introducing the key process and stages
<b>Chapter 2 Literature Review</b>	The literature review covers relevant literature of the various applications of expert systems, within steel making and other industries
<b>Chapter 3 Scrap Adherence Expert System</b>	The chapter looks into a system that has been developed to look in to a specific mix of scrap being charged into the vessel for individual heats
<b>Chapter 4 Desulphurisation Expert System</b>	This chapter looks into the pre-treatment of liquid iron before the steel making process for the removal of sulphur, isolating causes for issues
<b>Chapter 5 End Blow Carbon &amp; Temperature</b>	This chapter looks into a system to diagnose deviations in the steel making process involving End Blow carbon & temperature
<b>Chapter 6 Hard &amp; Soft Blowing Expert System</b>	This chapter details a system that advises adjustments on lance height, for improved process control within the steel making process
<b>Chapter 7 Implementation</b>	This chapter outlines the methods and techniques used to implement the 4 systems developed in an industrial environment.

## 1.2 Introduction to Steelmaking

The production of steel, which in 2014 was 1.64 billion tones worldwide (World\_Steel\_Association, 2014) is primarily carried out in integrated steelworks. Steel is considered to be an alloy of iron (Fe) and Carbon (C), with a C content between 0–1.5% (Ghosh & Chatterjee, 2014). For high alloy steels, there can be up to 10% of other additional alloying elements. Within an integrated steel plant the process consists of molten iron, also known as Hot Metal (HM) being supplied by a Blast Furnace (BF) to a Basic Oxygen Steel (BOS) plant where it is refined into steel. The BOS process accounted for 70.6% of crude steel output worldwide in 2014, compared to that of the Electric Arc Furnace (EAF) which accounted for 28.7%(World\_Steel\_Association, 2014).

Tata Steel Port Talbot and Llanwern is an integrated steel plant, as it is a self-contained site where the entire steelmaking process is undertaken, from iron making, through to steelmaking, hot and cold rolling to hot dip galvanising of strip steel. The site has a capacity of 5.2Mt of raw steel per annum, producing strip products for a wide range of applications, although at time of writing the planned annual production rate at 3.6Mt.



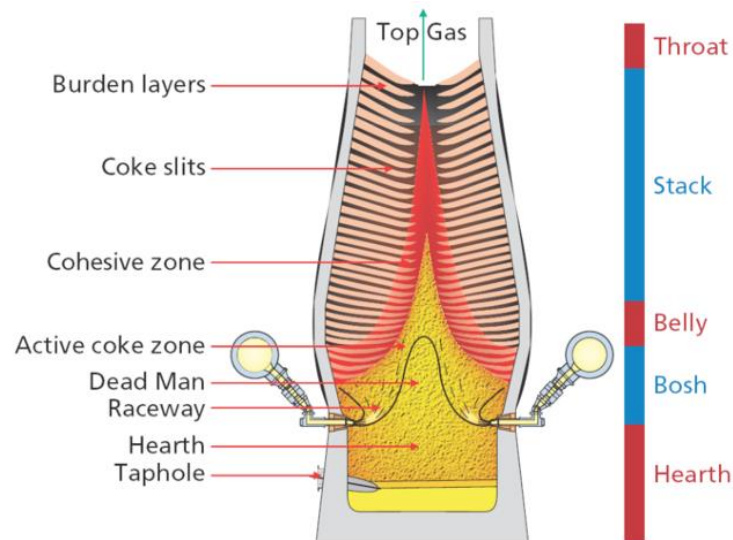
**Figure 1.1 - Steel Production At Integrated Steel Works Reproduced from (Co, 2016),  
Overviewing Key Processing Stages**

The schematic in Figure 1.1 shows the processes within an integrated steel plant, which takes iron ore and other raw materials and make a cold rolled coil of steel. This thesis is focused on the steel converter, which is the point in the process where liquid iron is

converted into liquid steel, ready for secondary refining. To fully understand the BOS process it is best to briefly look into iron making, as the HM generated by the BF is the largest input into the process. Additionally the desulphurisation process will be covered, as this is an intermediary process between the blast furnace and BOS process, and is an integral part of one of the systems developed for this thesis.

### 1.3 The Blast Furnace

The BF is a continuous process that can be operating for several years until it is necessary to shut the process down for refractory repairs or modifications. As shown in Figure 1.2, the BF is filled with material from the top of the stack line where materials are fed in, to the bottom where the iron is tapped, making complete shutdowns of the process difficult due to the quantity of material contained within, which will be in various states.



***Figure 1.2 - Schematic Of A Blast Furnace Reproduced from (Geerdes, 2009), Showing The Varying Material Zones Within***

Within the BF, the sources of iron within the burden are lump iron ore, sinter and pellets produced from iron ore fine particles. The exact make up used varies from plant to plant, depending on cost and availability of material. These materials are charged into the BF along with coke and enriched air. Pulverised coal is blown into the bottom via the tuyeres. The coke and coal along with the enriched air facilitate the reduction of the iron oxides, which provides sufficient thermal energy to melt the solid inputs. To allow the separation of the liquid iron, from the gangue in the feed materials, fluxes are added. These typically include

lime and dolomite, which form a slag. The flux materials are either added separately or as part of the sinter and pellets.

During tapping of the BF, the slag layer sits on top of the denser liquid iron and is separated out within the cast house, before the liquid iron is transported to the steel plant via refractory lined torpedo ladles. The chemistry of the HM, in particular Sulphur (S), Manganese (Mn), Phosphorus (P) and Silicon (Si) content of the HM, along with the temperature (T) are key parameters that can affect the steel plant. The average chemistry of the iron produced at the BF is shown in Table 1.2, along with the chemistry of the steel at the end of the BOS process. As can be seen all values are lower in the steel than in the iron, the largest difference being the C content.

***Table 1.2 - Average Iron & Steel Chemistry For Port Talbot Steelworks***

	C %	Sulphur %	Phosphorus%	Manganese%
Iron	4.5	0.03	0.07	0.2
Steel	0.05	0.01	0.008	0.08

#### **1.4 The Desulphurisation Process**

The desulphurisation process is designed to be a pre-treatment of the HM to remove sulphur (S) before it is charged into the BOS vessel. This is because the BOS process is better suited to removing Phosphorus (P) whilst refining the iron into steel, rather than S. A view of the desulphurisation station is provided in Figure 1.3.



***Figure 1.3 – A Desulphurisation Station At Port Talbot Steel Plant***

The desulphurisation plant has two stations, north and south, which are operated from the same office, though by different operators typically. The process involves a refractory coated lance being lowered into the HM. Once in place a powdered lime (CaO) and magnesium (Mg) mixture is injected into the HM with a nitrogen carrier gas.



***Figure 1.4 Basic Schematic Of Desulphurisation Process, Reproduced from***  
(ThyssenKrupp, n.d.)

The buoyancy of the gas and the powder mixture causes the CaO & Mg particles to rise through the HM, and to heat up. This causes the removal of S from the HM, as the heated CaO and Mg react with the S. The S rich compounds then float out of the HM to form a slag layer on top. To remove this S rich layer of slag, the transfer ladle is tilted, after the injection is complete, and the slag layer is scraped off of the top of the HM using a rabble (rake), as shown in Figure 1.5.





***Figure 1.5 Rabbiling A Ladle At The Desulphurisation Station, Taken At The North Desulphurisation Station At Port Talbot Steel Works***

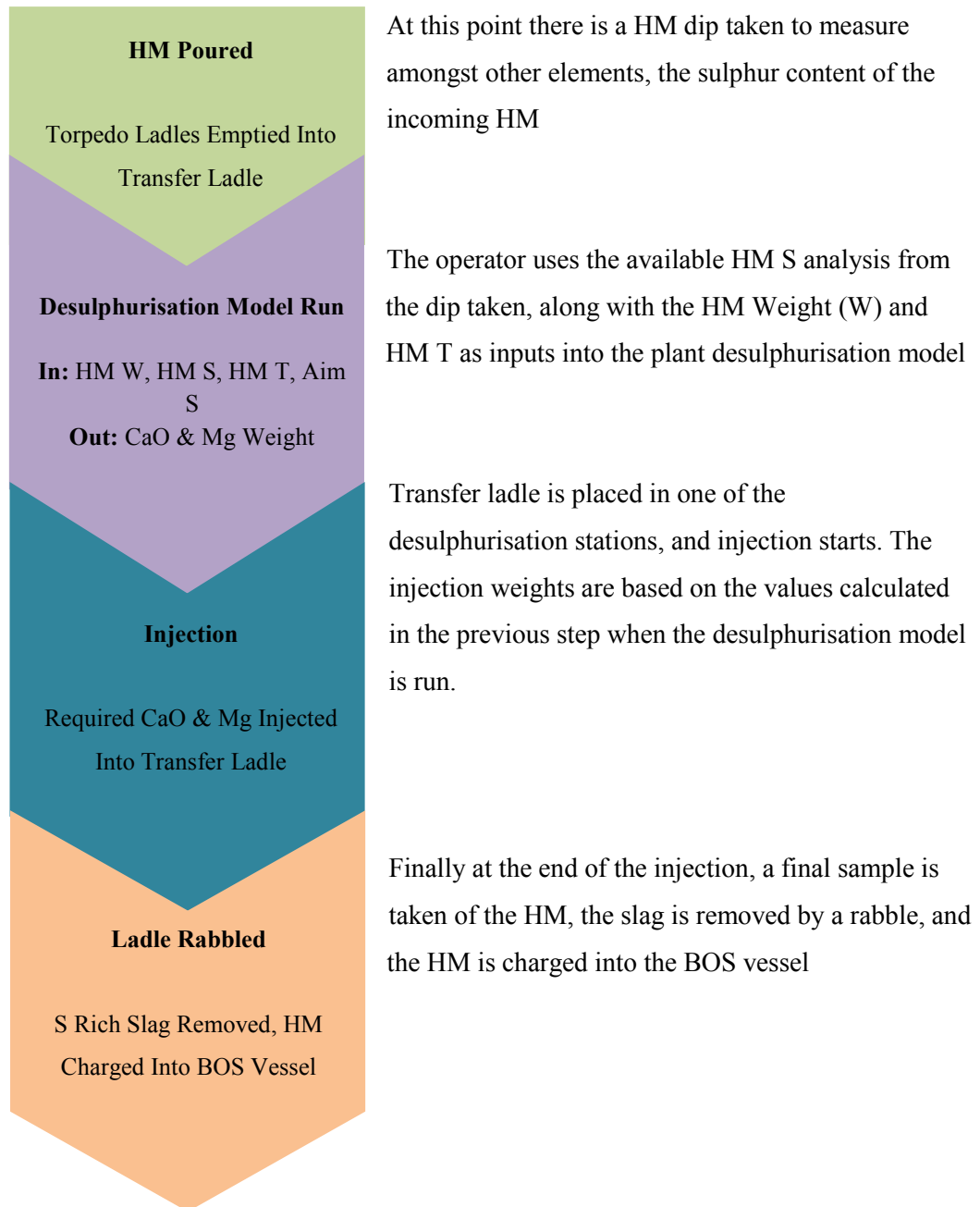
In most steel applications S is seen as being an undesirable element, as it can adversely affect the quality of the steel in the following ways:

- Affects the internal and surface quality of steel.
  - Contributes to steel brittleness and when it exists in a sulphide phase it acts as a stress raiser in steel products.
  - Forms undesirable sulphides which promote granular weakness which can lead to the formation of cracks during solidification.
  - Produces adverse effects on the mechanical properties.
  - Lowers the melting point and intergranular strength and cohesion of steel.
- (Deeley, Kundig, & Spendelow Jr, 1981)

It is most economical to remove the S before it reaches the BOS vessel, as the high Temperature's (T) within the vessel promote reversion of the S from the slag back into the steel. The cost of desulphurisation is reduced at this point in the process compared to after the BOS process, by the increase in desulphurisation efficiency (Gupta & Chatterjee, 1995)

The desulphurisation plant at Port Talbot uses a model that has been developed by a TATA R&D team. Based on incoming HM S levels and Aim S levels it calculates the required Mg & CaO quantities required for the process. The only values that get recorded for this model however are the values that were used; there is no record of what should have

been used, or how the calculation was performed meaning there is no direct way to see if the model was adjusted (correctly or not) by the operator.



The desulphurisation process involves lowering a nitrogen lance into the HM, where powdered CaO and Mg are added into the nitrogen stream and transported into the HM. There are three steps to this process involving the lance flow. First the flow of nitrogen begins, once this is steady the valve from the lime bunker is opened and CaO is added to the nitrogen flow. Once the flow again becomes steady, then the valve to the Mg bunker is opened, and the Mg powder is added to the flow. This then continues until the required Mg is injected, and the process finishes. These three stages of injection are known as start

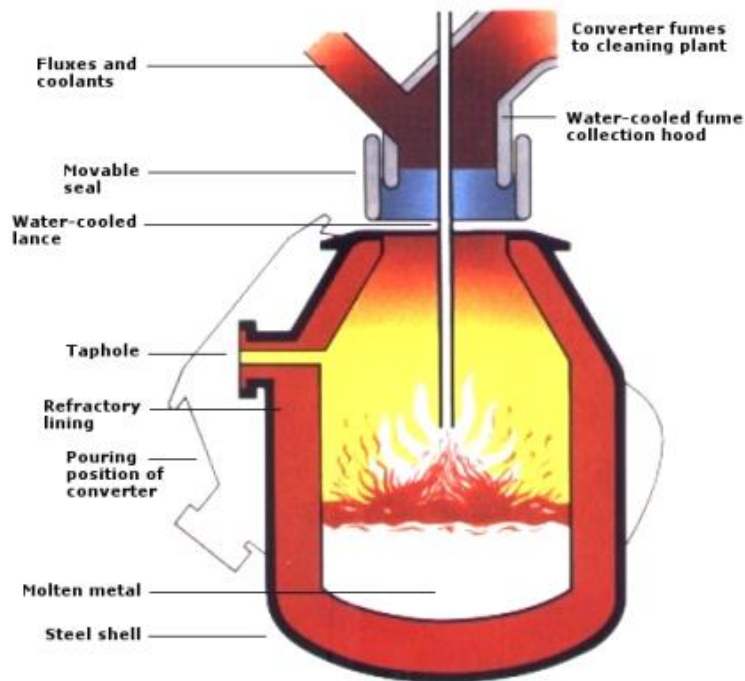
injection, mono-injection and co-injection respectively. These are highlighted if and when they occur as the cause of a delay to the process.

## **1.5 Basic Oxygen Steelmaking**

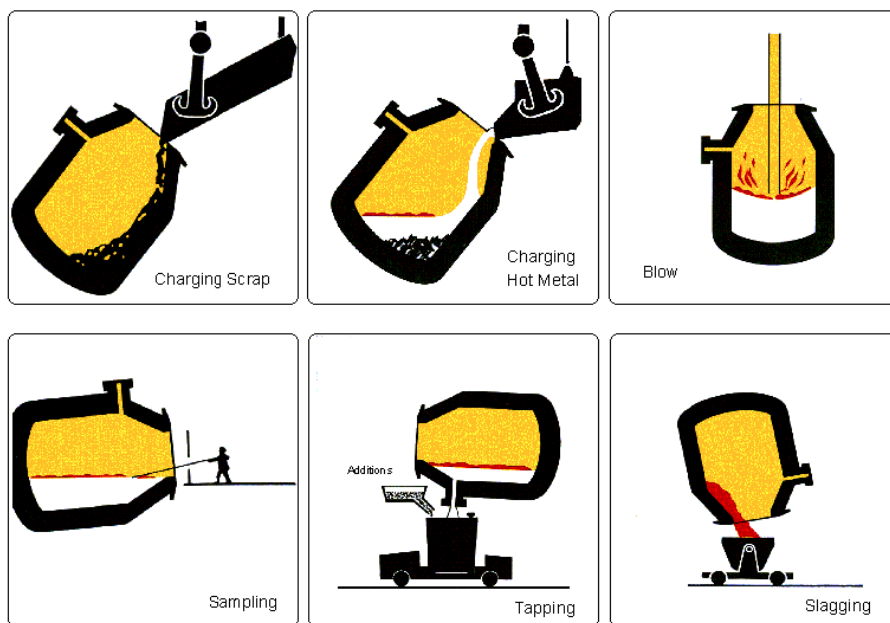
BOS is the first main process in steel processing after the production of HM at the BF. The principal function of the BOS process is the reduction of C and impurity content within the molten iron, by oxidation, to form steel. The conversion of iron to steel within the BOS vessel is a very quick process, with batch times at a typical steel plant with a 300T converter being < 40 minutes. The quick processing time of the converter provides issues for the determination of an exact end point in the process, and effective process control. This is partly down to the inability to have reliable continuous measurements of the batch chemistry and T throughout the process. To better understand the process, the stages, the inputs and the outputs along with the available measurements will be outlined in more detail in the following sections.

### **1.5.1 BOS Process Stages**

The general layout of the BOS vessel is shown in Figure 1.6, outlining the vessel during the process. The key stages of the BOS process are shown in Figure 1.7, although most modern steel plants undertake sampling with the vessel upright, by lowering an automated lance into the vessel for sampling, instead of traditionally rotating the vessel over for an operator to sample the vessel. As can be seen the first two stages are the charging of the scrap and the HM into the vessel. These two constitute the bulk of the metallic charge into the vessel, with only minor additions of iron ore or other Trickle Feed (TF) additions being made during the process. Along with the scrap and HM, flux additions are also charged into the vessel. Depending on the steel plant these are either made before the blow or in the first few minutes of the blow through bunker systems above the vessel. The fluxes are added to allow the formation of a slag layer, which will facilitate the removal of oxides and impurities within the steel.



**Figure 1.6 – BOS Vessel Schematic Reproduced From** (Metallurgyfordummies.com, 2012), **Showing Layout Of A BOS Vessel & Surrounding Equipment**



**Figure 1.7 - BOS Process Stages Reproduced From** (SteelConstruction.info, 2016), **Focusing On Key Stages In The Process**

The main stage of the BOS process is the blow. This is where a water-cooled refractory coated lance is lowered into the vessel, and pure oxygen is blown through a converging diverging multi-port nozzle at a speed of approximately mach 2. The velocity of the oxygen creates a number of impact craters on the surface of the HM, depending on the number of

ports in the lance, which cause droplets of the HM to be thrown up into the slag layer. This creates an emulsion of gas, slag and metal within the vessel, which is where a lot of the reactions within the vessel take place. The metal droplets within the emulsion rapidly increase the available surface area of the HM within the vessel available for the oxidation reactions to take place, increasing the rate of these reactions. The level of emulsification varies throughout the process and depends heavily on the state of the slag and its viscosity along with the lance height. During the blow to improve the mixing of the HM and slag within the vessel and improve the homogeneity of the HM chemistry whilst the oxidation reactions are taking place, argon and nitrogen are bubbled through tuyeres in the bottom of the vessel.

The next stage in the BOS process is sampling, which is typically done twice through the process. Technological developments in sub-lance technology allow a sample to be taken whilst the vessel is in an upright position, without the requirement of an operator to lower a probe into the melt to recover a sample. This is done at approximately 80% through the blow, which is called an In Blow (IB) dip. This is done to check the state of the process and allow fine-tuning of additions and oxygen volumes to reach the desired End Blow (EB) C content and EB T. During this dip, the oxygen flow rate through the lance is reduced although not stopped, as shown at approximately 16:34 in

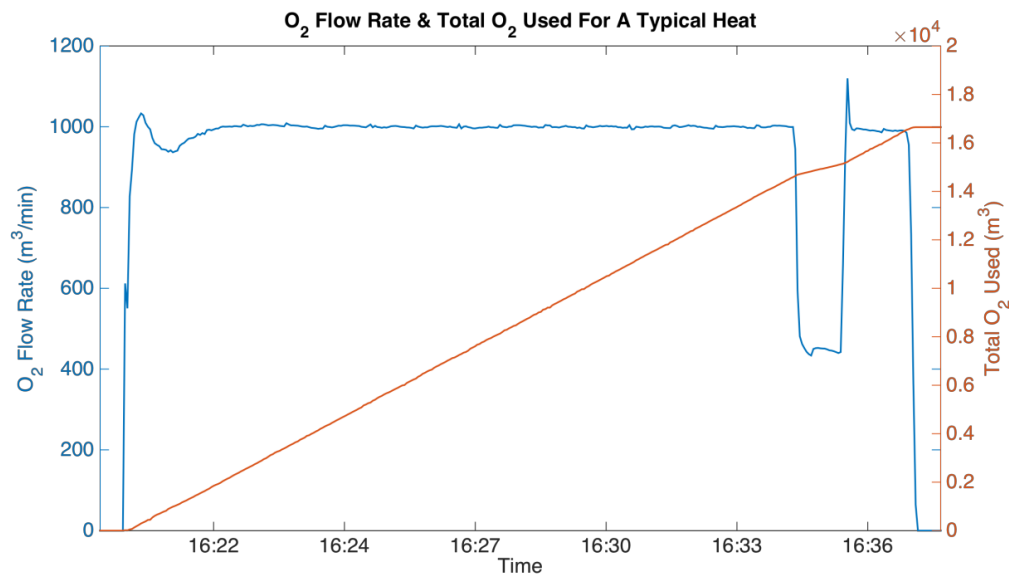


Figure 1.8.

**Figure 1.8 - O<sub>2</sub> Flow Rate & Total O<sub>2</sub> Volume For A Typical Heat At Port Talbot BOS Plant**

A final sample is taken at the end of the blow, this time with the oxygen flow rate completely stopped. This is to check the final chemistry and T of the steel, to ensure it is within the required ranges to allow it to be tapped and sent to secondary steelmaking where

final adjustments to the steel chemistry will be made before casting. If the EB C and or EB T are out of specification, then the heat will be re-blown in order for these specifications to be met.

When the vessel is tapped, a key process aim is to retain as much of the steelmaking slag within the vessel as possible, as it contains a lot of impurity oxides that are undesirable within the steel. Separating the slag and steel at this point means less of the impurity oxides can revert from the slag back into the steel within the secondary steel making processes, where there is potentially a lot of steel and slag mixing processes. This separation is often achieved by the use of slag darts, which have a density between that of the slag and the steel and so float at the interface between the two. These darts are set into the tap hole and stop the flow out of the tap whole at the point when the steel level is sufficiently low that the slag would start to be tapped.

The final stage in the BOS process is slagging, which is where the slag within the vessel is tapped off into a ladle where it will be left to cool. This will then be sent to the metal recovery plant, where any steel left within the slag will be recovered to be recycled into the vessel as part of the scrap charge. It is important to note that the slag before it is tapped off can be used to condition the refractory lining of the vessel. This is done typically by adding doloflux (also known as raw dolomite) - to the slag retained in the vessel, followed by either a blow of nitrogen into the vessel through the lance to splash the slag onto the refractory lining, or by rocking the vessel to wash the lining with the slag. This layer of slag that is applied to the refractory lining will extend the lining life, by wearing prior to the lining itself. Although not done on every heat, this is typically done every 3-4 heats to ensure lining thickness is maintained, and lining life is extended.

### **1.5.2 BOS Process Inputs**

The BOS process has a wide range of inputs, at various points in the process. The charge at the start of the process includes the HM along with scrap and fluxes for slag formation. During the process a number of gases are added to the vessel, including oxygen and argon, through the lance and tuyeres respectively. To fully appreciate the complexity of the process these inputs are explained in more detail in the following sections.

#### **1.5.2.1 BOS Charge**

At the very start of the process the vessel is charged. Generally the charge consists of everything that is loaded into the vessel, before the flow of oxygen through the lance begins. In general this will be the HM, scrap for cooling and the fluxes which are there to

form the slags. The fluxes can also be charged during the blow through the Trickle Feed (TF) bunkers, typically done 2 minutes into the blow. The HM is the main component of the steel making process and is produced within the BF primarily from iron ore, sinter and coke. In most integrated steel works torpedo ladles transport the HM across the site, on a network of railway tracks. When these torpedo ladles arrive at the BOS plant, they are emptied into transfer ladles, which depending on the grade being made are either charged directly into the BOS vessel, or go through a desulphurisation treatment. This is where the low oxygen and high Si and C content of the HM enhance the desulphurisation capability, compared with S removal in the BOS.

The purpose of the added scrap is to provide cooling during the blowing, as the process is highly exothermic. The scrap prevents the HM within the vessel getting too hot and damaging its refractory lining, and achieve aim temperature. As the scrap melts within the vessel it uses a lot of the excess heat energy that is released from the exothermic reactions due to the oxidation reactions that occur. The benefit of this to the steel plant is that the productivity is increased; as the melted scrap becomes an additional source of steel in the process, resulting in an increased tapped steel weight when compared with the charged HM weight. The HM weight is typically 280 tonne, compared with a tapped steel weight of 320 tonne predominantly due to scrap additions.

The last section of the charge is the fluxes that are added to the vessel to form the slag. The purpose of these is to provide the environment within the vessel to allow the impurity oxides to be able to float out of the iron and settle within the slag layer on top of the steel. The flux additions are important as the capability of the slag to facilitate the removal of the oxide impurities has both thermodynamic and kinetic features. However the slag performance is more prominently linked to the kinetics of the slags, as thicker slags slow the reaction times down, decreasing slag performance. Each of the fluxes is added to perform separate jobs within the vessel. Magnesium Oxide (MgO) which is contained within doloflux for example is added to reduce the dissolution of MgO within the refractory walls into the slags, increasing the life span of the refractory lining at the slag line. As with the scrap, the only measurement used for fluxes are the weights, which consists of two values; required and actual. The different fluxes used are now considered.

Lime (CaO), also known as burnt lime due to the nature of converting limestone to lime by calcination, is used to form the main slag bulk. Lime reacts with the Si within the iron to form the slag. Typically the amount of lime used is approximately three times that of the SiO<sub>2</sub>. This ensures enough lime is present to fully react with the Si, as well as enough

free lime to perform reactions with other oxides such as S or P. This describes essentially how basic (alkaline) the slag is, which is very important for P removal, although exact calculation varies between steel plants. The V ratio calculation for Port Talbot considers the ratio of the lime within the slag which is the main basic components, to silica ( $\text{SiO}_2$ ) and phosphorus pent-oxide ( $\text{P}_2\text{O}_5$ ) which are the main acidic components of the slag. Here this gives;

***Equation 1.1 - V Ratio As Calculated At PT Steel Plant***

$$\text{V ratio} = \text{CaO}/(\text{SiO}_2 + \text{P}_2\text{O}_5)$$

Where: V ratio > 1, slag is basic

V ratio = 1, slag is neutral

V ratio < 1, slag is acidic

Dolomet, also known as burnt dolomite, is added to saturate the slag with  $\text{MgO}$ , which reduces the dissolution of  $\text{MgO-C}$  refractories into the slag. The benefit of this is that it increases the life of the refractory lining, especially around the slag line. Doloflux, also known as dolomite, is used in the same way as limestone but preferentially in Port Talbot. When heated it also undergoes calcination which is an endothermic reaction, which cools down the ladle T. With the doloflux, the calcination produces  $\text{CaO}$  and  $\text{MgO}$ , which once again settle within the slag.

Silica is formed by the oxidation of Si, which generally occurs within the BOS vessel when the oxygen being blown reacts with the Si in the HM. If the Si level is particularly low in the HM, or high in impurities silica gravel is added to increase the slag bulks. The silica reacts with lime and dolomet to form the basic steelmaking slag. The high slag bulks within the vessel remove P from the steel in the form of  $\text{P}_2\text{O}_5$ .

Ferro silicon ( $\text{FeSi}$ ) is added to the vessel as an additional heat source, as the oxidation of the Si is a highly exothermic reaction. This means that extra scrap can be charged as there is more excess heat within the vessel to melt it. This is beneficial when iron output from the BF is low, such as periods when repairs are occurring on one of the two BF in Port Talbot. The Si also gets used to form the basic steelmaking slag used for amongst other things, P removal. The downside of using  $\text{FeSi}$  is its high cost. In addition extra  $\text{CaO}$  is needed to balance the extra silica within the slag, which further increases process costs. So typically this is only done when increase steel output is required from reduced HM supplies.



Waste Oxide Briquettes (WOBS) are made up from sludges and grits obtained from dust capture from BOS exhaust gases and sinter fines. This dust is combined with CaO and binders and formed into briquettes. These briquettes are then cured over a period of time to remove all of the moisture before being used as part of the charge. The briquettes are very high in iron content, typically 60% or higher. Due to the reduction of the iron oxides in the process, which is an endothermic reaction, they are a very efficient and cost effective coolant.

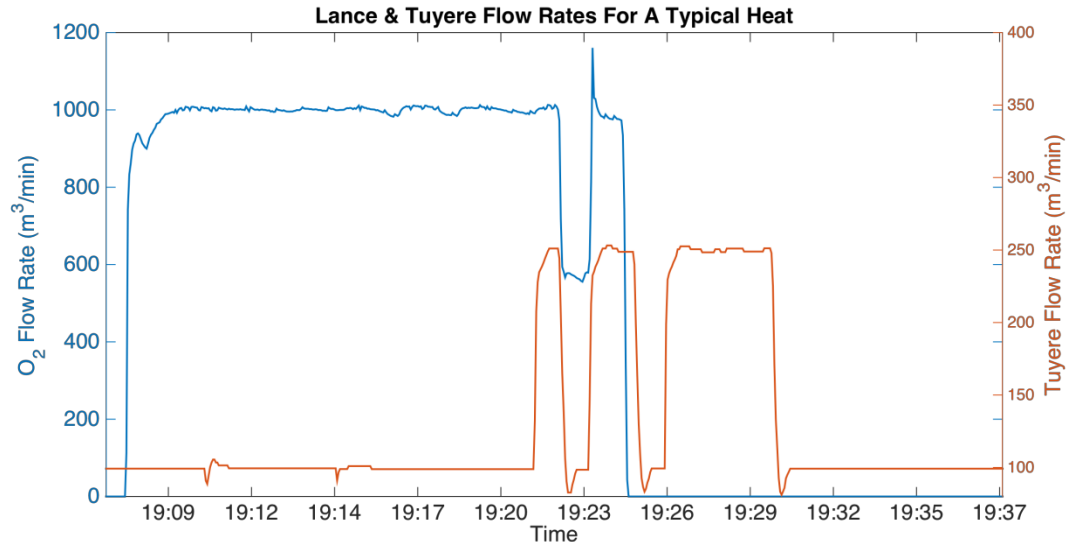
Iron ore is charged into the vessel as a substitute for scrap, as it acts as a coolant. This is due to the reduction of the iron oxide within the ore being an endothermic reaction, which means it requires heat to occur. The cooling effect of iron ore is approximately three times that of scrap, which increases the HM to scrap ratio, as less scrap is needed for cooling. A problem with using iron ore arises from the significant amount of gas released during the reduction of the ore, which increases slag foaming and consequently adds to the chances of slopping. Slopping is the loss of containment of the slag within the BOS vessel. This can decrease yield as well as being a detrimental environmental effect.

#### **1.5.2.2 Injected Gases**

There are three main gases used within the BOS vessel during the blowing section of the process; oxygen, argon and nitrogen. The oxygen is blown through the lance and is there to remove the impurities within the HM through oxidation. The argon and nitrogen are added through the bottom of the vessel through the tuyeres. The prime objective of the tuyeres is stirring of the charge within the vessel as this ensures a better steel/slag mixing within the vessel so improving the rate of all oxidation reactions, providing a more homogenous state. However, in high nitrogen grades, nitrogen is also added for part of the blow through the lance to increase entrapment of nitrogen within the steel.

As has been mentioned, oxygen is used within the BOS process to decarburize the HM to form steel. The oxygen that is used during blowing is very pure, typically consisting of 99.99% oxygen with the rest being nitrogen and argon, to avoid nitrogen pick up in the steel. The main use for argon at this stage in the process is for the Bath Agitation Process (BAP). This gas is used in particular because it is inert and does not react with the steel during the process. The BAP is used for two main reasons; to ensure homogeneity of C removal throughout via stirring of the bath and to prevent the vessel from slopping. It prevents slopping by increasing stirring of the HM within the vessel which collapses the emulsion. Nitrogen is generally used through the tuyeres, as with argon. However for high nitrogen grades to increase entrapment of nitrogen within the steel it is also top blown

through the lance for part of the process, additionally nitrogen is also cheaper than argon and can be used in parts of the blow where nitrogen pickup is not an issue. Figure 1.9 depicts the flow rates of the tuyeres during a heat.



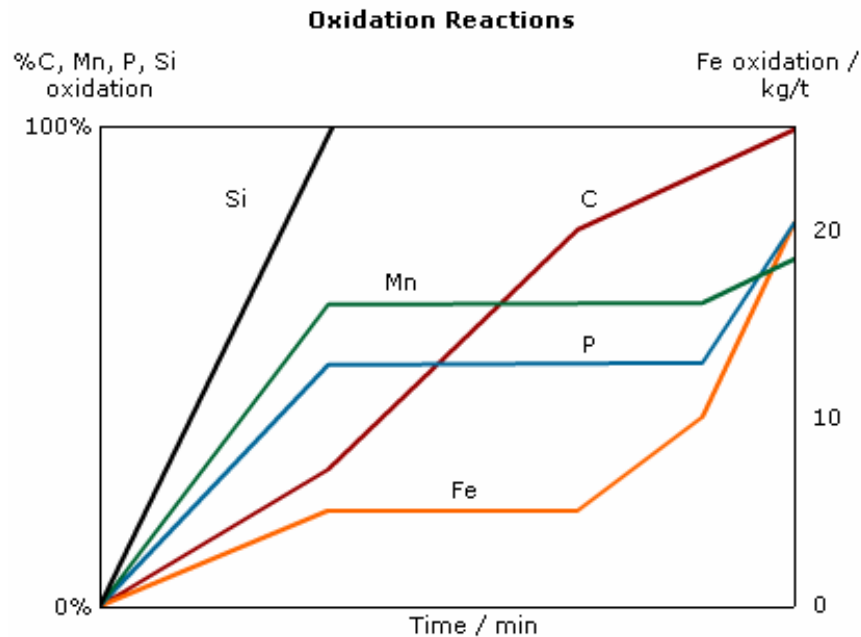
**Figure 1.9 – O<sub>2</sub> & Tuyere Flows Seen Within The BOS Vessel For a Complete Blow In Port Talbot BOS Plant**

It can be seen in Figure 1.6 that the flow rates drop at the same time as the oxygen, which is when the IB and EB dip occur. The tuyere flow also continues after the oxygen stops. This is because the bubbling continues until tapping begins, which is depicted by the final drop in flow rate for the tuyeres. This extra stirring after the oxygen flow has stopped is for P removal. It allows the bath to settle and all slag products to float out of the steel and into the slag layer. It is worth noting that the tuyere flow in this case doesn't drop below 100 m<sup>3</sup>/min. It stays at this low level constantly through charging and tapping to prevent them from covering over with slag and blocking.

### 1.5.3 BOS Process Chemistry

The BOS process involves blowing a jet of oxygen at very high speeds, through water cooled refractory coated lance, into a bath of molten iron. The oxygen combines with the majority of the impurities within the iron. These are then removed either a gas created with a reaction with C which forms CO or CO<sub>2</sub> gas, or as oxides and other compounds which float out to form the slag such as phosphorus and silica. Once the vessel has been charged, the oxygen lance is lowered into the vessel, and the high speed jet of oxygen impacts the melt. During this process, argon or nitrogen is blown through the bottom of the vessel through tuyeres to facilitate stirring of the melt. The pure oxygen then causes a large number of oxidation

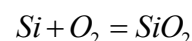
reactions, which refine the iron into steel. Figure 1.10 shows the oxidation reaction rates that occur through the process.



**Figure 1.10 - BOS Oxidation Reactions For Key Elements Within The Steel reproduced from (Steel\_University, 2006), Showing How Oxidation Rates Vary Throughout The Process**

The oxidation reactions that occur within the vessel whilst refining the iron are typically exothermic. These generate enough heat to increase the iron T from its original level of around 1300-1400°C to the steel tapping T of around 1630-1700°C, and would be much hotter without the cooling effect of scrap. There is also sufficient excess heat generated by these reactions to additionally melt scrap iron and steel within the vessel. These typically constitute around 20% of the charge weight. The first reaction to occur is the oxidation of Si within the iron to form silica, shown in Equation 1.2. This is a very important reaction within the BOS process, as the oxidation of silicon to silica ( $\text{SiO}_2$ ) is highly exothermic, which means the reaction generates significant amounts of heat. This heat increases the overall T of the charge, which causes the scrap to melt. The silica also then reacts with the fluxes that are charged, lime and dolomet, to form the basic steel making slag. This slag is then used to help reduce the phosphorus content within the steel, as well as reduce other impurities.

**Equation 1.2 - Oxidation Of Silicon** (Ghosh & Chatterjee, 2014)



The oxidation of C is the most extensive and important reaction within the process. It is the reduction of C content from 4.5% to 0.05% from the formation of CO and  $\text{CO}_2$  gas that

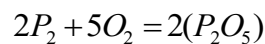
creates the steel. The decarburization reaction is initially slow, as the Si has a higher affinity to oxygen and so oxidizes more readily than the C. Once the Si level begins to drop however, the oxidation rate of the C can increase, as shown by the step change in Figure 1.10. This reaction like the Si oxidation is exothermic and adds heat to the vessel causing it to heat up aiding scrap melting. The oxidation of Mn from the HM is initially fairly constant, increasing as the Si levels within the HM are decreasing, forming MnO. As shown in Figure 1.10 it plateaus, however towards the end of the blow the Mn content decreases.

P removal is important within the BOS vessel, as the oxidizing environment within the vessel favors dephosphorisation. This process is where P oxidizes to  $P_2O_5$ , following the reaction shown in Equation 1.3. The removal of P is improved by a number of parameters:

- A highly basic, lime rich slag (Ghosh & Chatterjee, 2014)
- High slag iron oxide (FeO)
- High slag fluidity
- Effective stirring

The slag basicity describes essentially how basic (alkaline) the slag is, which is very important for P removal. It's a ratio between the basic elements and the acidic elements within the slag, with P removal favouring a more basic (alkaline) slag. As can be seen by Figure 1.10, dephosphorisation increases near the end of the blow as the FeO content within the slag begins to increase. The P removal reaction is:

**Equation 1.3 - Phosphorus Reaction In Steel** (Ghosh & Chatterjee, 2014)



## **2 Expert Systems in Steelmaking Literature Review**

Expert Systems (ES) are a branch of applied artificial intelligence (AI), which mainly began with developments during the mid-1960s. An expert system is a computer program that incorporates the knowledge and reasoning of human experts as a decision tool. The benefit of this sort of system is that users can call upon the computer for specific knowledge and advice as needed, making the process less reliant on expert personnel. Using the built-in knowledge the computer can make inferences and arrive at a specific conclusion for the given problem. The expert system will supply the knowledge and advice for the operators to assess and if possible fix the given problem. Unlike more traditional and orthodox methods that have been used, ES are more powerful and flexible in obtaining solutions to a variety of problems. Potentially they can be provided with the ability to deal with noisy and missing data. Since the start of development into ES the technology has made great progress and has been applied to a very broad range of fields such as geosciences, agricultural planning, military, fault diagnosis, chemistry, management etc. (Liao, 2005).

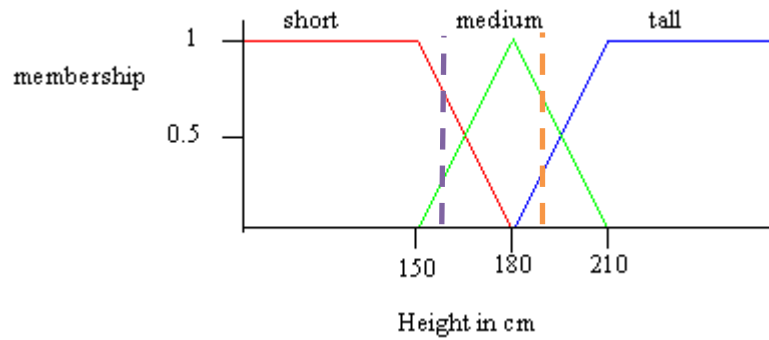
The application of expert systems within the steel industry has grown within the last few decades, as it has with many non-linear processes. This is because it makes the process less reliant on expert personnel, as their knowledge and reasoning is applied to the logic within the computer system, making it accessible to the plant operators always. ES also makes techniques available to comfortably deal with noisy and non-linear data and processes. The application of expert systems to the steel industry has been diverse, and has covered the entire process, from the blast furnaces, through to the BOS or EAF, the casters and even galvanising lines. The applications of ES found to be relevant to this project may be split into two main categories: End Point Prediction and Diagnostics for which the key techniques used will now be discussed.

### **2.1 Techniques**

There has been a wide range of developments that have come under the umbrella of expert systems within the literature, however these are best split into the relevant branches of techniques used, which are predominantly Fuzzy Logic, Neural Networks, Clustering, Machine Learning and Multivariate Statistics. A brief overview of these methods will be presented to facilitate in understanding the reasoning behind the method predominantly used for this project.

#### **2.1.1 Fuzzy Logic**

Fuzzy Logic is a development of multivalued logic, and is used to map a set of inputs to an output space using a set of if then rules. The important thing about these rules is that they refer to a set of variables, which are then described using adjectives. Consider the following example:



**Figure 2.1 - Fuzzy Logic Membership Function Height Example**

Consider the table 2.1 which outlines the heights of 2 people, one at 152cm and another at 183cm. When using the fuzzy logic membership functions shown above, we can assign a membership for each of the 3 categories based on the membership values, and conclude a category that best fits the different people.

The first person who is 183cm, as indicated on the figure above by the orange dotted line, crosses the blue and green lines of the tall and medium categories, but not the red. This indicates that it has a membership of both the tall and medium categories, which is indicated by values above 0 in both in the table below. Where it intersects, these lines define the actual level of membership however, so in this case it is more a member of the medium category and so would be defined as medium height.

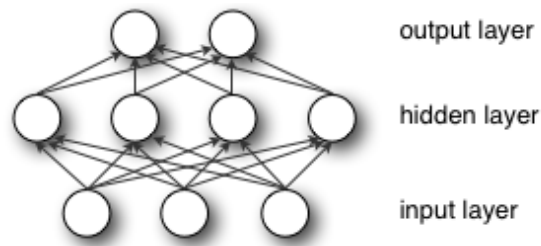
The second person at 152cm, indicated by the purple dotted line, shows a membership of the medium and short categories but not the tall category. As with the previous example, where it intersects these two categories defines the membership values. As the table and the figure shows, due to this, 5ft would be inferred as being short in this example.

**Table 2.1 - Fuzzy Inference Results For Height Example**

	<b>Short</b>	<b>Medium</b>	<b>Tall</b>	<b>Result</b>
<b>183cm (6ft)</b>	0.00	0.96	0.04	<i>Medium</i>
<b>152cm (5ft)</b>	0.95	0.05	0.00	<i>Short</i>

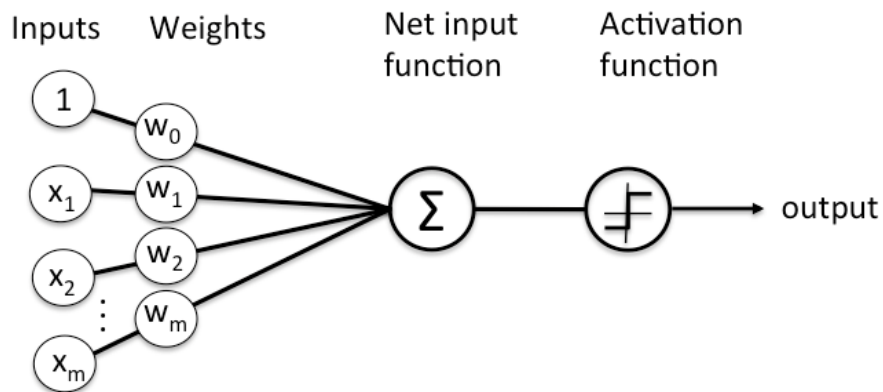
### 2.1.2 Neural Networks

Neural Networks (NN) are a class of computational models, loosely based upon the neural nodes and connections seen within the human brain. Typically there are multiple layers of nodes to facilitate in the learning ability of the neural network, there is an input layer where the required data is input into the network, hidden layers where the bulk of the data processing is done within the network, and the output layer where the network outputs the results. This layered structure is shown below in Figure 2.2.



**Figure 2.2 - Neural Network Structure Layout Reproduced from** (Skymind, n.d.)

The inner workings of each of the nodes is shown below in Figure 2.3. The weights shown in the figure are values used to manipulate the data inputted into the node, and will either amplify or dampen the input. The net input function is the sum of all the inputs after the weights for each of the inputs have been applied, and is used as the input into the activation function for the node. Finally the activation function is used to determine if the node generates an output, and the magnitude of the output.



**Figure 2.3 - Diagram Showing Workings Of Neural Network Node Reproduced from** (Skymind, n.d.)

An important aspect of NN is the ability to learn unsupervised, which is where no labels are applied to the data, and the network learns by comparing the outputs generated by the network to the values that are expected from a training dataset. There is a wide range of approaches used to train the neural networks, but these are outside of the scope of this thesis.

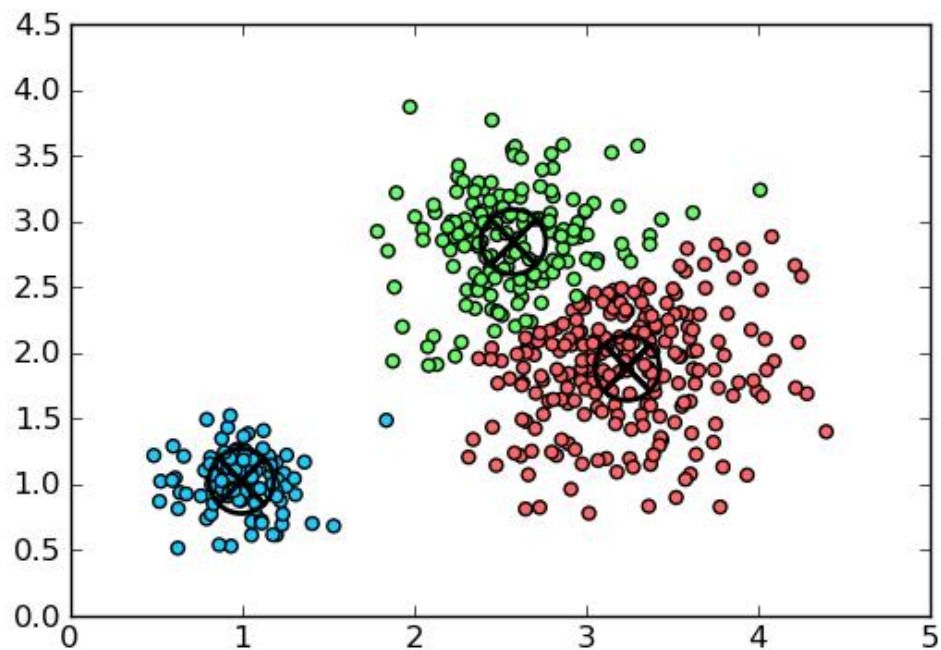
During training the outputs of the network will be compared to the expected outputs from a training set of data. If the error is outside of the target range, then whichever training method is used, it will result in the activation functions and weights across the network being adjusted, which nodes and by how much the values are adjusted is dependent on the method used. Through the adjustment of the weights and activation function, the network will be trained to estimate the required output based upon the provide inputs.

### 2.1.3 Clustering

Clustering is a method used to process a collection of objects into groups which share a level of similarity. The exact measure of similarity is down to the method used, but a good example is distance between the centroid point of the group and the object across all dimensions.

The example shown below in Figure 2.4 shows a collection of 2 dimensional objects that have been grouped into 3 groups. The crosses mark the centroid points for each of the groups, and are used to determine which group each object fits in.

When there is 2 dimensional objects to group, as shown below, it can be fairly easily done visually without the need for any calculation. The power of clustering algorithms however is the ability to group collections of objects, where the dimensions exceeds 3 as this is no longer possible to do visually.



**Figure 2.4 - Data Clustering Example For 2 Dimensional Objects**

For diagnostic purposes clustering is very powerful as it can be used for classification of the condition of a process for example.



### **2.1.4 Summary**

This thesis focuses on the development of expert diagnostics systems, with implementation in the steel industry, in doing so there were several key requirements for the approach used:

1. Transparency of inner workings of any system developed
  - a. This was primarily due to operator and manager scepticism over ‘black box’ modelling
  - b. Systems additionally needed to be designed to facilitate operator knowledge development
2. Capable of applying expert knowledge to the expert system logic
  - a. There was a large number of highly knowledgeable experts at the steel works that could be utilised to develop the expert system

Neural networks fail on point one, as they are a black box modelling technique, in that the reasoning behind the optimised weightings and activation functions cannot be easily interpreted to facilitate in the understanding of the inner workings of the system. This was additionally a technique that the management at the steel works were aware of, and had bad prior experience and so was avoided for this project.

Clustering additionally fails on point one, as although the training mechanism is easier to understand than neural networks, as the results can be displayed visually easier, the reasoning for the centroid points still isn’t sufficiently transparent to allow easy integration with personnel at the steel plant, and so this technique was also avoided for development for this project.

This indicated that fuzzy logic was the primary approach for expert system development for this thesis. Fuzzy logic is very transparent, as it is in its simplest form a set of if then statements to reach a conclusion. Additionally, these if then statements can be defined based on natural language as explained previously, and so this technique fitted the two main requirements well.

## **2.2 Expert system applications**

The use of expert systems within industrial environments varies significantly depending on both the industry and the application, although they can be grouped into two key themes. These themes are primarily end-point prediction and diagnostics.

### **2.2.1 End-Point Prediction**

The use of expert systems for end point prediction is based upon the application of a machine learning methods such as neural networks. This can act as an indirect measurement in some applications and output estimated process data. End point prediction using expert systems has been used on the BOS for T and C content calculations (Cox, Lewis, Ransing, Laszczewski, & Berni, 2002). This technique has also been applied to EAF for T, C and manganese estimation, which can help to reduce electricity consumption by reducing over heating (Ferna et al., 2008; Ping & Fu-li, 2007), or to reduce processing times and cost by reducing sampling rates during processing (Das, Maiti, & Banerjee, 2010). It has also been applied to the BF to estimate the Si and S content of the hot metal being tapped and used in conjunction with a Programmable Logic Controller (PLC) to adjust input parameters to improve efficiency and yield (Radhakrishnan, 2000).

Although an important area of expert system development, as this thesis is focused on the development of expert diagnostic systems, end point prediction will not be further considered.

### **2.2.2 Diagnostics**

The area of diagnostics involves identifying abnormal operating conditions, and dealing with the process before any damage or loss of yield occurs, such as a breakout in the caster. Within the steel industry diagnostic systems have been developed for a number of applications, those for the coke ovens (M Saiepour et al, 2008), casters (Zhang, 2003; Zhang & Dudzic, 2006a, 2006b) and blast furnaces (Tian & Wang, 2010). However, as previously stated, the approach used for development within this thesis has been Fuzzy Logic, for which no other diagnostic approaches within the steel work were found thus research was conducted into applications within other industries.

## **2.3 The Industrial Application of Fuzzy Logic Expert Systems**

The oil and gas industry has hosted a large amount of research into expert systems, due to the potential cost of any equipment failures and related environmental damage. A fuzzy inference expert system was developed for the crude oil desalination process, where water and salt are removed from the crude oil (Zahedi, Saba, al-Otaibi, & Mohd-Yusof, 2011). As with many industrial chemical processes this process was complex and so an extensive rule base was developed for the Fuzzy Inference System. The Mamdani FIS was used, with triangular membership functions for the inputs and trapezoidal membership functions used for the outputs of the system. The offline model produced showed good inference capabilities with successful diagnosis. The system will need to be optimized by adding/changing or removing rules within the rule base before being implemented online within the

process. The system's overall aim was said to be to assist operators in swiftly identifying faults, which will inevitably help to reduce the economic and health impact of any plant failures or faults.

Fuzzy logic expert systems have also been applied to the power industry, in assessing power transformer condition (Flores, Mombello, Jardini, Rattá, & Corvo, 2011). This system was developed using type two fuzzy inferences, using the interval type over the general type due to improved computational efficiency. The system was designed to summarize each input using membership functions, into a small number of sections such as good, bad or terrible. These are then summarized further into an overview of the transformer condition, by essentially averaging the condition of each section into one output. The system showed effective inference using this method, with a few successful case studies.

The chemical industry has also undertaken a great deal of research into expert diagnostic systems due to the complexity of the processes undertaken. An example of this is the FIS developed to diagnose a Continuous Stirred Tank Reactor (CSTR) (Dash, Rengaswamy, & Venkatasubramanian, 2003). This system used fuzzy inference of trends within the data to isolate the fault and diagnose it. The trends within the data were isolated for each fault using interval halving, which recursively keeps halving the signal length until a quadratic function can fit well within the error bounds represented by the noise. The noise levels within the data set are estimated using wavelet analysis. Under the assumption that the fault signatures are broadly the same under different severities only one representative signature for each sensor for each fault is stored. Fuzzy logic is then used to infer the magnitude of the fault, using modeled fault cases for comparison. The system diagnosis was shown to be robust, capable of dealing with large and small severity faults correctly. However due to the data driven nature of the diagnosis, poor fault resolution results when simultaneous faults with similar fault signatures occur. This issue can be overcome by introducing expert knowledge into rule base along with the trend inference, instead of the data derived rule base, and so will be considered for the application of fuzzy logic for the work developed in this thesis.

## **2.4 Summary of the Literature Review**

The steel industry has used expert systems for a wide variety of applications, from end point prediction to diagnostics with varying degrees of success. Within other industries such as Nuclear & Chemical industries there has also been a lot of development into expert diagnostic systems. The aim of these systems being to assist operators, in dealing with these complex processes, by identifying and advising on occurring faults. As has been mentioned, there have been a wide variety of techniques used, due to the varying application and requirements of the systems.

There is a place for machine learning techniques within ES at the BOS, as they excel at end point prediction and could be very applicable to missing data (Ferna et al., 2008; Ping & Fu-li, 2007).

However due to the lack of transparency and the high level of inconsistency in both the process state and the quality and availability of data within the steel making process, this approach isn't directly applicable to this project, where diagnostics is the focus.

The application of Fuzzy Inference techniques has been very broadly and successfully applied with expert diagnostic systems. The technique has been very popular due to its transparency for the operators, as it allows them to see the logic behind the inference and allows flexibility on fault definition. Recent developments in this area, have been in using genetic and evolutionary algorithms, which give the fuzzy inference system a learning capability, by allowing rule generation from data sets. The use of Fuzzy Inference is very applicable to the BOS ES, especially for the main fault identification system, as it can deal with very large rule bases for the faults. This approach also lends itself to being designed to reflect expert knowledge and process logic, making it a powerful transparent tool.

#### **2.4.1 Proposed Research Methods**

There have been two separate, previous attempts to design and develop a diagnostic expert/advisory system for the BOS within TATA Steel Europe. Initially this development occurred in Ijmuiden in the form of the ConvEx system from 1992-2000. The specifications for the system were made by close interaction between BOS2 personnel and the steelmaking research department, which was responsible for the development of the system. The expert system software Gensym's G2 (Gensym, 2016) was utilised. Since the research department did not have the expertise to develop such a system, a software company that specialised in G2 programming, Selmers, was contracted to develop the system in collaboration.

However the system development was very low down on the list of plant priorities. The use of outside contractors to resolve every problem with the system meant that the system development took an extended period; the system took 8 years in total to develop. As the development was undertaken with a restricted budget there was not sufficient resources to write adequate user manuals, functional descriptions or to test the functionality of the system. Due to the lack of sufficient internal personnel needed to maintain and update the software the system became outdated and was never implemented online. In all of the above the key element that needed to be addressed was that the functional requirements of the system were never clearly defined.

A second attempt at a BOS expert diagnostic system was made by the Research Development and Technology (RDT) team for the Scunthorpe plant. This system was designed to consider the T and C requirements of the process. It was intended to identify when and where in the process either of these two parameters were out of specification. This particular system used Cogsys Pilot (Morgan, 1990) software. At the time of writing the company no longer exists so no external support is available for the software. The system used an extensive rule base for the tracking of C and T parameters,

allowing fault identification when these were out of specification. The knowledge base of the system and the scope covered were seen to be too narrow for the application, as the BOS process can be very dynamic. It can be influenced by market conditions for example, as this can vary amongst other things the coolant materials used. This created an environment within which the operators distrusted the system, as it was found to be inaccurate for several situations within the process. The low level of operator interaction with the system and perceived distrust by them in its accuracy led to the system being disused and removed from the steel plant.

It was clear from the previous TATA based work that the development of a single system to provide a diagnostic capacity for all aspects of the BOS process was going to be exceptionally difficult, due to the complexity of the process. The development of separate diagnostic modules for individual aspects of the process, with the long-term aim being to combine those with a mutual interest was being feasible. This approach, which was adopted in this research programme, allows further expansion of the project as work progresses.

The literature review on expert systems has shown a body of research in end point prediction, including within the BOS process. However the more successfully reported applications were based upon using some form of black box modelling technique, to data mine the available process data to understand and reflect the underlying process interactions. However most of the papers have not addressed the essential element of how the operators interacted and managed these systems. Understanding and developing this interaction will be very important during this project to ensure the systems developed maximise the impact on the process. To facilitate the adoption of any systems developed during this project they will be made with transparency of the logic behind the systems to the operators in mind. This does however mean avoiding, where possible, black box modelling techniques.

The clear majority of the information needed for the development of the system is the knowledge from the expert personnel operating the processes. The most promising approach that has been found for this application during the literature review was one that utilises some form of fuzzy logic. The ability to deal with uncertain boundaries, such as those used by experts to describe process states and parameters, is exceptionally important as this is the main source of process information for the systems. Therefore, where applicable, one of the main approaches is going to be the application of fuzzy logic to help discern the expert knowledge into programmable logic.

### **3 The Scrap Adherence Expert System**

After the HM, scrap is the second largest source of iron in the steel making process, typically accounting for 15-25% of the total metallic charge. Scrap is iron or steel that has been recycled. This includes material obtained from internal sources generated from skulls, damaged strip or cuttings. Skulls are sources of solidified iron or steel generated within the process, from the iron or steel ladles. It also includes material sourced externally at the end of life of a product, ranging from old industrial equipment, to incinerator scrap or even bales of used tin coated steel cans. The chemical composition of the scrap is incredibly important in the manufacture of steel, as the introduction of tramp elements such as copper, molybdenum, tin and nickel cannot be oxidised and hence cannot be removed from the metal, only diluted (Freuhan, 1998). It is due to this that the scrap used within the steel making process is graded depending on its origin and its chemical composition.

The type of scrap that is charged into the BOS is very dependent on the grade of steel being made. Generally high quality grade steel will have to be very low in S and residuals; meaning extra clean scrap boxes should be used to prevent the addition of any tramp elements or excessive S to the steel.

#### **3.1 Scrap Charging Process**

A contracted company called Harsco are responsible for all of the handling and processing of scrap on site. This ranges from externally sourced scrap being brought into site, to internally generated scrap such as skulls, which are processed by Harsco at the Metal Recovery Plant on site. They are also responsible for loading the scrap boxes for each heat at the BOS with the required mixture and weight of scrap. At this stage there are two main considerations: the current End Blow  $\text{Al}_2\text{O}_3$  & S levels and the current scrap type availability.

Since scrap boxes are typically loaded 1-3 heats in advance, depending on speed of work, Harsco need to know the required scrap mix in advance. The key stages in the charging of scrap into the BOS vessel where any deviation in the required scrap mix could occur are by the Charge Balance Model (CBM) coordinator or by Harsco. These affects and the knock on deviations on scrap adherence are explored in the sections that follow. The initial development that is required for the scrap adherence system to benefit the steel plant was therefore the monitoring of the scrap mixes and weights supplied by Harsco. This will then

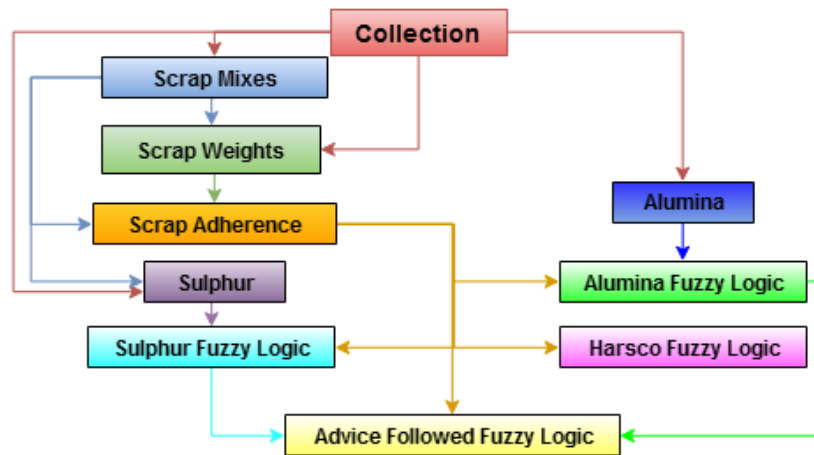
be compared with the scrap type and mixture requested by the steel plant by the CBM coordinator.

Each scrap mix has a known chemistry based on the known composition of the varying scrap types used; those with lower S and alumina ( $\text{Al}_2\text{O}_3$ ) content are considered to be cleaner and have a higher associated cost with their use. The alumina content considered within the scrap will all be from primary aluminium sources such as aluminium cans found within the incinerator and tin can bale scrap types. The CBM coordinator will balance the grade requirements for S and alumina for each heat, between incoming HM quality and scrap mix. Each grade has a default scrap mix to be used based on these requirements, although these will occasionally be adjusted by the CBM coordinator for a number of reasons, such as insufficient stocks of specific scrap types.

The aim of this section of the scrap adherence expert system is to ensure the type and mix of scrap requested by the steel plant is supplied by Harsco. This is important, as the scrap mix selection has a direct impact on the quality of steel produced within the vessel. The use of poor quality scrap will clearly have a detrimental impact, both in terms of steel quality and the measures that have to be taken within the BOS process to make good any deficiencies. Alternatively the use of excessive amounts of high quality scrap for low quality steel grades will have a detrimental effect on the financial performance of the plant. The other area of development required relates to understanding the logic behind the correct scrap mix selection by the CBM coordinators. This is important as it will take into account the grade of steel being made and also address any issues arising within the steel from poor quality scrap. This understanding will allow a system to be developed and deployed to assist the CBM coordinators in the task of correctly selecting the scrap mix to be used, producing a more efficient BOS operation so making a positive financial impact on the process.

### **3.2 Expert System Structure**

The structure of the expert system developed will now be outlined, to allow the structure and processing to be better understood. Each of the sections used for data handling and processing shown in Figure 3.1 will be considered in this section.



**Figure 3.1 - Overview of data handling and processing**

### 3.2.1 Data Collection

The data collection for this system involves 2 main sections, collection of data from the plant databases (PSMET & PSSUP), and from log files written in previous runs of the expert system.

PSSUP is an Oracle RDB database version 7.3, which is a level 2 plant production database for discrete data. PSMET is also an Oracle RDB database version 7.3, however is a BOS plant level 3 Manufacturing Information System (MIS) for discrete data, used for long term archiving and reporting functions. The tables accessed within the respective databases for the required plant data are listed in **Figure 3.2**.



Collection
<b>PSSUP</b>
SCRAP_MODIFIER
SCRAP_MIX
SCRAP_AVAILABILITY
SCRAP_BOX_LOAD
<b>PSMET</b>
HEAT_PSSUP
SLAG_ANALYSIS
METAL_ANALYSIS
PROGRAM_ANALYSIS
MAT_CHARGED
DES_TREATMENT
COORD_LINK
TORPEDO
AIMS
<b>Matlab Workspace</b>
lag
laga
sag
saga
output

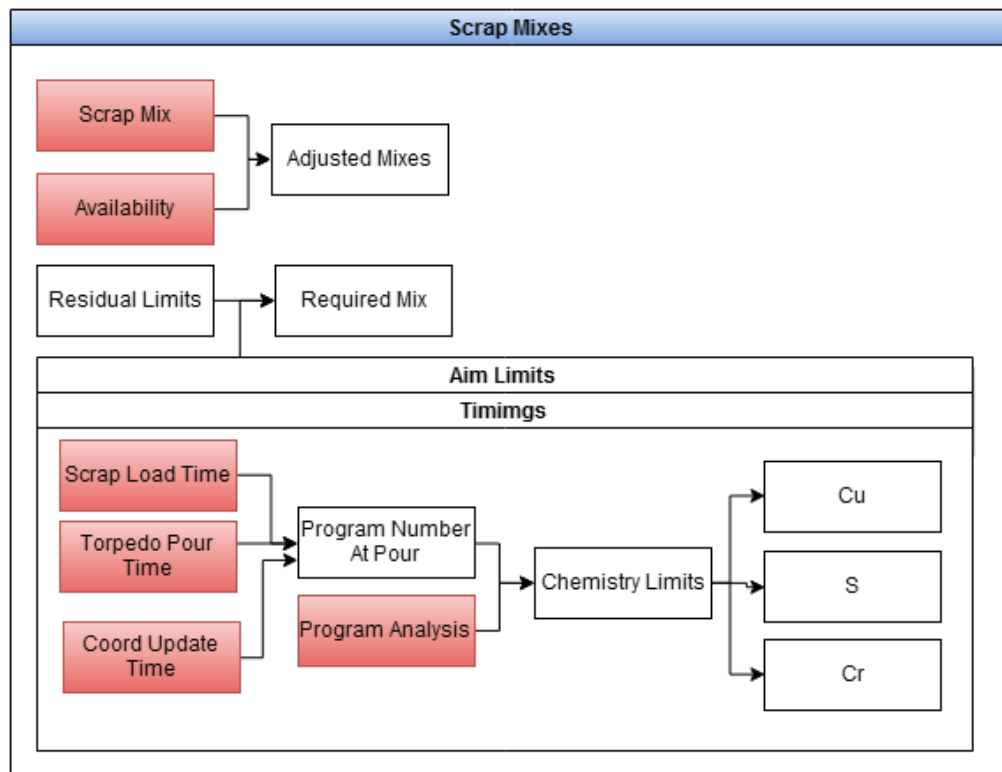
Within PSSUP the SCRAP\_ tables, which will be discussed in more detail, contain information surrounding the scrap. MODIFIER contains information about which scrap type should be used to replace another if there are low stocks. MIX contains all the scrap mixes associated with the various grades and weights of scrap box used. AVAILABILITY contains a number between 0 and 100 representing % availability of each scrap type. BOX LOAD contains information on which scrap mix was loaded into the scrap box.

The PSMET tables all contain data from plant. HEAT PSSUP contains data used for associating timings with heat numbers. SLAG ANALYSIS contains slag analysis lab results for each heat. METAL ANALYSIS contains all of the cabin and stage lab steel analysis results. PROGRAM ANALYSIS contains a list of program numbers, which are associated with a particular heat, and the limits of certain elements such as copper and sulphur for specific points in the process. MAT CHARGED contains all weights for all materials charged into the BOS vessel. DES TREATMENT contains treatment information from the deuslphurisation stations, such as injection weights. TORPEDO contains torpedo ladle information, such as timings and weights. The AIMS table contains the chemistry and temperature aims of the steel for all points in the BOS process.

**Figure 3.2 - Collected data for expert system**

### 3.2.2 Scrap Mixes

The scrap mix section of the expert system is designed to calculate firstly the available scrap mixes, and secondly the required scrap mix based on grade requirements as shown in Figure 3.2. Red boxes in the figure below indicate data acquired directly from the databases with little or no pre-processing. Residual elements that are of key focus within scrap mix selection are particularly S, Copper (Cu) and Chromium (Cr).



**Figure 3.2 - Scrap Mixes Module Processing Stages. Showing Data Sources & Processing Used To Calculate Required Scrap Mix**

### 3.2.2.1 Adjusted Mixes

As the figure above shows, the adjusted scrap mix is calculated by comparing the preset scrap mixes from the Scrap\_Mix table in PSSUP with the availability of scrap from the Scrap\_Availability table in PSSUP. The actual mix required is extracted from of the Scrap Mix table, which contains for each scrap mix the required scrap weights for a total demand weight of any of the following: 20, 30, 40, 50, 60, 70, 80, 85, 90, 95 and 100 tonnes. Table 3.1 shows some data from the Scrap\_Mix table to give some insight into the data. The Scrap\_Mix table contains separate rows for each scrap type, for each individual scrap mix, 0 below defines the dirty scrap mix, and for individual weights. The table below shows the data for a 20T dirty scrap box. The make up material column indicates the appropriate replacement material to be used if the availability of some scrap types are low, in this case mill products is suggested.

The total weight of scrap demanded is rounded down to the nearest scrap mix weight as any excess will be made up with filler materials, which are predominantly mill products. These values are then finally adjusted based upon values for availability from the Scrap\_Availability table, which contains values between 0 and 100 for each scrap type. If

the value is below 100 it then has a preferred replacement material, which is indicated. An example of data contained within the Scrap\_Availability table is shown in Table 3.2.

**Table 3.1 - Scrap\_Mix Table For Scrap\_Box\_Type = 0 And Scrap\_Box\_Weight = 20t**

<b>MATERIAL_REFERENCE_NUMBER</b>	<b>WEIGHT</b>	<b>MAKE_UP_MATERIAL</b>	<b>MATERIAL_DEFINITION</b>
SCRAP_A	3	0	Scrap - Turnings
SCRAP_B	0	0	Scrap - A Steel Skull
SCRAP_C	0	0	Scrap - C Steel Skull
SCRAP_D	0	0	Scrap - O/Size. Demo. Cobbles
SCRAP_E	10	0	Scrap - A Desulph Scrap
SCRAP_F	0	0	Scrap - C Desulph Scrap
SCRAP_G	0	0	Scrap - Cold Iron
SCRAP_H	0	0	Scrap - Tundish Skull
SCRAP_I	0	0	Scrap - Tin/Steel Can Bales
SCRAP_J	2	0	Scrap - Incinerator Scrap
SCRAP_K	0	0	Scrap - HBI
SCRAP_L	0	0	Scrap - Detinned Bales
SCRAP_M	0	1	Scrap - Mill Products / Slab
SCRAP_N	5	0	Scrap - Loose and Light
SCRAP_O	0	0	Scrap - Chrome Rolls
SCRAP_P	0	0	Scrap - Contaminated Iron

The scrap mix table in *Table 3.1* contains the ratios of each of the scrap mixes the steel plant uses, for a range of different total scrap box weights up to 100 tonne. The scrap availability shown below in **Table 3.2**, contains a value between 0 and 100 as a percentage for each scrap type used on plant, which indicates the stock availability of the scrap. If the value is below 100, the remainder will be supplied by the scrap type indicate alongside in the substitute material column within the table.

**Table 3.2 - Scrap\_Availability Table For A Selection Of Scrap Types Used At Port Talbot BOS Plant**

MATERIAL_REFEREN CE_NUMBER	AVAILABLE	SUBSTITUTE_MAT _REF_NUMBER
SCRAP_P	0	SCRAP_D
SCRAP_O	0	SCRAP_M
SCRAP_N	100	
SCRAP_M	100	
SCRAP_L	100	
SCRAP_K	0	SCRAP_M
SCRAP_J	100	

### 3.2.2.2 Required Mixes

There are five separate scrap mixes used within the Port Talbot steel works, based upon grade aims for S, Cu & Cr. These limits and their respective names are shown in Table 3.3.

The analysis shown below, will show an example where the particular heat requires a Normal scrap mix, as the S is between 0.025 - 0.02, and the Cu & Cr is below 0.1. The logic for this is depicted by the yellow rows in each of the tables in this section.

**Table 3.3 - Scrap Mix Grade Aims For All Scrap Mixes Used At PT BOS Plant**

	S	Cu	Cr
Dirty	0.04 – 0.03	-	-
Normal	0.025 - 0.02	-	-
Normal High Residual	0.025 - 0.02	>= 0.1	>= 0.1
Clean	0.018 – 0.012	-	-
Extra Clean	<= 0.01	-	-

The nature of the process makes it very changeable, with the specific grade of steel assigned to a batch of steel potentially changing many times between the torpedo ladle arriving in the steel plant and the steel being cast at the casters. This will be down primarily to processing issues such as poor chemistry, or plant issues such as caster cap offs, where casting stops. Therefore within the steel plant, grade numbers are not used to define process aims, such as EB S for example. Instead there is a program number assigned to each heat number, which has associated ladle limits for various elements including S, Cu & Cr. Although this will mean that these program numbers will change less often, they can still change a number of times much like grade numbers. This flexibility is required to allow for unforeseen issues,

such as a treatment failure in the desulphurisation process. This would lead to higher than expected incoming HM S into the vessel, which will typically lead to a down grade.

Every process in the steel plant and their associated aims needs to be traceable. Therefore every time the schedule is updated the current program number is saved along with an Update Time, and the grade/grades associated with that heat, shown below in Table 3.4. This can then be matched up with a process time to provide the given aims at any point through the process, shown in

**Table 3.5.** Unfortunately, there is not a set time that can be used for scrap mix calculation. It was therefore decided that, where possible, the first time stamp when a scrap box is beginning to be loaded would be most applicable. This time will identify the scrap mix that should have been demanded by the CBM coordinator at the time the scrap box was loaded.

**Table 3.4 - Coord\_Link Table Containing Scheduling Information For BOS Plant**

HEAT_NUMBER	PROGRAM_NUMBER	GRADE_1	GRADE_2	UPDATE_TIME
24534	748	3034		09/06/2016 11:22
24534	748	3034		09/06/2016 11:20
24534	748	3034		09/06/2016 11:19

A contingency plan was required since, as was highlighted previously, there are a number of occasions when there is no recorded start load time due to a weighing issue with Harsco. So when this issue occurs, it was decided instead of start load time, the system would use the Torpedo tip time. This is the time when the Torpedo begins emptying the HM into the transfer ladle. This was decided upon because the scrap boxes are often loaded a few heats in advance, so by using torpedo tip time it is possible to make a good estimate of when the scrap boxes would have begun loading.

Depending on the availability of data an appropriate time is decided upon. This is then matched to the nearest update time within the Coord\_Link table, in Table 3.4. This is the coordination table that contains the grade, program number and timings of every single heat every time the schedule is updated. So this will contain a number of records for each heat,

allowing changes in grade to be easily tracked through the process. Within this table, the applicable program number can be found based on the timing for the given heat number.

**Table 3.5 - Torpedo Table**

HEAT_NUMBER	TORPEDO_NUMBER	POUR_STATION_TIME	TOTAL_POURED_WEIGHT
24434	39	09/06/2016 11:25	150.3525
24434	26	09/06/2016 11:30	54.18256

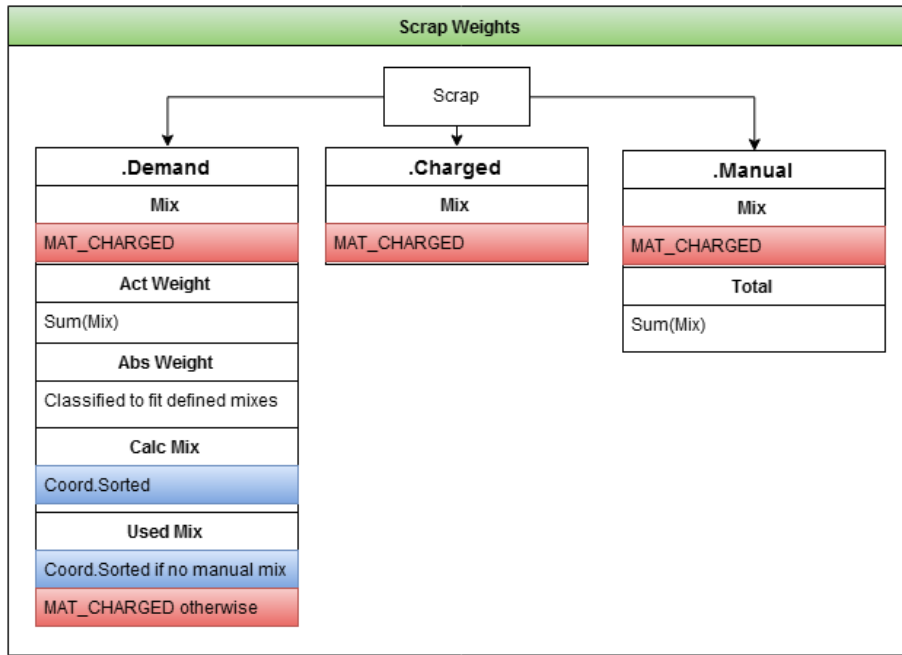
The program number is then used to get the S, Cu & Cr aims from the Program\_Analysis table, shown in Table 3.6. The table contains aim values for all stages in the process, with a Unit value of 3 representing the Vessel, and 5 the ladle. The Analysis\_Type describes the nature of the value, if it is a max a min or an aim value, with 0 representing the aim.

**Table 3.6 - Program\_Analysis Table**

HEAT_NUMBER	PROGRAM_NUMBER	UNIT	ANALYSIS_TYPE	ELEMENT_S	ELEMENT_CU	ELEMENT_CR
24434	748	5	0	0.02	0.08	0.06
24434	748	3	0	0.02	0.08	0.06

### 3.2.3 Scrap Weights

This next section of the system deals with the handling of the actual scrap mix data, covering the mix and weights demanded by the operator, those actually supplied by Harsco and any weights that were manually inputted into the database. As can be seen in Figure 3.3, this section of the system is more to do with the gathering of relevant data than with processing of the data. As can be seen by the colours of the tabs in the tables, the data comes directly from the databases (in red) and from scrap mixes section of the system (blue).



**Figure 3.3 - Scrap Weights Overview, Showing How The Scrap Data Structure Used Within The Expert System Is Structured, With Data Sources & Processing Used**

The MAT\_CHARGED table contains a record of all materials used within the steel plant, and so there are several columns to allow the filtering of this data to the relevant processes. Material descriptor is a short description of the materials being charged, in this case the type of scrap. Point of charge, not shown above as set to 1, describes the point in the heat cycle the material has been charged, so in terms of the vessel, 1 is for in blow, 2 for end blow and 3 is for a re-blow addition. The initiator type is simply a 1 or a 0, with 0 implying the data has been recorded automatically, and a 1 is used when the data has been put in manually. This data is then ready to be used elsewhere within the expert system.

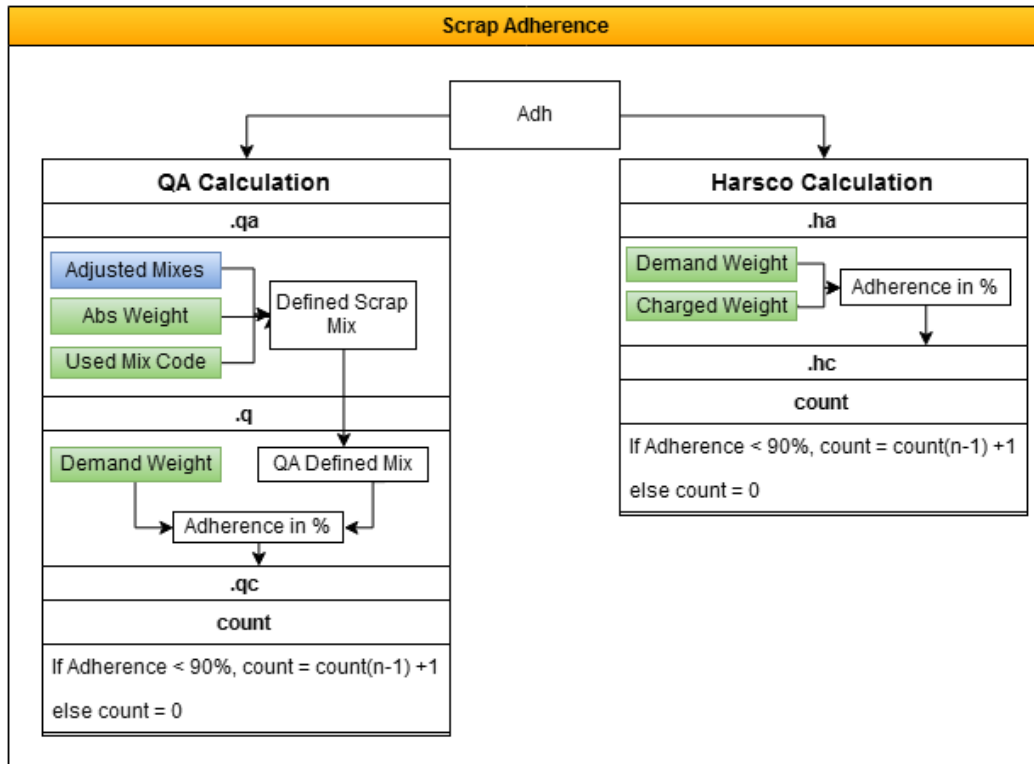
**Table 3.7 - Mat\_Charged Table For A Single Heat Number For Charging Materials**

MATERIAL_ DESCRIPTO R	CHARGED _TIME	CHARGED _TIME_GM T	QUANTIT Y	INITIATO R_TYPE	DEMAND _WEIGHT
SCRAP_N	14/06/2016 09:38	14/06/2016 08:38	2	0	2
SCRAP_M	14/06/2016 09:38	14/06/2016 08:38	10.5	0	10.9
SCRAP_J	14/06/2016 09:38	14/06/2016 08:38	6.5	0	6
SCRAP_I	14/06/2016 09:38	14/06/2016 08:38	5	0	5
SCRAP_G	14/06/2016 09:38	14/06/2016 08:38	4.5	0	5
SCRAP_C	14/06/2016 09:38	14/06/2016 08:38	5.5	0	5
SCRAP_B	14/06/2016 09:38	14/06/2016 08:38	8.5	0	8
SCRAP_A	14/06/2016 09:38	14/06/2016 08:38	2.5	0	3

### **3.2.4 Scrap Adherence**

This section of the system handles the adherence calculations for QA and Harsco adherence. An overview of this process is shown in Figure 3.4.





**Figure 3.4 - Scrap Adherence Module Overview, Showing The Adh Data Structure, & The QA & Harsco Adherence Calculation, From Data Sources To Processing Steps**

### 3.2.4.1 QA Calculation

The QA defined scrap mix is calculated using 3 inputs: the adjusted scrap mix; total scrap weight demanded; scrap mix code. The adjusted scrap mix data comes from the scrap mix section of the system (blue), and is defined by checking the predefined scrap mixes against availability of the respective scrap types. The total weight of scrap demanded is rounded down to the nearest scrap mix weight, as any excess will be made up with filler materials, which are predominantly mill products. The scrap mix code comes from the scrap mix section of the system, as is defined based on the grade limits for S, Cu & Cr at the vessel.

The scrap mix is used to define which adjusted scrap mix table is required; the absolute weight (green) is used to define the weight category within this selected table, to define the QA scrap mix. Once the correct scrap mix and then the correct weights have been calculated, the difference between these weights and those demanded by the operator's gives the adherence to QA. To keep a rolling record if this is a consecutive issue, the qc value within adh.qa is used to count the number of consecutive heats where adherence for each individual scrap type has been below 90%. So as shown in Figure 3.4, if it is below 90% then the value for qc is the current value plus one, so if this was the first heat it would be 0 + 1 which equals 1.

### 3.2.4.2 Harsco Calculation

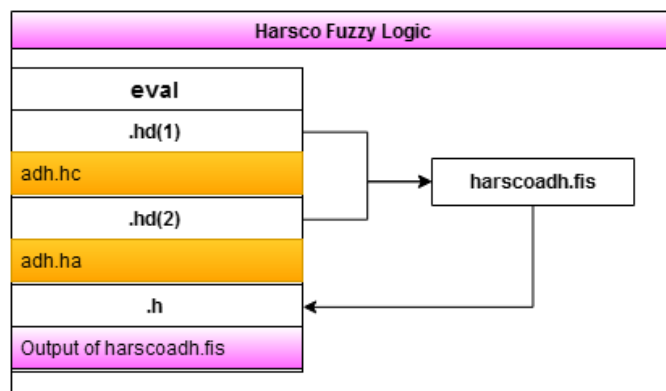
This section of the expert system was designed to compare the requested and supplied scrap weights and mixes. This involved looking at the weight and mix demanded by the CBM coordinator and the weight and mix charged by Harsco. There is little calculation required for this, although some preprocessing of the data to get it assembled into a matrix format is required. This is due to the way the MAT\_CHARGED table is designed, requiring that data is extracted one scrap type at a time. This means that the Heat Numbers need to be matched and all of the scrap data assembled into a single table. There is one formula used to calculate the scrap adherence, shown in Equation 3.1. This simple formula calculates the adherence as a percentage, which was identified as the easiest way to assess performance.

**Equation 3.1 - Harsco Scrap Adherence Calculation**

$$Adherence(\%) = \left[ \frac{Scrap_{Requested}}{Scrap_{Demanded}} \right] \times 100$$

### 3.2.5 Harsco Fuzzy Logic

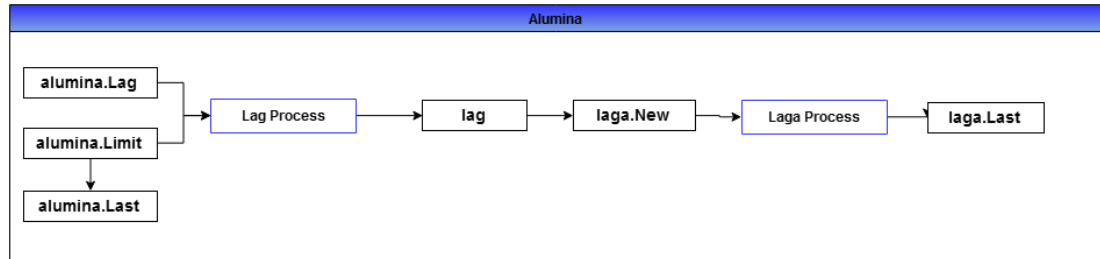
This section is designed to assess the state of the scrap adherence by Harsco, shown in Figure 3.5, it has 2 inputs from the scrap adherence section of the system (yellow), these being adherence for each scrap type in a %, and number of consecutive heats of adherence below 90%. The details of harscoadh.fis will be explained later on with the Harsco outputs.



**Figure 3.5 - Harsco Fuzzy Logic Overview, Showing The eval Data Structure & Contained Data**

### 3.2.6 Alumina

This section of the system handles all of the data extraction and processing around alumina levels within the vessel, shown in Figure 3.6. The lag and laga processes will be described in more detail, along with more detail on the overview below within the alumina chapter 3.4.1.

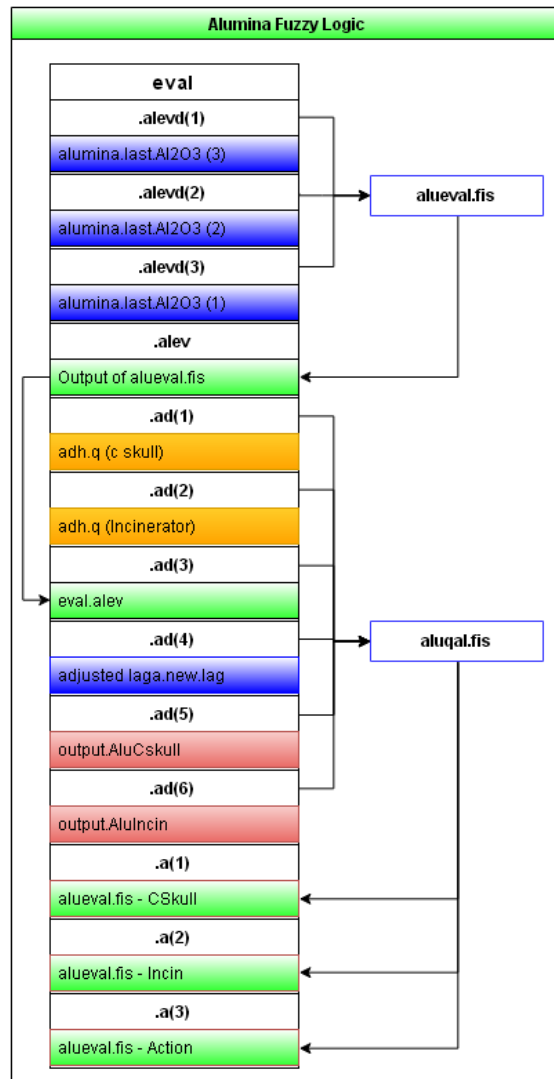


**Figure 3.6 - Alumina Module Overview, Showing Data Processing & Handling Undertaken To Calculate The laga.last Variable**

This section of the system uses data directly from the Slag\_Analysis table for alumina levels and sample timings. It has no input from any other sections of the system, and supplied data only into the Alumina Fuzzy Logic section, which will be mentioned next.

### 3.2.7 Alumina Fuzzy Logic

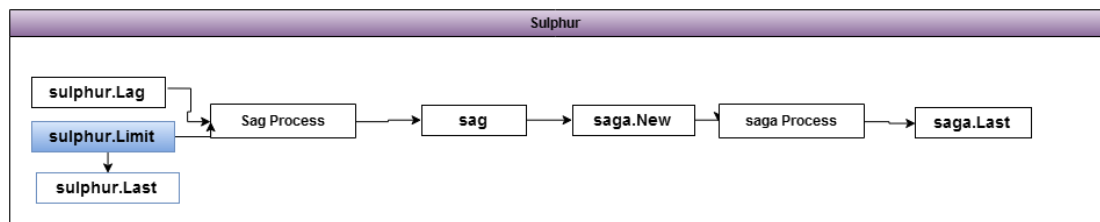
An overview of the alumina fuzzy logic section is shown in Figure 3.7, this section involves a large amount of data from various other parts of the system. The red sections show data directly from the databases, blue from the alumina section, orange from scrap adherence, and green is data generated by the Fuzzy Inference Systems (FIS) within the alumina fuzzy logic section. There are 2 FIS used, alueval.fis and aluqa.fis, which will be fully expanded and explained later on. The outputs of this section of the system are then directly used to generate the relevant outputs of the overall expert system.



**Figure 3.7 - Alumina Fuzzy Logic Overview, Outlining The Data Contained Within the eval Data Structure, & Data Input & Output From alueval.fis & aluqa.fis**

### 3.2.8 Sulphur

This section is the same as the alumina section of the system, except the inputs vary slightly as it is designed to deal with the sulphur content of the steel, instead of the alumina content of the slag.

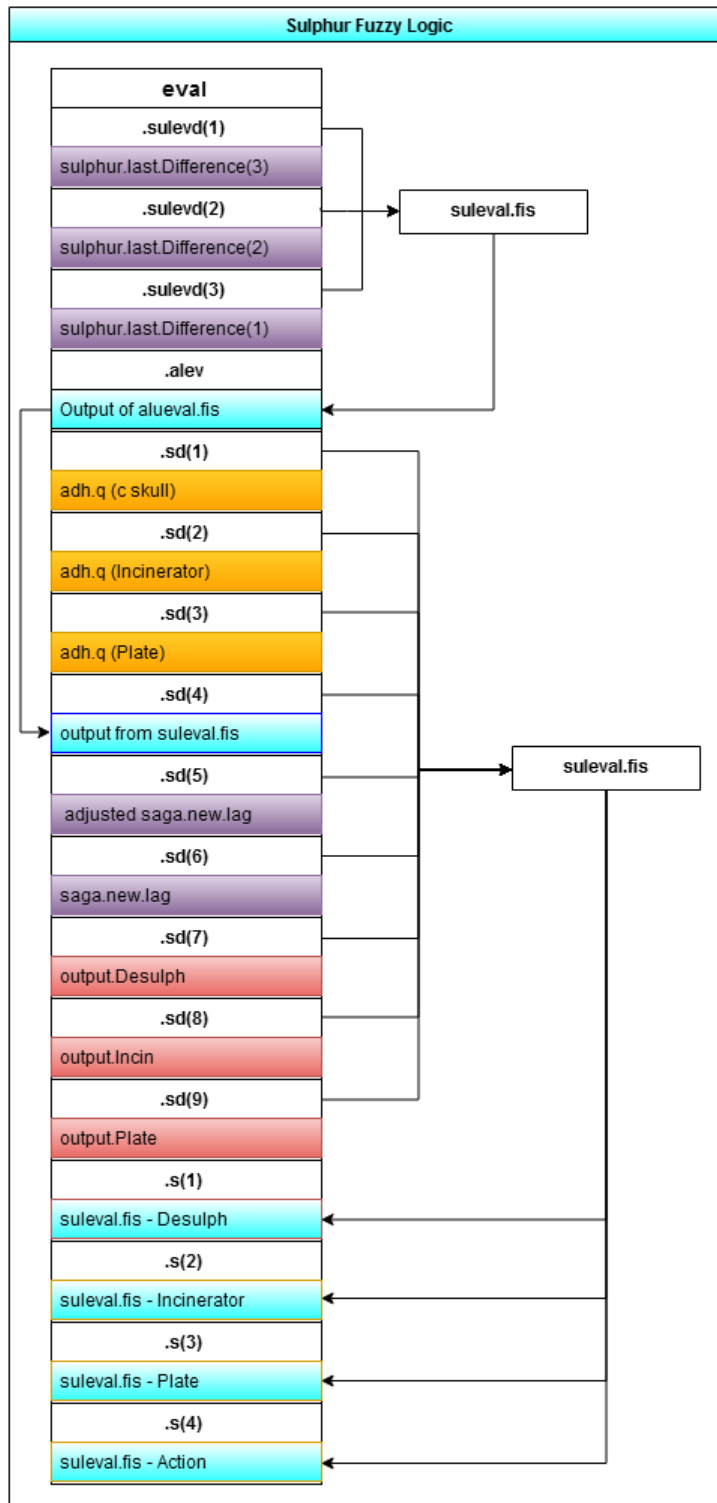


**Figure 3.8 - Sulphur Overview, Showing Data Processing & Handling Undertaken To Calculate The saga.last Variable**

Much of the data processing within this section is undertaken within the sag and saga processes as shown in Figure 3.8, which will be touched upon in Sulphur QA Procedure on page 61. This section feeds the processed data into the sulphur fuzzy logic section of the expert system, which will be outlined in the next section.

### **3.2.9 Sulphur Fuzzy Logic**

An overview of the sulphur fuzzy logic section is shown in Figure 3.9, this section again utilizes large amounts of data from various other parts of the system.



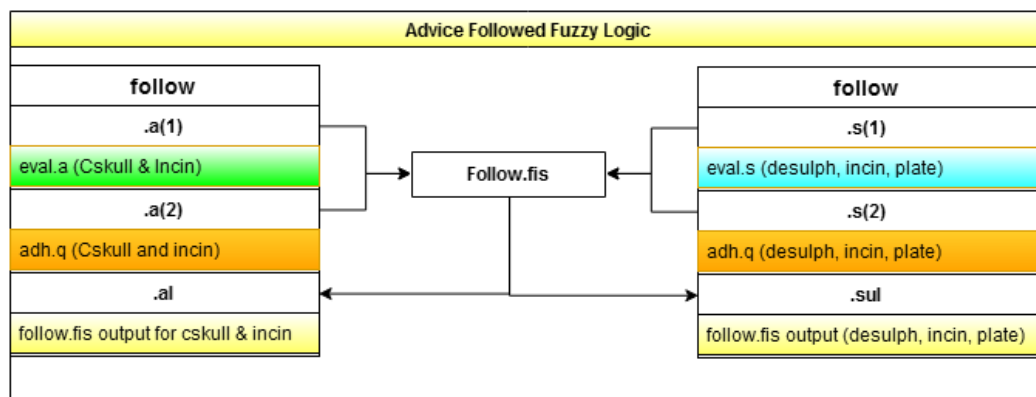
**Figure 3.9 - Sulphur Fuzzy Logic Overview, Outlining The Data Contained Within the eval Data Structure, & Data Input & Output From suleval.fis & sulqa.fis**

In Figure 3.11 the red sections show data directly from the databases, orange from scrap adherence, purple from the previous sulphur section, and light blue is data generated by the Fuzzy Inference Systems (FIS) within the sulphur fuzzy logic section. There are 2 FIS used, suleval.fis and sulqa.fis, which will be fully expanded and explained later on. The

outputs of this section of the system are then directly used to generate the relevant outputs of the overall expert system.

### 3.2.10 Followed Fuzzy Logic

An overview of the followed fuzzy logic section of the system is shown in Figure 3.10. This section takes in data from the alumina (green) and sulphur (blue) fuzzy logic sections, as well as the scrap adherence (orange) section of the expert system. This section has been designed to use the same FIS to handle both the alumina and sulphur adherences, and evaluate if the advice has been followed. The FIS Follow, will be expanded and explained in detail in subsequent chapters.



**Figure 3.10 - Followed Fuzzy Logic Overview, Showing The Inputs & Outputs Of Follow.fis For Both Alumina & Sulphur**

### 3.3 Harsco Adherence

An outside contracting company called Harsco are responsible for all of the handling and processing of scrap on site. The nature of the data processing for this section has been outlined within the scrap adherence section 3.2.5, and the Harsco fuzzy logic section. The Harsco adherence, as previously mentioned, is simply comparing the scrap mix demanded by the steel plant, to that delivered by Harsco. This section of the expert system has been designed to compare the requested and supplied scrap weights and mixes. This involved looking at the weight and mix demanded by the CBM coordinator and the weight and mix charged by Harsco. This information is important for a number of reasons. Firstly it can highlight to the CBM coordinator that there is a potential stock issue. Clearly if there are low stocks, then regardless how much is demanded, that scrap type is unavailable. Secondly there is an associated cost with each of the scrap types demanded, with cleaner scrap such as mill products being inherently more costly than the various skulls used. Finally, since Harsco

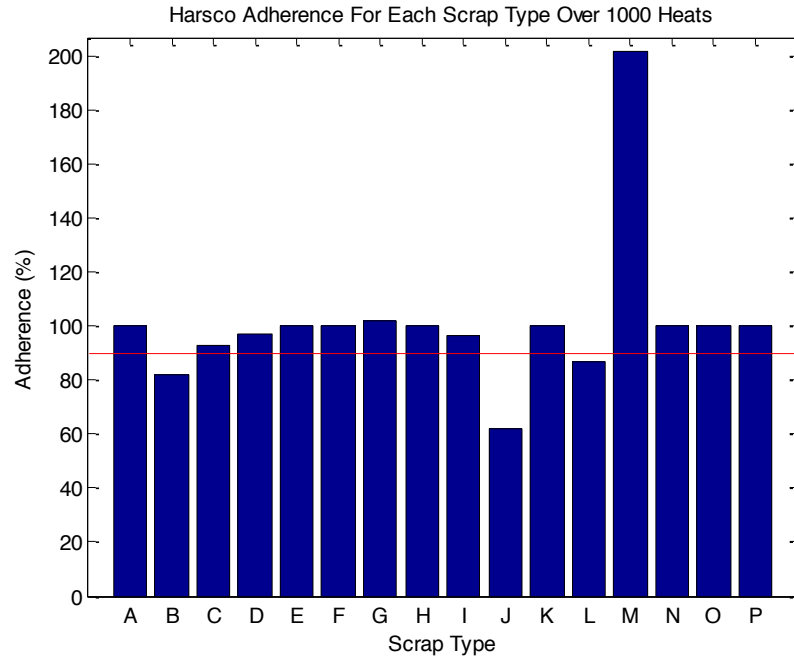
is an external contractor it is in the interests of TATA that their performance is monitored and the BOS Plant gets the scrap mix that is demanded at the correct cost.

The initial assessment of Harsco's performance is explained in the scrap adherence section of this thesis. The data used allows the system to firstly assess whether or not Harsco have loaded the scrap weight that has been requested and secondly that they have used the correct mix of scrap. This monitoring of the data also allows the highlighting of any issues with missing data as this is a possible indication of weighing issues, such as a broken weigh bridge.

### **3.3.1 Harsco Fuzzy Logic**

Calculating the level of adherence for each scrap type is useful in itself, but if this system is to be developed as an expert system, it needs to discern the unnecessary information and only highlight that which is useful to the operator. To assess at what stage adherence should be highlighted by the system, data analysis was carried out across a dataset of 1000 heats. The analysis was aimed at analyzing Harsco adherence across all scrap types. The aim was to firstly find out what level of adherence is typical for each scrap type and secondly to ascertain the best level to set the threshold value at which poor adherence is highlighted. This analysis is shown in Figure 3.11, where the red line depicted is at 90% adherence. After discussions with process managers it was decided that this would be an appropriate threshold value to use, as this is the level of adherence the steel plant expects from the contracting firm Harsco.

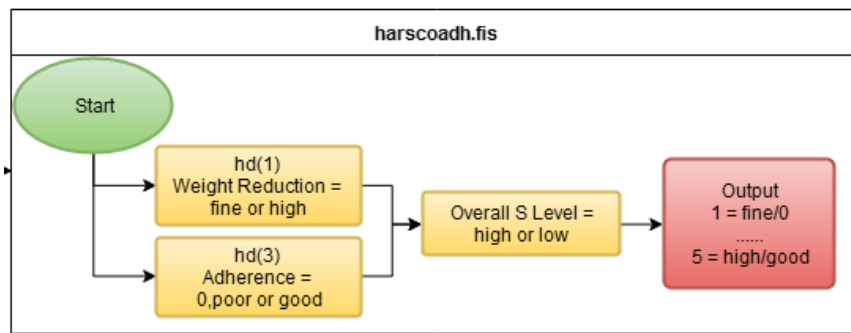




***Figure 3.11 - Harsco Adherence For Individual Scrap Types For 1000 Heats At Port Talbot BOS PLant***

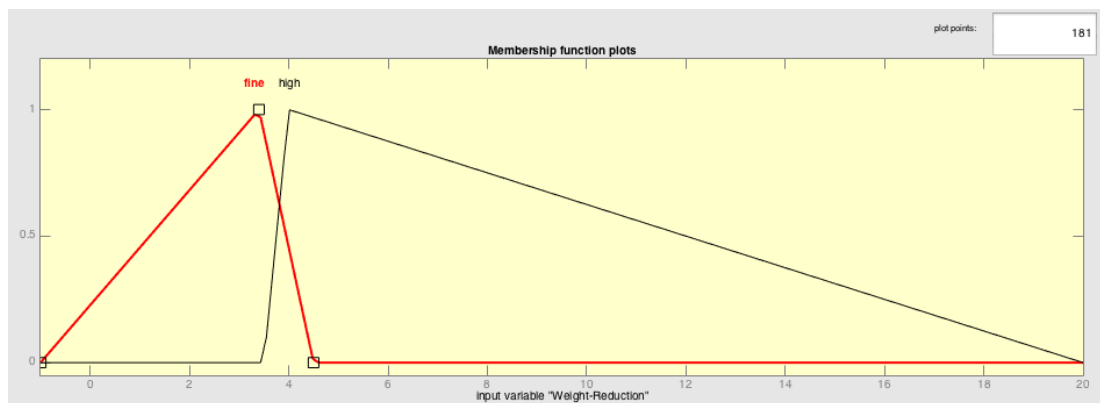
Due to the nature of the process it was also concluded that it would be most beneficial to the CBM coordinator if adherence below 90% were only highlighted if it occurred for four or more consecutive heats for each individual scrap type. The reasoning for this is that an issue may arise that could affect a single scrap box, such as issues with loading the bays. This does have an effect on the process, but if it is only for a single heat the effect isn't significant enough for the operator to be concerned by this. Instead only consecutive poor adherence is highlighted, as this could be an indication of an ongoing issue that could affect the CBM coordinator. In this way the system would provide an alert for issues with cranes or low stocks, therefore the number of consecutive heats is used as an input into the FIS.

As shown previously, the FIS used for the Harsco adherence uses data calculated within the scrap adherence section of the system, outlined in Figure 3.4. The level of adherence for each scrap type as a percentage, along within the number of consecutive heats below 90% adherence is passed to the FIS for analysis.



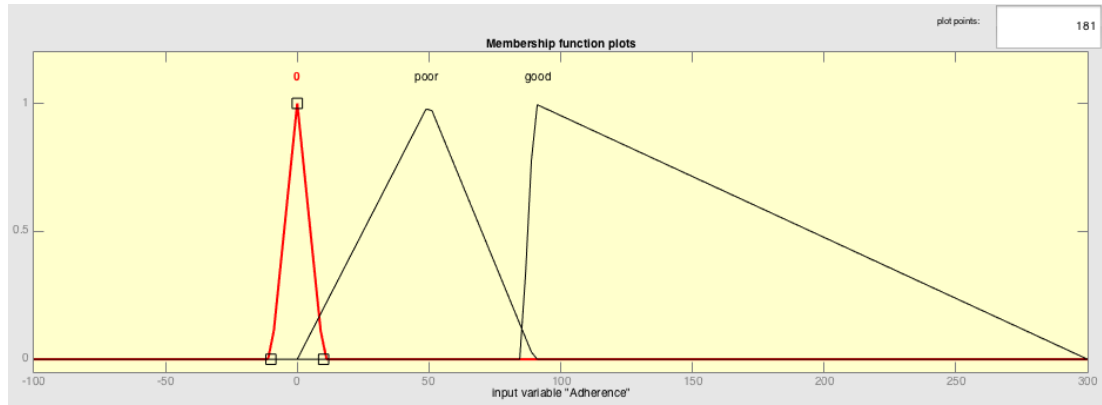
**Figure 3.12 - harscoadh FIS Flow Diagram, Relating Inputs To Output**

The FIS for Harsco adherence is very simple as shown in Figure 3.12, it has 2 inputs as mentioned and a single output. A single scrap type is analyzed at a time, and so it has been designed to handle data for a single scrap type for each analysis run. As the yellow box for hd(1) depicts, there are two different memberships for this input, as shown in Figure 3.13. These are defined as fine or high, depending on the number of consecutive heats where adherence has been below 90%.



**Figure 3.13 - Weight Reduction Membership Function, Showing The Boundary Values Used To Determine Fine & High Levels**

The second yellow box for hd(2) is for the actual adherence of the current heat in %, and has 3 memberships: 0, poor and good. The boundaries of the membership function for these are depicted in Figure 3.14.



**Figure 3.14 - Adherence Fuzzy Logic Membership Function, Showing The Boundary Values Used To Determine 0, Poor & Good Adherence Levels**

The outputs of the FIS have been designed to accommodate all possible combinations of the outputs for the 2 membership functions. There should be 6 possible outcomes, however if the adherence level is good, then the weight reduction membership will always be fine as it is based on whether the current level of adherence is above 90%. Therefore there are actually 5 possible outcomes, given a value between 1 and 5, to be interpreted by the outputs, which will be described next.

### 3.4 Quality Assurance Procedure Adherence

This section of the system has been designed to monitor the scrap mix selection the CBM coordinator makes for each heat. This selection is based on the grade of steel being made, the available stock levels as well as the affect the scrap is having on the EB steel chemistry.

There are Quality Assurance (QA) procedures in place for scrap mix selection that are based on the monitoring of EB S and EB slag  $Al_2O_3$  content. The reason these two factors are monitored is because the lower quality scrap types are a source of both  $Al_2O_3$  and S content to the steel, which for some grades is undesirable and can have detrimental effects on steel chemistry.

Internally generated skulls are amongst the highest sources of S and  $Al_2O_3$  meaning the procedures instruct the operators to remove these scrap types incrementally to attempt to isolate the cause. For high  $Al_2O_3$  it is often the case that there is an excess of fines within the scrap bays. If there is an improvement in the S and  $Al_2O_3$  levels when a certain scrap type is reduced or removed from the scrap mix, the respective scrap bays will get cleaned (fines removed) before the scrap type is reinstated completely.

### 3.4.1 Alumina QA

This part of the system concerns the Quality Assurance procedures that have been put in place by the technical department for the BOS plant. These have been put in place to control alumina and sulphur levels within the process, by adjusting the scrap mixes, as certain scrap types are a major source of these elements into the process. The procedures are implemented when certain criteria have been met, for example the alumina QA procedure begins when three in the last five heats have had alumina levels greater than or equal to 2.8% in the slag. The system has been designed to highlight when these criteria have been met, and advise changes on current scrap mix by following the QA procedure. At each point in the procedure, once it has been followed by the operator, the system also evaluates the current state of the process. It then assesses whether the reduction in certain scrap types has made a notable change and then advises on a relevant course of action. This will be either to clean the scrap bays for the given scrap type and then incrementally increase levels of the scrap back into the mix. Alternatively it can suggest a reduction in another scrap type relevant to the current issue.

To fully understand why high alumina levels are an issue, it is necessary to explain what effect alumina actually has on the slag and more importantly on the process. The alumina within the slag affects the viscosity, with lower alumina slags being very viscous. Low alumina slags, which aren't typically an issue within Port Talbot, would create a very viscous slag, which will create a poor emulsion and reduce the refining capability within the vessel. Alternatively, if the slag has too low a viscosity, with high alumina content, then the slag will potentially mix too well into the steel, which will cause a large slag carry over at tapping, as the slag and steel will be difficult to separate. This is an issue, as it will allow phosphorus reversion within secondary steelmaking, amongst other issues.

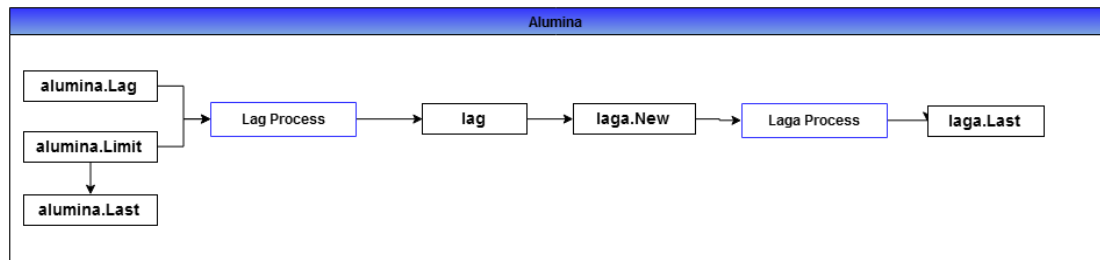
The procedure has been designed to identify as quickly as possible the source of the excess alumina into the process, which is typically due to the scrap. Due to this, the procedure outlines the incremental removal, at certain stages of the procedure, of C Skull and Incinerator scrap. These two scrap types are considered the highest source of alumina across the various scrap types used. To allow the logic of the procedure to be properly programmed into the system, it was first important to create a decision tree to assess what all of the possible courses of action could be. The decision tree that was created to show the process logic of the QA procedure is shown in Appendix A.

When there is an improvement after a scrap type has been reduced, it points towards the particular scrap type being the source of the excess alumina. Therefore it is advised that the respective scrap bays are cleaned, to remove the fine material, which is generally considered the source within the scrap of alumina.

### 3.4.1.1 Methods & Calculations Used

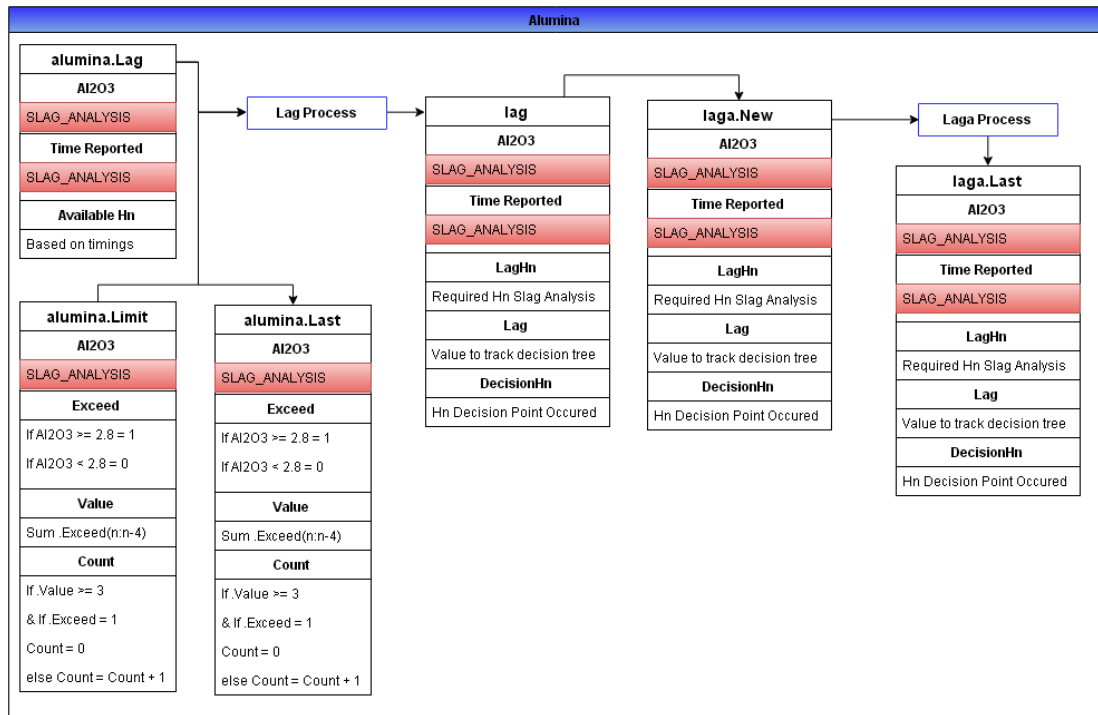
As was discussed within the literature review, the predominant approach to be taken was the application of Fuzzy Logic. Matlab was used for all of the development of the expert system, with the fuzzy logic toolbox. The nature of the QA procedures suits this application well, therefore where appropriate Mamdani type Fuzzy Logic was used.

The key process indicator for this part of the procedure is the slag alumina content at the EB point in the BOS process. The availability of this data and the timing however provided a number of issues. There is only a slag sample available when a slag dart is used during tapping. When the darting machine is lowered into the vessel there is a small chain attached to the bottom of the arm that the slag sticks to. This then gets used as the sample. Additionally, due to the way the samples are prepared and tested, they are analysed typically in batches. This means that it can be an hour or more between the sample being taken and the analysis being available.



**Figure 3.15 - Overview Of Alumina QA Calculation & Fuzzy Logic, Showing The Direction Of Data Processing**

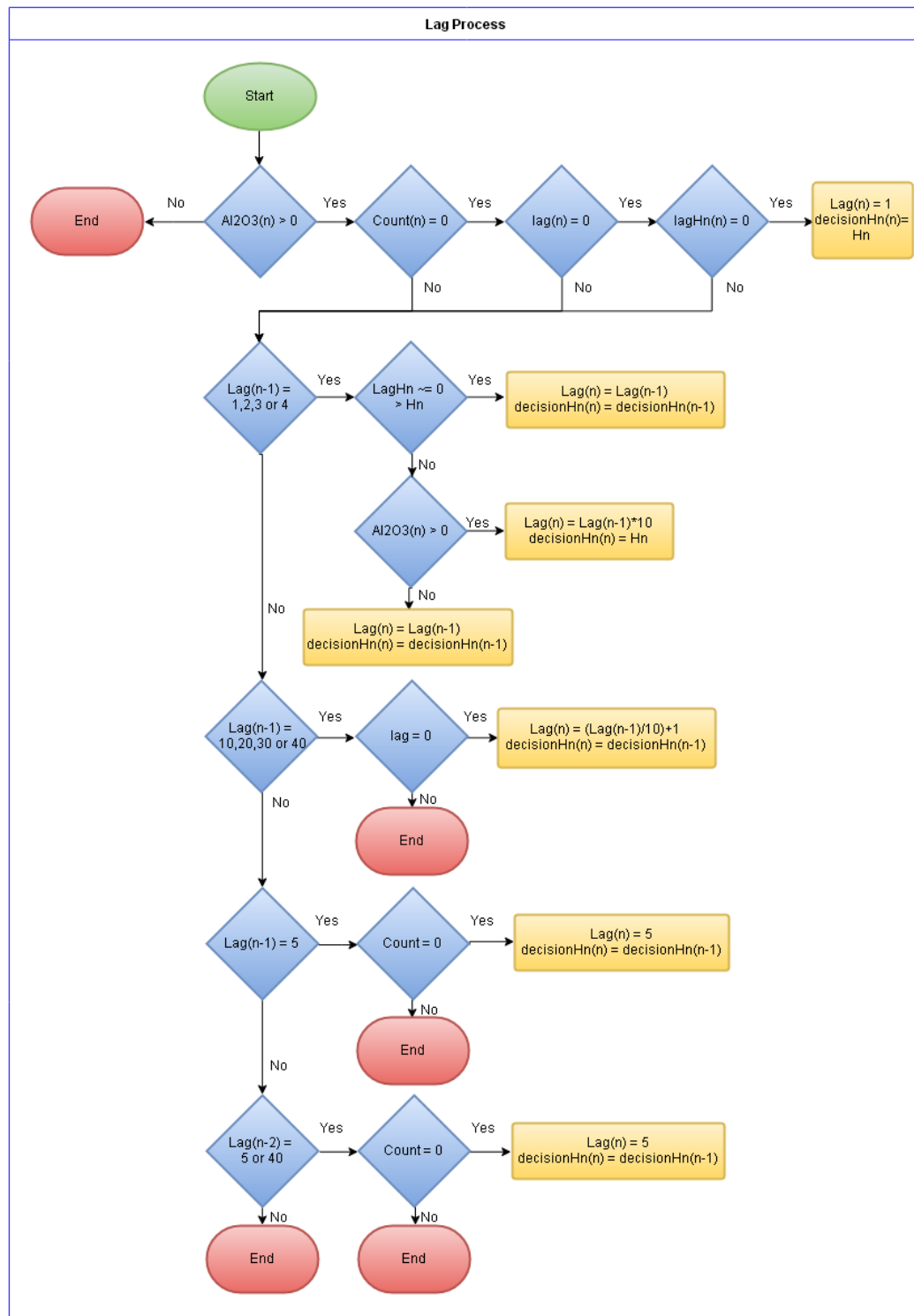
As with all industrial applications of any system, a key development criterion is that they are built in a robust manner. This application requires the ability to deal with missing and late analysis to ensure robustness. An overview of the different sections used within this system to process data for the alumina QA is shown above in Figure 3.15, with an expanded view of what data is being used shown below in Figure 3.16.



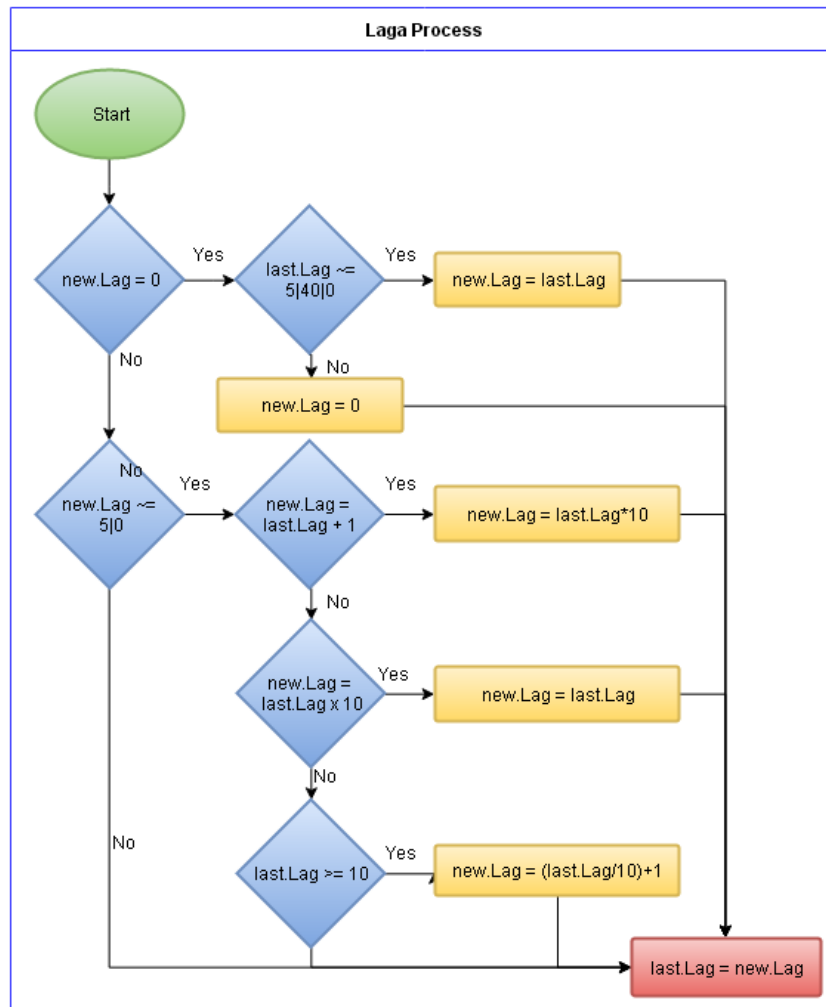
**Figure 3.16 - Expanded View Of Alumina Calculation Showing Data Used, And Explaining The Logic & Values Used**

As can be seen, the data used predominantly within this section of the expert system is the slag analysis results directly from the SLAG\_ANALYSIS table in PSMET. Flow diagrams have been used to fully illustrate the process logic in the Lag and Laga process below, as these are integral to the system being able to follow the decision tree for alumina issues within the BOS process. The Lag processes data to be handled by Laga, which then feeds into the Alumina fuzzy logic section of the expert system.

The purpose of the flow diagram for the Lag process represented in Figure 3.19 is to keep track of where on the decision tree the process currently is. This is done using the Lag value, LagHn which is the Heat Number at which point a decision on scrap mix needs to be made, as it will be 3 heats since the last adjustment, and the decision Hn which is the heat number a decision point is reached to keep track of how long the process is taking. More detail will be given on how exactly this is used below.



**Figure 3.17 – A Flow Diagram Outlining The Logic Used By The Lag Process To Calculate Position On Sulphur Logic Decision Tree**



**Figure 3.18 – Flow Diagram Outlining The Logic Used By The Laga Process To Calculate The Lag Value For The Next Heat**

In contrast to the Lag calculation, the Laga process, represented in Figure 3.20, is designed to assess what the value should be for the next heat, setting this up for when the next set of analysis comes through. The exact steps will be explained in more detail below, but the primary role of the Laga process is as a back-up in case a processing step within the Lag process goes wrong.

**Stage 1:** Start of diagnostic procedure: 3 out of the last 5 heats  $\text{Al}_2\text{O}_3$  above 2.8%

The logic behind this is shown firstly in Figure 3.16:

1. Exceed = 1 for each heat that has a value above 2.8%.
2. Value then sums the last 5 Exceed values, so if this is greater than or equal to 3 then this implies that at least 3 in the last 5 heats have an  $\text{Al}_2\text{O}_3$  result higher than 2.8%.



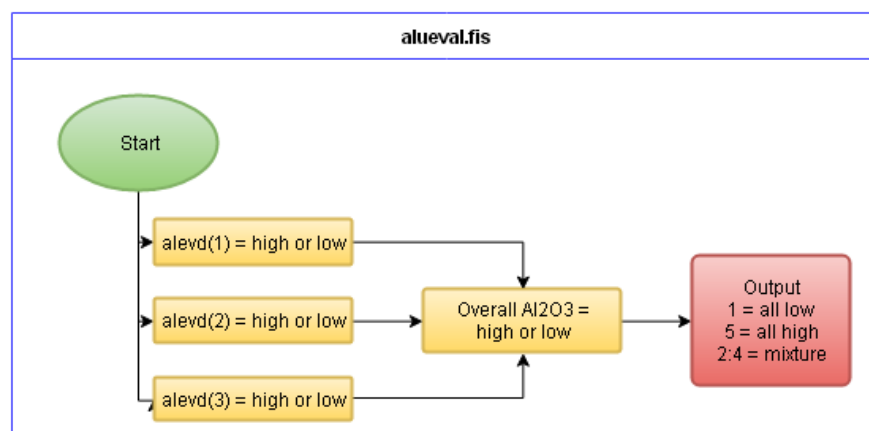
3. Count looks at the Exceed and Value values, if Exceed is  $\geq 3$ , and Value = 1, i.e. the current heat has an Al<sub>2</sub>O<sub>3</sub> above 2.8%, Count is set to equal 0, as this is a current issue.

The second stage of this is then interpreted by Lag, as shown in Figure 3.17.

1. Current heat has Al<sub>2</sub>O<sub>3</sub> result
2. Count = 0, as explained above
3. Lag = 0, there hasn't been an issue yet so this process hasn't started
4. LagHn = 0, no previous issue, so no heat number to monitor for.
5. Therefore set Lag = 1 to start diagnostic procedure
6. decisionHn is set to equal the current heat number being analysed.

The third stage is for it to be run through Laga, this essentially checks if the system has skipped a decision point unintentionally. At this point as new.Lag is equal to 1, but as no previous issue, last.Lag is equal to 0, the system simply ends up at the red square in the bottom right corner, saving all values as they are with no changes.

The final stage is the application and interpretation of the Fuzzy Inference Systems (FIS), which in this case are alueval.fis and aluqa.fis. Figure 3.7 above explains the input data into both of the FIS used, and shows how the first alueval.fis feeds into the second aluqa.fis as an input. The first of the 2, alueval.fis is by far the simplest, it has 3 inputs which evaluate the last 3 Al<sub>2</sub>O<sub>3</sub> results individually as high or low, and then assess' the state of all three before generating an output. The output has a value between 1 and 5 to evaluate the current state of alumina. A value of 5 indicates all 3 samples are high, 1 indicates all are low, and the values 2:4 are for a mixture, the FIS is depicted in Figure 3.19.



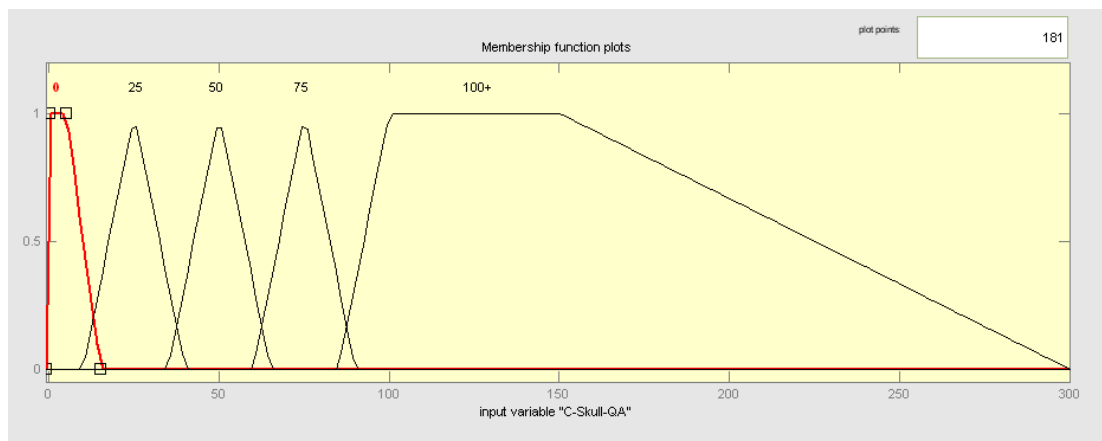
**Figure 3.19 - alueval.fis Flow Diagram, Relating Inputs To Output**

The second FIS, aluqa.fis is more complex in nature, as it contains 6 different inputs:

1. Current C Skull scrap level
2. Current Incinerator scrap level
3. Output from alueval.fis assessing Al<sub>2</sub>O<sub>3</sub>
4. Lag value, as described above
5. Previous aluqa.fis output for C Skull scrap
6. Previous aluqa.fis output for incinerator scrap

Inputs 1,2) As Figure 3.20 below shows, the various inputs are categorised using fuzzy logic; C Skull, Incinerator - these are categorised into 5 different categories as a %:

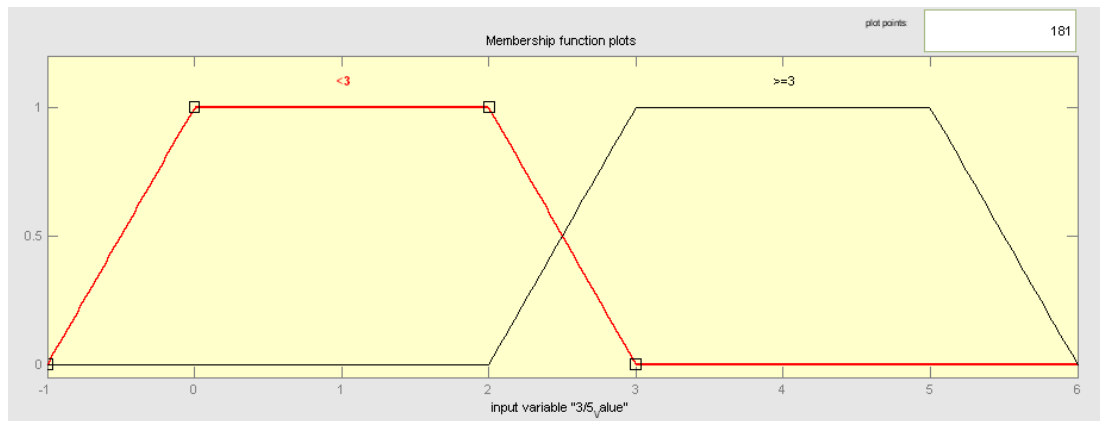
- a. 0%
- b. 25%
- c. 50%
- d. 75%
- e. 100%



**Figure 3.20 - C Skull Membership Functions, Showing The Shape & Values Used For All Membership Functions**

Input 3) The assessment of the output from alueval.fis is shown in Figure 3.21, it simply has 2 categories to effectively discern between high and low:

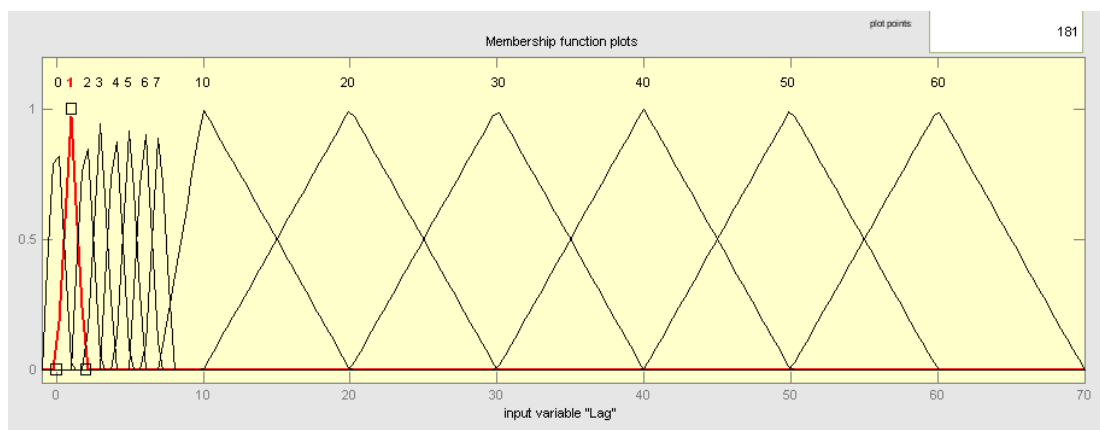
- a. < 3
- b. >= 3



**Figure 3.21 - 3/5 Value Membership Function, Showing The Shape & Values Used For All Membership Functions**

Input 4) The assessment of Lag has a lot of categories as shown in Figure 3.22, to help the system accurately categorise between the various values of lag:

- a. 0    b. 1    c. 2    d. 3    e. 4    f. 5    g. 6    h.7    i. 10    j. 20    k. 30  
l. 40    m. 50    n. 60

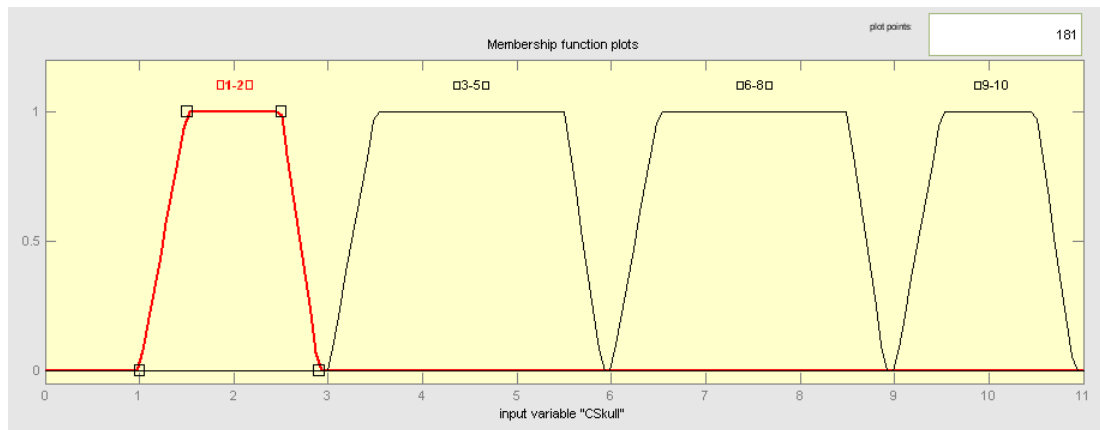


**Figure 3.22 - Lag Membership Functions, Showing The Shape & Values Used For All Membership Functions**

Input 5,6) The final input into aluqa.fis is the previous outputs from aluqa.fis, as these provide detail on what the previous advice was, to ensure continuity with the system outputs.

The categories used are shown in Figure 3.23:

- a. 1-2    b. 3-5    c. 6-8    d. 9-10

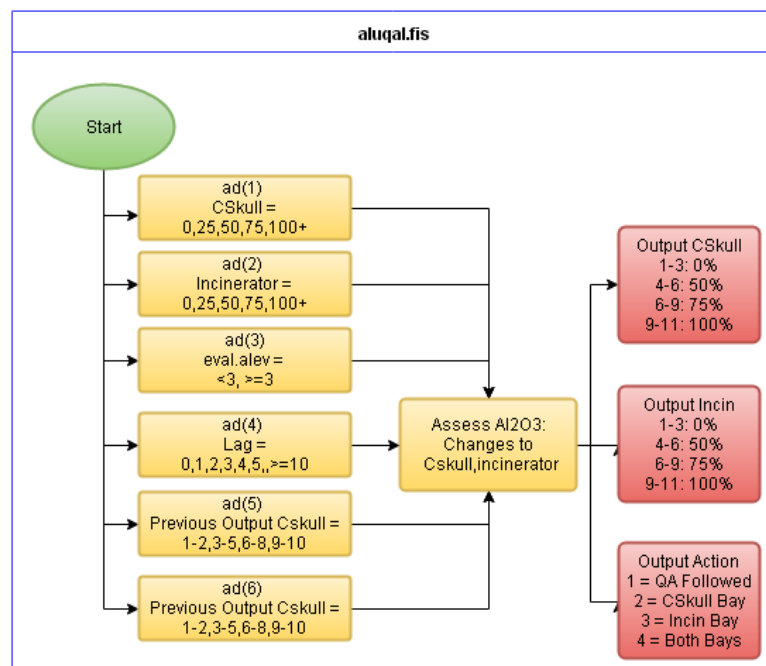


**Figure 3.23- Previous aluqa.fis Output Membership Functions, Showing The Shape & Values Used For All Membership Functions**

The reason for these categories is best explained by Figure 3.24, as this describes the output from the system in the red boxes. The system has been designed to have 3 outputs for every model run:

1. C Skull adjustments
2. Incinerator adjustments
3. Advice on cleaning scrap bays, or contacting technical

As can be seen, for the first 2 outputs for C Skull and Incinerator adjustments 1-3 corresponds to setting the scrap level to 0%, 4-6 to 50%, 6-9 to 75% and 9-11 to 100%.



**Figure 3.24 - aluqa.fis Flow Diagram, Relating Inputs To Output**

**Stage 2: Monitor scrap mix advised by system**

There are 2 different cases for this stage, although the first steps are the same for both. As with stage 1, Figure 3.17 is used to explain the logic of Lag process:

1. There is an  $\text{Al}_2\text{O}_3$  sample
2. Lag = 1
3. The LagHn is currently at 0 so this is ignored

Now on row 2 of this flow diagram setting 2 values:

1. Current Lag value = previous Lag value
2. Current decisionHn = previous decisionHn

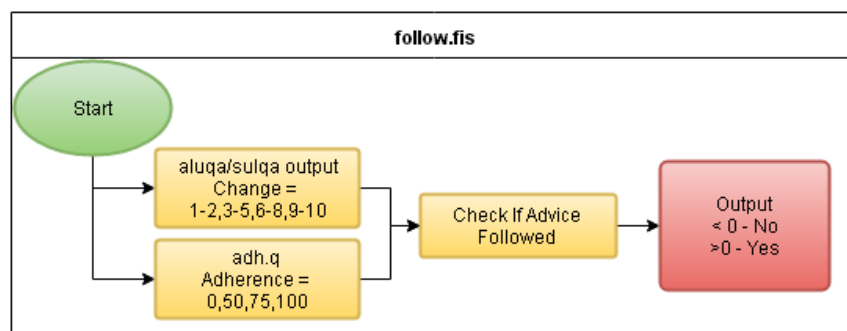
Next this is interpreted by the Laga process to check if the system has reached a decision point.

1. new.Lag = 1 as same as previous heat
2. last.Lag = 1

Therefore no changes are made to last.Lag, and save the values as they are.

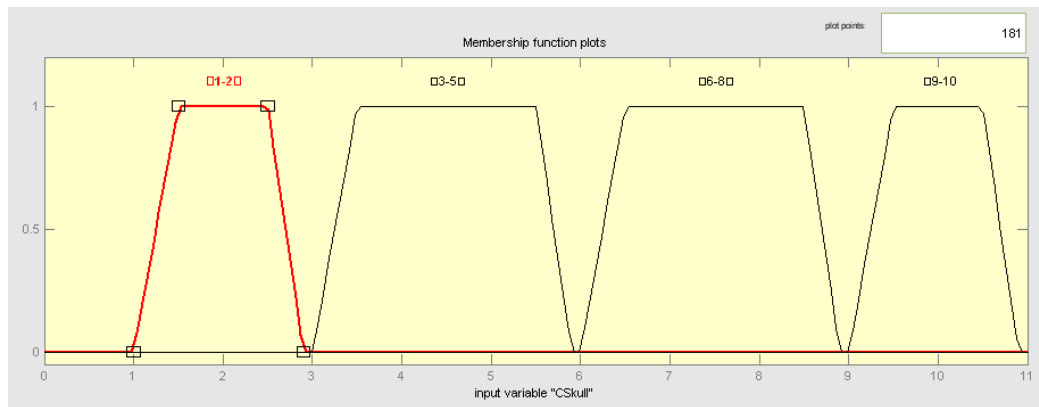
The final step is to put data through the three FIS that have been created, firstly alueval.fis which will evaluate the current  $\text{Al}_2\text{O}_3$  state of the process, though for this stage in the procedure it won't be considered in the second aluqa.fis.

The third FIS used at this stage is follow.fis, which has been represented in Figure 3.10, and is designed to simply check if the advice from aluqa.fis is being followed. Figure 3.25 provides an outline of the FIS used, as can be seen there are 2 inputs.



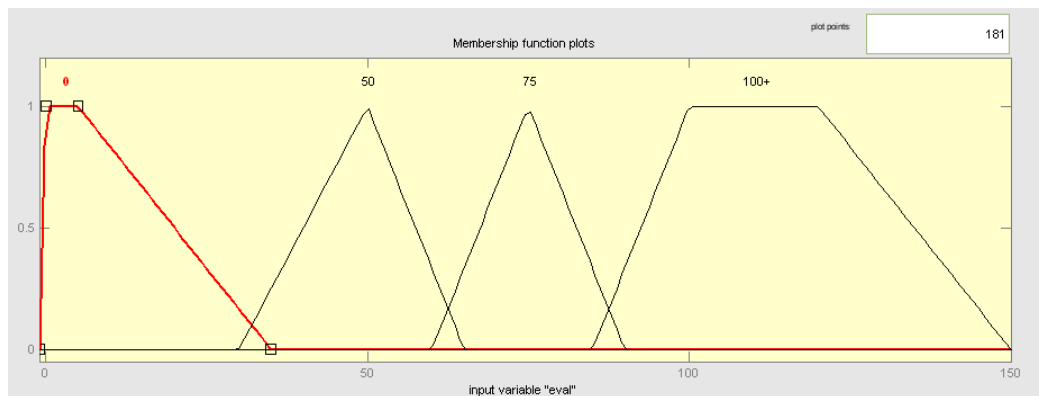
**Figure 3.25 - Follow.fis Flow Diagram, Relating Inputs To Output**

The first of the two inputs is for the output from aluqa.fis, and sulqa.fis which is the sulphur QA equivalent. As can be seen, this is designed to link up with the outputs from aluqa.fis described in detail earlier in this section. The inputs of 1-2 correspond to 0%, 3-5 to 50% and so on, depicted in Figure 3.26. This first membership function assesses what the demand scrap adherence should be, and the second is designed to assess the current state of the scrap.



**Figure 3.26 - Change Membership Function For C Skull, Showing The Shape & Values Used For All Membership Functions**

As can be seen in Figure 3.27, the membership functions are designed to classify the current level of scrap adherence for the selected scrap type, to match them up with the output categories from aluqa.fis; 0, 50, 75 and 100%.



**Figure 3.27 - Adherence Membership Function For eval Variable, Showing The Shape & Values Used For All Membership Functions**

The outputs from this FIS are very simple, a value between 0 and 1 is considered a yes, so the advised reduction/improvement is being followed, and a value below 0 corresponds to a no, the advice isn't being followed. What happens next is the setting of LagHn, which is a variable shown in Figure 3.17. The task of this is to have a value of the current heat with adjusted scrap mix plus 2. This is done so there are 3 heats with an adjusted scrap level to properly assess the impact on the process.

The 2 cases are down to aluqa at this stage, if the advised scrap mix is being followed, then the system will simply advise to keep at the current scrap levels. However if the scrap mix is not being followed, aluqa.fis will output to suggest reducing to the required scrap mix.

### **Stage 3: Target heat number reached, and Al<sub>2</sub>O<sub>3</sub> sample available**

This stage is applied when there is an alumina result available for the target heat number, or a heat number after the target heat number. If there is a missing sample, the previous lag value is multiplied by 10. This makes the lag value 10 as this is a decision point in the procedure. Then the alumina results for the target heat number and the two previous heats are input into alueval.fis where the alumina performance is evaluated. The output from this along with all of the other required inputs are input into aluqa.fis where the system calculates a new scrap level for C Skull and Incinerator scrap. If there has been an improvement in alumina levels, the system will advise increasing certain scrap types and the cleaning the scrap bays of the scrap type deemed to be the cause. If there has been no improvement in the alumina performance the system will advise further reductions in one or both of the scrap types to try and improve the alumina levels.

In more detail, the first step is once again depicted in Figure 3.17, this case by row 3:

1. previous lag = 1
2. LagHn is not > current Hn
3. current heat has valid Al<sub>2</sub>O<sub>3</sub> analysis

This puts us on row 3 of the Lag flow diagram:

1. Lag = previous Lag \* 10 - this will be interpreted as a decision point
2. decisionHn set to current heat being analysed
3. LagHn set to 0

The next stage is to run this through Laga processing:

1. new.Lag = 10
2. new.Lag = last.Lag \* 10 - row 3 on flow diagram
3. therefore it's saved as is, with no additional adjustments

The next step is the FIS analysis, firstly by alueval.fis to assess the state of the last 3 heats in Al<sub>2</sub>O<sub>3</sub>. This is then fed in as an input into aluqa.fis. At this stage, there will be 2 directions which aluqa.fis will send us on the decision tree:

If alueval.fis has indicated an improvement:

1. Will advise an increase in scrap levels
2. Advises cleaning of relevant scrap bay/bays

Otherwise

1. Advises further reduction of other scrap types

### **Stage 4: Previous Lag Value Checked**

Regardless of whether there has been an improvement in alumina performance or not, the system will then make the lag value the current value divided by 10 plus 1. So if the current lag value was 10, then it will be made to equal 2. Then the procedure simply repeats until the end of the decision tree is reached. So the system will advise the adjustment of the scrap levels until they match what's being advised. Once this happens a target heat number will be made and the system will monitor the process until the alumina sample is available for the target heat number at which point the new scrap levels will be calculated and the process repeated. What this means in terms of the flow diagrams and the process variables is, at this point in Figure 3.17, the system gets to row 4:

1. Previous lag value = 10
2. Current Lag = 0 as not set yet

Therefore :

1.  $Lag = (previous\ Lag/10)+1$ : Lag of 10 goes to 2
2. decisionHn = previous decisionHn
3. if advise followed LagHn set to current heat + 2

In terms of the Laga process, some of the sections on the flow diagram are there in case for some reason the Lag process skips a step. If all has gone to plan, once again no adjustments should be made at this point, however if for some reason the Lag process hasn't changed the Lag value of 10 to 2, then the final row in Laga will do this as shown in Figure 3.18.

### **3.4.2 Sulphur QA Procedure**

This part of the system deals with the manner in which the expert system was built to operate and apply the QA procedure set out by BOS technical to deal with sulphur issues within the vessel. Unlike with the alumina issues that occur, sulphur doesn't affect the BOS process itself, instead it is monitored because it has an affect further down the process chain within secondary steelmaking, as sulphur is part of a grade specification. The reason sulphur is a consideration is because it can lead to inclusion type defects, which is an issue when forming and bending the steel in particular.

#### **3.4.2.1 Procedure Logic**

The general idea behind the procedure is to identify as quickly as possible what the cause of the high sulphur is. This is typically a combination of slag carry over from the desulphurisation process and scrap. Slag carry over cannot be controlled by the CBM



coordinator, but scrap can, so it is the control of scrap that is outlined in the QA procedure. The decision tree in Appendix B shows the procedure and logic used for this process.

The sulphur procedure varies slightly to that of the alumina procedure; firstly because this is less of an issue, it is evaluated across the last 10 heats and not five like the alumina procedure. Secondly there are two causes for the procedure to be initiated, either an EB sulphur exceeding the grade max, or if three out of the last 10 heats have had sulphur levels within 0.002% of the grade maximum. Finally as all of the scrap used contains a certain level of sulphur, there are more scrap types that could be a potential source of the increased levels. There are three types of scrap considered to contain high levels of sulphur, so it is these three types that are adjusted when following the procedure. These scrap types are A Desulph Skull, Plate Iron and Incinerator scrap.

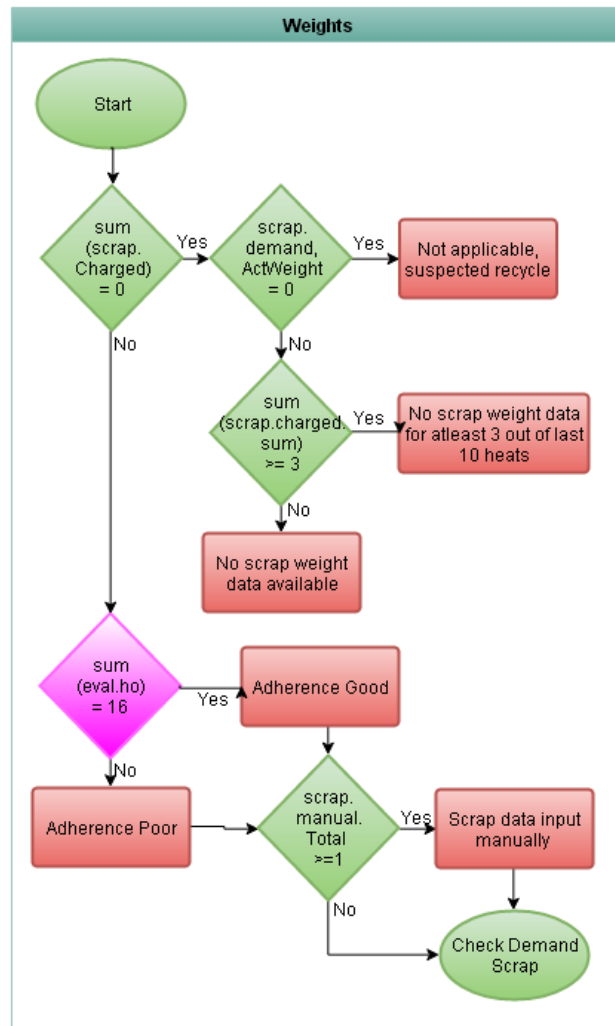
Due to this the sulphur QA procedure is slightly more complex from a programming perspective. However it follows the same steps as the alumina procedure, but requires more steps and higher lag values to be used. The Sag & Saga processes, same in structure to the Lag and Laga processes used for the alumina QA are shown in the Appendix C.

### **3.5 Scrap Adherence Expert System Outputs**

The actual outputs from the expert system will now be explained, and shown for all aspects of the system scope. The outputs for this type of system need to be designed to be concise and easily understandable. If this can be achieved it is going to be beneficial for the CBM coordinator as they can quickly and easily see and understand the issue. For this reason the outputs for the scrap adherence expert system have been designed to be run through sequentially, going through all possible situations, and generating all relevant outputs where applicable. Due to this, all outputs will now be shown in the form of flow diagrams, and fully explained where necessary, to show the order and the process used.

#### **3.5.1 Missing/Edited Scrap Weight Data**

This section of the system outputs, shown below in Figure 3.30, uses the data from the scrap weights section of the system (green), specifically looking into scrap.manual. This contains records from the Mat\_Charged table, which indicates if the data has been written in automatically, or manually uploaded by Harsco into the database. It additionally uses data from the Harsco fuzzy logic section of the system (pink), to check over all adherences.



**Figure 3.28 – Flow Diagram For Weighing Outputs, Showing Applied Logic**

This section has been designed to consider information in two ways, on a heat-by-heat basis and across the last ten heats to see if this is a recurring issue. To ensure records are kept complete when there is missing data Harsco will manually input the data. This is typically done later on in the shift and therefore is not necessarily as accurate as at the time the scrap box was loaded, as the weights tend to be rounded, some times more severely than others depending if the issue was known, and the operators were able to make an accurate note of the weights.

### 3.5.1.1 Process Logic & Data Processing

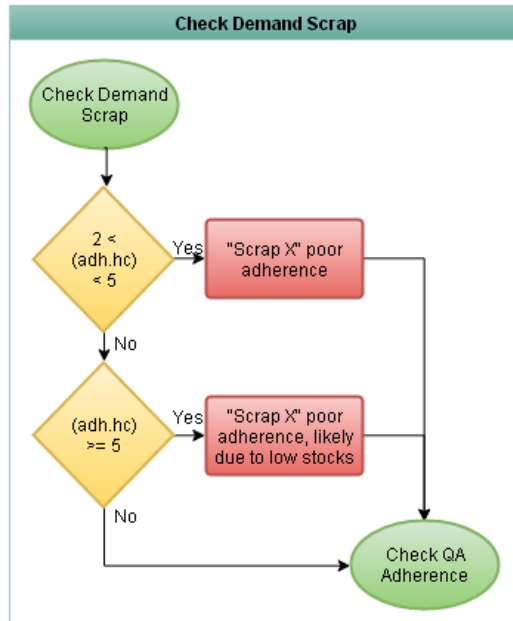
It is important to understand though that there are occasions when there is no scrap demanded. On these occasions the zero values, which may be assumed to be missing data, are not missing. This typically happens when there is a recycle, which is a ladle of steel being

brought back from secondary due to an issue with the casters, to be re-blown to increase T. No scrap is needed for this process. Due to this issue it was necessary to create a decision tree for the process, to allow the logic to then be programmed into the expert system to allow it to discern between a Harsco issue, either missing or manually inputted data, and a recycle. The logic used for this part of the scrap adherence expert system is shown in Figure 3.30. It shows how the outputs differ for 'Missing Data' to 'Suspected Recycle' or 'Manually Inserted Weights'.

As Figure 3.30 shows when a recycle occurs there is firstly no scrap demanded by the operator, additionally the blow is shorter. This results in a reduced volume of O<sub>2</sub> being used. Typically a normal blow in the BOS would use ~17,500m<sup>3</sup> of O<sub>2</sub>, where as a recycle will typically use less than 12,000 m<sup>3</sup>. This information isn't explicitly indicated within the output logic, however it is used to set the demand weight to 0 within the data processing. This information is an important step, as this allows the system to make an expert decision on the process.

### **3.5.2 System Outputs For Harsco Scrap Adherence**

The nature of Harsco adherence means that the outputs required for this are also fairly simple, as shown by Figure 3.29. There are two outputs from the expert system used to assess Harsco adherence for heats where adherence has been below 90%. The first output is for occasions where the last 1-3 consecutive heats have had poor adherence for a given scrap type. The adh.hc value used to assess this, as shown in Figure 3.4, simply gives a value of 1 for every additional heat where adherence is below 90%, or a value of 0 if adherence is above 90%.



**Figure 3.29 – Flow Diagram For Demand Scrap Outputs**

If this is a short term issue, the first output in Figure 3.29 is used, as adh.hc will be below 5, otherwise the second output is used if adh.hc is above 5, meaning 5 or more consecutive heats have been below 90%. If this occurs, it is typically that there is a low stock issue for the given scrap type. Given that there is a cost associated with using different scrap types, when there are low stocks of a given scrap type, the managers and operators should be made aware of it by Harsco. However this doesn't always happen as the issue arises, and so this part of the expert system was designed to give the CBM coordinator a warning if this issue occurs, in an attempt to minimize any delay that may have occurred. There can be a delay in Harsco contacting the steel plant due to a number of reasons, be it around manning issues at a given time or other issues such as equipment failures.

### 3.5.3 System Outputs For QA Adherence

The next section of the system outputs concentrates initially on the QA adherence of the scrap mix selection by the operators, checking for each individual scrap type; other than C Skull, Incinerator, Desulph skull and plate iron, as these are checked as part of the QA procedures, to check for adherence below 90%.

#### 3.5.3.1 QA Adherence

The first two outputs shown in Figure 3.30 are based on eval.qo (bright green), which is very simply calculated. This measures over all adherence across all scrap types, with any scrap type having an adh.q value, shown in Figure 3.4, below 90%. Assuming that at least 10 of

the scrap types have adherence above 90%, the sum of eval.qo will then be above 10, and the system has been designed to consider this as good adherence.

#### 3.5.3.1.1



**Figure 3.30 – Flow Diagram Showing Process Logic Used For QA Adherence Outputs**

#### 3.5.3.2 Manual Scrap Mix Changes

There are a number of occasions when it is necessary to charge a cleaner scrap mix than that required for the grade of steel being made. If there are issues with sulphur or alumina in the vessel, then certain scrap types are changed, but it is essentially the same scrap mix. However if there are issues within the desulphurisation plant, or if there is insufficient time to allow a pre-treatment of the HM, it is necessary to charge a cleaner scrap mix and allow a direct charge. This is done to maintain a sulphur balance within the vessel, as a reduction in sulphur inputted into the vessel from scrap will allow an increase in sulphur from the HM, without detrimentally affecting the EB S chemistry.

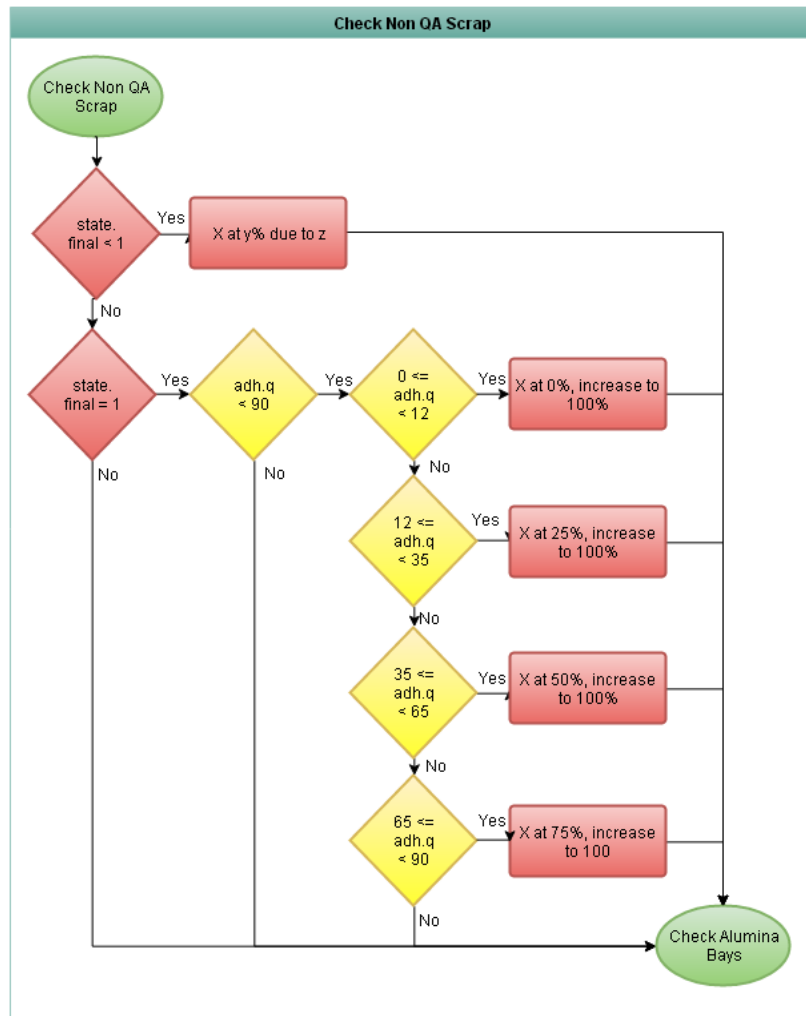
There can be issues within the desulphurisation process itself, or insufficient time for a treatment, which means that the HM needs to bypass the desulphurisation plant and be

directly charged. When this occurs it is valid that a cleaner scrap mix be charged, to maintain the sulphur balance within the vessel in order to meet the steel ladle aims. Due to this the system has been programmed to recognise when the charging of a cleaner scrap mix is valid due to the direct charging of HM. This hasn't been done for the benefit of the operator, as they will already be well aware of a desulphurisation or a speed of work issue. It has been done so that the technical staff or management can see either immediately or on a shift overview basis that there is potentially an issue, which is having a knock on effect on the BOS process.

There are 2 outputs corresponding to these issues, both rely on the system picking up within the scrap weights section of the data processing shown in Figure 3.3, that a manual scrap mix selection has occurred. The first output is generated if this is the case, and additionally the `desulph.direct.charge` value is checked. This is set to equal 1 if a direct charge has occurred, and so the additional comment on direct charging is added to the output, as shown in Figure 3.30.

#### **3.5.4 Non QA Scrap**

The outputs shown in Figure 3.31 correspond to all scrap types not used within the QA alumina or sulphur procedures. QA adherence is a measure of the difference between the scrap mix demanded and the predefined scrap mix set out for a given grade of steel. Simply calculating the adherence for all scrap types and outputting all of the adherences below say 100%, would be a lot of information for the operator and potentially contradictory to the QA procedures that need to be followed if an issue arises. For example, if the desulphurisation skull was dropped out of the scrap mix due to sulphur issues and was set at 50%, to simply highlight this as being low as it was at 50% would be wrong. It would be at that level as per the QA procedure, to determine if the scrap is the root cause of the higher sulphur levels. Due to this, the adherence is only calculated in this way for 12 of the 16 scrap types. The remaining four, C Skull, Incinerator, A Desulphurisation and Plate Iron are all used within the QA procedures, so their adherence is dealt with separately.



**Figure 3.31 - Flow Diagram Showing Process Logic Used For Non QA Scrap Outputs**

### 3.5.4.1 Scrap Modifier

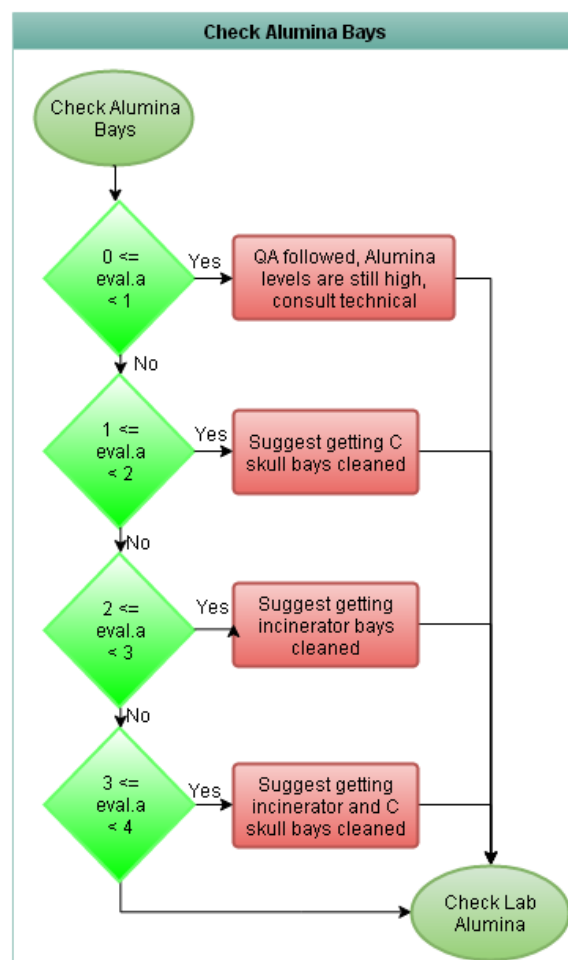
If the CBM coordinator reduces a particular scrap type for all scrap mixes, it is recorded within PSSUP as a scrap modifier. This record contains the level of reduction along with a reason. Before the system comments on any reduced scrap adherence however, it is necessary to check if there is a scrap modifier in place for the given scrap type. This has been handled within the variable called scrap.state, which is set to equal 0 if a modifier is in place, or 1 otherwise. If there is a scrap modifier currently in place it is not worth the system advising the CBM coordinator to increase the scrap level to 100%. Instead, if there is a scrap modifier in place, this is highlighted as the cause of poor adherence to allow future reference if looking at the adherence over a shift, which is shown as the first output in Figure 3.31.

### 3.5.4.2 Normal Adherence

The coordinators can adjust the demanded scrap mix into one of five different states; 0,25,50,75 and 100%, due to stock issues for example. If there are low stocks of a specific scrap type, before removing it completely, they will reduce the demand weight to one of the above states first. It was decided that it was important to reflect the specified state within the outputs as well as it would reflect the state of the scrap mix more accurately. Therefore any adherence level that is calculated is categorised into one of these levels, before one of the outputs in Figure 3.31 is used. The system calculates the output based upon the adh.q variable, as shown in Figure 3.4, which simply calculates the adherence as % per scrap type.

### 3.5.5 Alumina Scrap Bays

An output from aluqa.fis, described in Figure 3.24, is advice on the state of the scrap bays of C Skull and Incinerator scrap. If there has been an  $Al_2O_3$  level improvement after removing one or both of the scrap types, this would typically point towards dirty scrap bays with a lot of slag particles in the bays, which cleaning should improve. This section of outputs is designed to interpret the outputs from the FIS system around this type of issue.



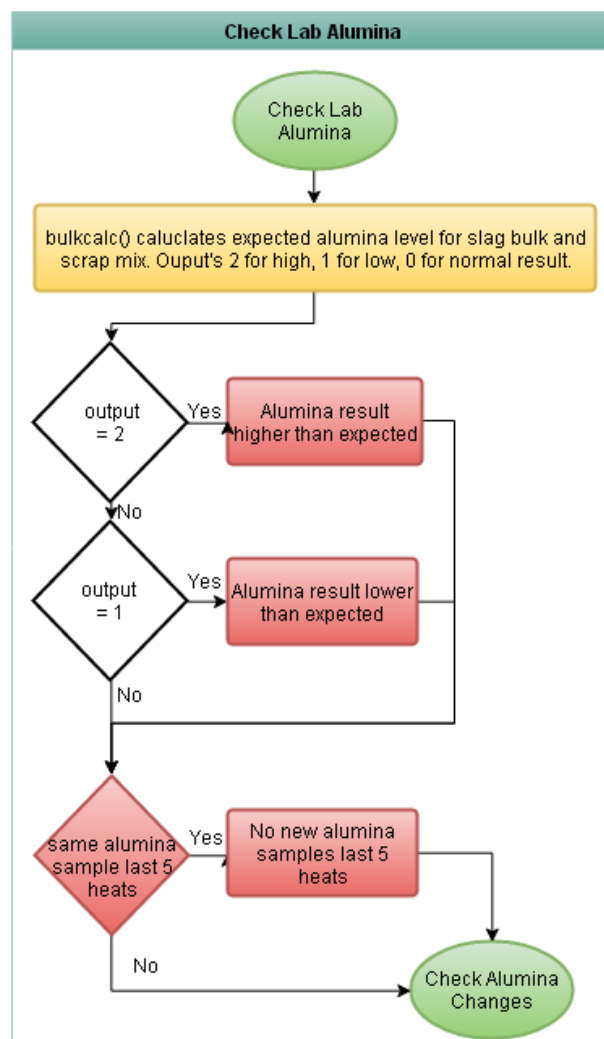


**Figure 3.32 - Flow Diagram Showing Process Logic Used For Check Alumina Bays**

The first output shown in Figure 3.32 results if the decision tree has been completed with no noticeable improvement in  $\text{Al}_2\text{O}_3$  levels, as this would indicate the source of the issue isn't scrap based. If this occurs, the operators are simply advised to contact the technical department for support on the issue. The final 3 outputs in this section are all around the scrap bays being cleaned, which would occur if an improvement occurred at reduced scrap levels of the respective scrap types.

### 3.5.6 Lab Alumina

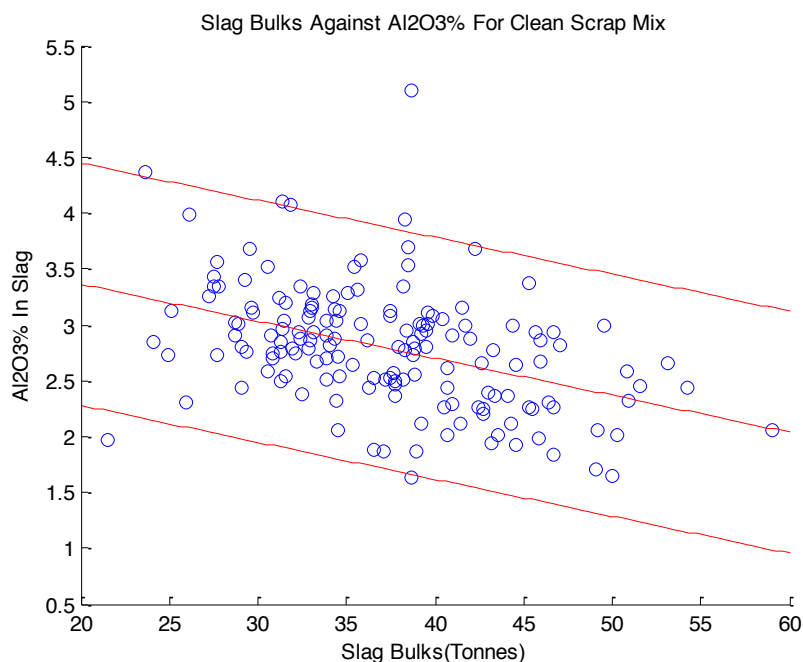
This section of the outputs deals with two distinct situations, firstly investigating the quality of the lab analysis, and secondly checking availability, with these being outlined in Figure 3.35.



**Figure 3.33 - Flow Diagram Showing Process Logic Used For Lab Alumina Results**

### 3.5.6.1 Lab Quality Analysis

This section deals with the analysis of the last batch of alumina results with the aim of highlighting if any of them are unusually high or low given the condition of the process. The alumina levels are affected heavily by the slag bulks within the vessel, as a higher slag bulk will effectively dilute the alumina in the slag. So if there is the exact same weight of alumina in a high slag bulk and a low slag bulk the alumina result from the low slag bulk will be significantly higher. As Figure 3.34 shows, as the slag bulk increases the alumina in percent decreases. The graph shows the slag bulks versus the alumina levels for all heats where clean scrap boxes have been used for the charges, across a dataset of 1000 heats.



***Figure 3.34 - Slag Bulk Against Slag Alumina For Clean Scrap Mix Selection, Showing Inverse Relationship Between Slag Bulk & Alumina Content In Slag***

This type of analysis needs to reflect the state of the process, so it has been designed to update itself every 100 heats, to ensure the analysis of the process is relevant and as accurate as possible. The system extracts the slag bulks, alumina results and scrap mix used for the last 1000 heats. It then splits the alumina results and slag bulks into the separate scrap mixes. This is because the cleaner scrap mixes have a lot less alumina and sulphur content. As can be seen in Figure 3.34, the data is represented well with a linear fit. It was decided that due to the variability of the process, that two standard deviations either side of this linear fit would depict the upper and lower boundaries. Two standard deviations were used as this would include approximately 95% of all data, ensuring that this would only highlight very

unusual results. If the new alumina results fall within this boundary then the system need not output anything. However if the alumina result is either above or below this then the system needs to make the CBM coordinator aware.

The analysis was carried out with a moving dataset; every 100 heats the dataset updates with analysis for the last 1000 heats. In between these 100 heats, it uses the linear fit equations and the standard deviations to calculate the upper and lower boundaries for each scrap mix. So for each new batch of alumina results, the slag bulk and scrap mix is entered into the function, which outputs two numbers. These are the upper and lower boundary limits, which are then compared to the current alumina result. This is done separately for each alumina result, as the slag bulks and scrap mixes will be different for each. This analysis is then used for the first 2 outputs shown in Figure 3.35, with the upper and lower limits being used to interpret the current lab analysis results. If the value is higher than the upper limit, the output variable is given a value of 2, and if it is below the lower limit it is given a value of 1, which is used to trigger the outputs shown.

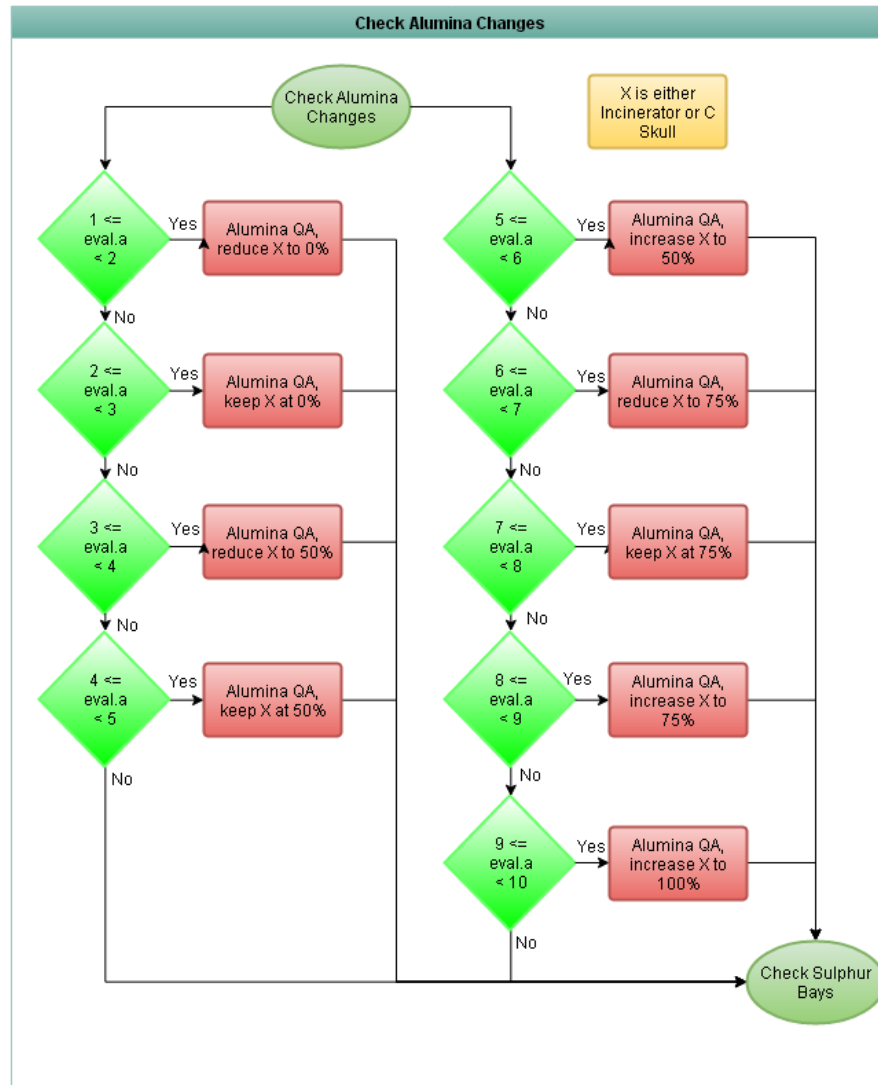
### **3.5.6.2 Availability Of Slag Analysis**

The laboratory analyses the slag samples to get an alumina result using an X-ray Fluorescence (XRF) analyser, which first requires the mixing of the slag sample with a flux and heating to form a glass bead. Due to the nature of this process it is easier for the laboratories to analyse these in batches. Because of this there can be a lag of over a few hours between the slag sample being taken and the results being ready, in the worst cases. This lag often makes it hard for the operator to tell when there has been an excessively long gap between the last available alumina results.

To overcome this problem this section of the system alerts the operator when there have been five or more heats since the last new alumina result was made available. Monitoring the alumina result stored in the output variable, which stores the latest alumina result every time the model runs, does this. If this value doesn't change in 5 heats that means no new samples have arrived, and so the output is triggered. This then allows the CBM coordinator to consult with the laboratories, as the alumina results are necessary to follow and progress through the QA procedure if there is an issue.

### 3.5.7 Advised Alumina Scrap Changes

The outputs for this section of the system, shown in Figure 3.35, are required to interpret the advice on adjusting C Skull and Incinerator scrap, from the aluqa.fis FIS system previously described. It is very simple, in that it just crosschecks the output from the FIS to what the system expects, and triggers the necessary output where appropriate.

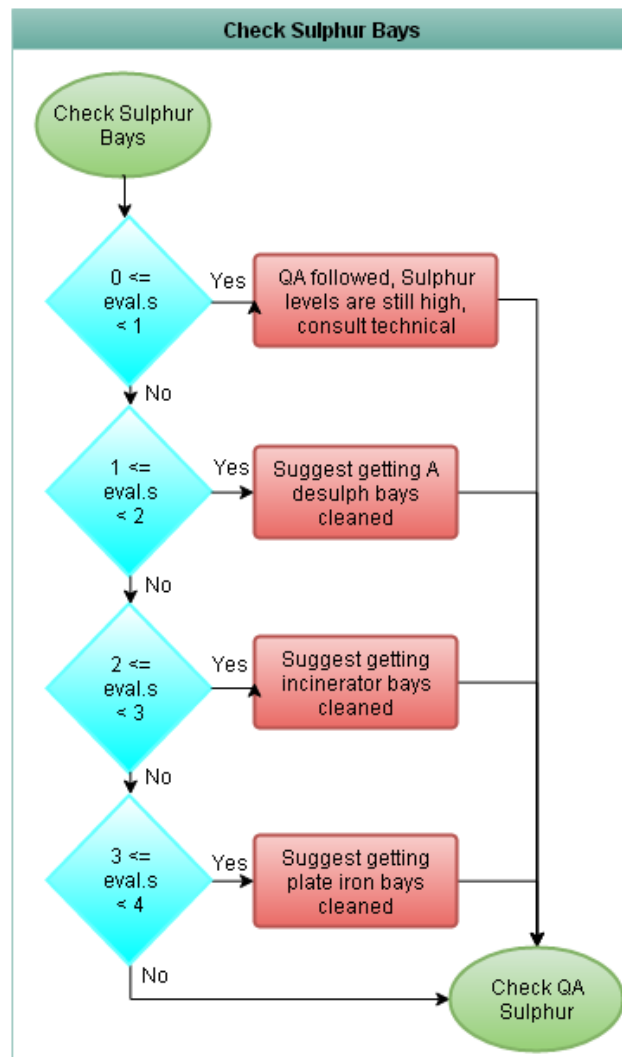


**Figure 3.35 - Flow Diagram Showing Process Logic Used For Alumina Scrap Changes Outputs**

### 3.5.8 Sulphur QA Advice Outputs

This section is almost identical to that shown earlier in page 69, describing the alumina bay outputs. The main difference is the scrap types that are described, as the alumina QA procedure deals with C Skull and incinerator, where as this needs to advise on Incinerator, plate iron and desulph skull, as shown below in Figure 3.36. The different colour of light

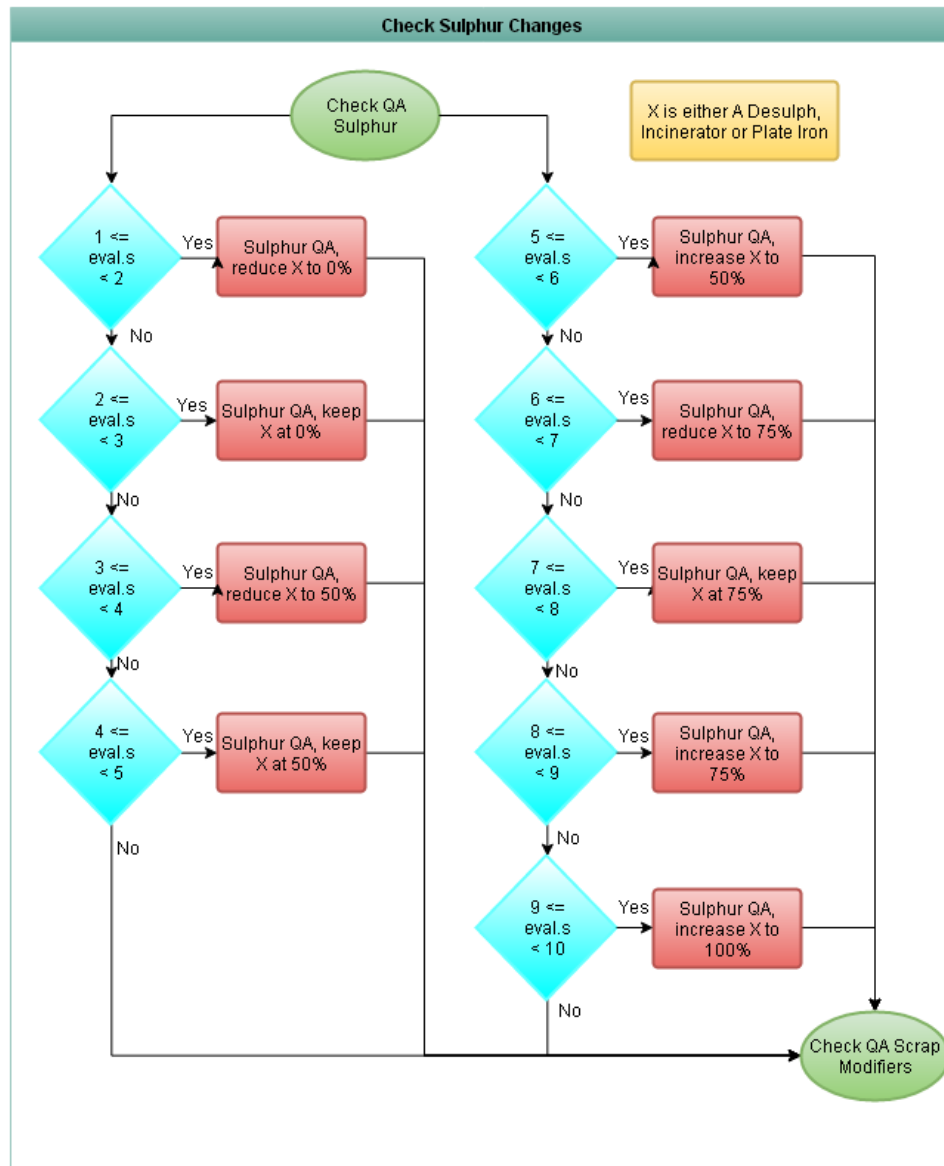
blue for the diamonds, indicate that a different data source is used, coming directly from the sulqa.fis FIS model.



**Figure 3.36 - Flow Diagram Showing Process Logic Used For Check Sulphur Bays Outputs**

### 3.5.9 Advised Sulphur Scrap Changes

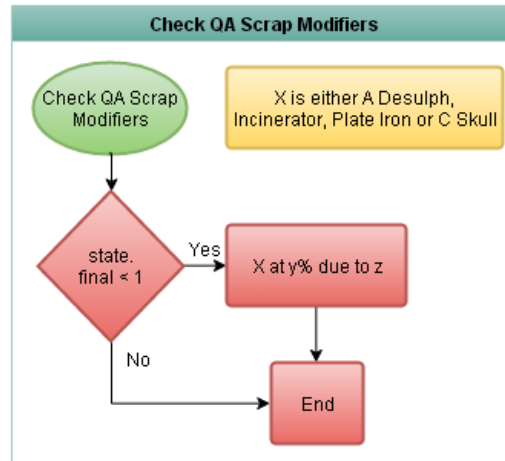
As with the previous section, this is once again a very similar replica to that defined for the advised alumina scrap changes. This section is simply designed to interpret the outputs from sulqa.fis, the FIS built to assess the state of the sulphur within the BOS process, and advise scrap adjustments to find the source of the issue. The outputs used are shown in Figure 3.37.



**Figure 3.37 - Flow Diagram Showing Process Logic Used For Check Sulphur Scrap Changes Outputs**

### 3.5.10 Scrap Modifiers For QA Scrap

This is the final section in the expert system outputs for scrap adherence, and it has been designed to check for scrap modifiers for QA scrap. As with the scrap modifiers for the non-QA scrap, it is based on the variable state, which is given a value of 1 if no modifier is in place, and 0 if there is for each individual QA scrap type. As Figure 3.38 indicates, this is used for the 4 QA scrap types; A Desulph skull, incinerator scrap, plate iron and C Skull.



**Figure 3.38 - Flow Diagram Showing Process Logic Used For QA Scrap Modifiers Outputs**

### 3.6 Summary

An expert diagnostic system has been developed for use at Tata Steel's Port Talbot BOS plant; with a focus on scrap mix selection. The system has been developed to firstly diagnose any sulphur or alumina related issues, and then provides support to the operators in following the QA procedures in place to diagnose a potential scrap type as the cause of the problem. This has been engineered within Matlab, with the use of Fuzzy Logic to help firstly assess any changes in alumina or sulphur caused from any scrap mix adjustments, and secondly to recommend the required adjustments in scrap mix selection.

The development, from data extraction through to data processing has been detailed within this chapter. Flow diagrams have been provided to explain the logic used by the system, when advising scrap mix changes, and scrap bay cleaning in the outputs. The scope of the system developed has incorporated measures of adherence of an outside contracting company called Harsco in supplying the requested scrap mix and weights. It has also been deployed to assess the adherence of the operators in selecting the correct scrap mix based upon the grade of steel being made.

Additional functionality was added to the system to improve it's potential impact for the operators, by monitoring the lab analysis results for alumina in particular against historic data to ensure results are realistic, and highlighting where appropriate if results are abnormal for the vessel conditions.

## **4 The Desulphurisation Diagnostic System**

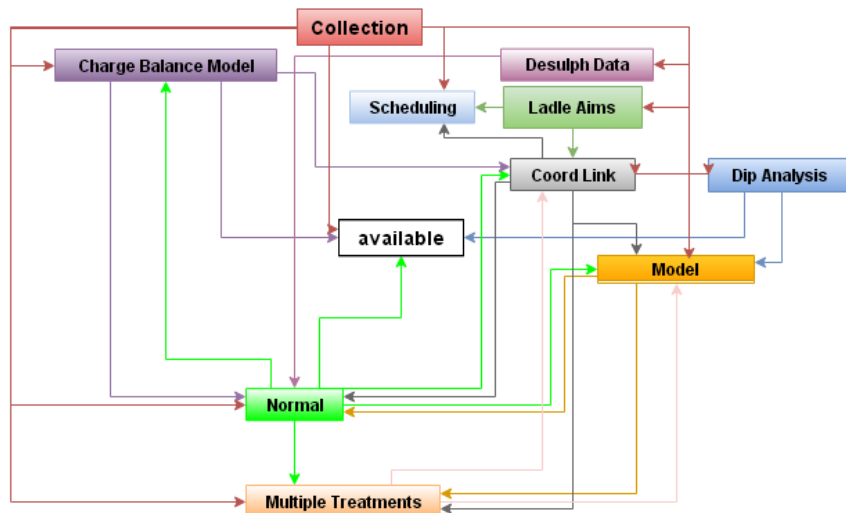
The desulphurisation process is a pre-treatment of the Hot Metal (HM) before it is charged into the Basic Oxygen Steelmaking (BOS) vessel. It was considered to be an appropriate process for the development and application of a diagnostics system, because it is a stand-alone process subject to known control procedures but is still not fully under accurate control. This means any development will likely have a big impact on subsequent processes and to steel quality. The desulphurisation process in its self is fairly simple, however the availability of data surrounding the process and the actions which the operators undertake during the process, can vary significantly. Due to lack of recorded data on the process, the deviation from standard operating procedure due to operator input is very difficult to quantify.

The general scope of the proposed diagnostic system is to highlight any issues arising within the process. Initially this work is focussed on mechanical process issues, such as interrupted treatments due to lance failures or blockages. Further aims were added with the intention of providing diagnostic tools that could also identify operator-generated adjustments to the process. This focused on highlighting how operators adjusted the process, the consideration of if their actions could be justified, why each adjustment was made and the effects these adjustments had on the process. Initial assessments of the effects were made in terms of material use and end point chemistry compared to target chemistry. The system outputs were split into three sections: “model” which covers any changes made to the model, “process” which highlights any issues detected during the desulphurisation process and “data availability” which highlights when there is a lack of HM samples being taken pre and post-treatment.

### **4.1 Desulphurisation System Overview**

A brief overview of the structure of the expert system will now be given, going through the different sections of the system, and the relevant data processing.





**Figure 4.1 - Desulphurisation Expert System Overview, Showing All Of The Separate Processing Modules Within The System**

All of the sections in Figure 4.1 will be explained in more detail within this section, with fully expanded views being available within Appendix D. The first thing to note about the desulphurization expert system is that there is a lot more interconnectivity between the different data units within the system than previously seen with the scrap adherence system. Each of the units shown above is a structure that contains many sections of data that have been filtered to represent a particular part or problem to do with the process.

#### **4.1.1 Collection**

This is the part of the system that extracts all of the required data, which in this case is data from three available databases on plant, PSMET, PSSUP and PI, shown in Figure 4.5. PI is an OsiSoft Plant Information database, used for realtime trending data, both continuous and discrete. As can be seen, this system uses an extensive array of data tables from PSSUP and PSMET, as well as the nitrogen flow rate from the PI database. This stage is key to the system, as can be seen in Figure 4.1, the Collect part of the system directly interacts with all other data units within the system.

Collection
<b>PSSUP</b>
SULPHUR_LEVELS
METAL_ANALYSIS
PROGRAM_ANALYSIS
HMDSM_RESULT
DIP_RESULT
PSSUP1_LOGICAL
CBM_RESULT
SCRAP_BOX_LOAD
PROGRAM_AIMS
<b>PSMET</b>
COORD_LINK
DES_TREATMENT
MAT_CHARGED
TORPEDO
MAT_CHARGED
DES_TREATMENT
<b>Pi</b>
Nitrogen Flow Rate

Within the PSSUP database, the Sulphur levels table contains information on desulphurisation Sulphur treatment aims. HMDSM results table contains analysis information from the HM dip at end of treatment. DIP RESULT contains HM analysis prior to the deuslphurisation treatment. PSSUP1 logical contains all a list of constants used in plant models. The CBM result contains data on the CBM model run, such as estimated HM chemistry from the torpedo ladles.

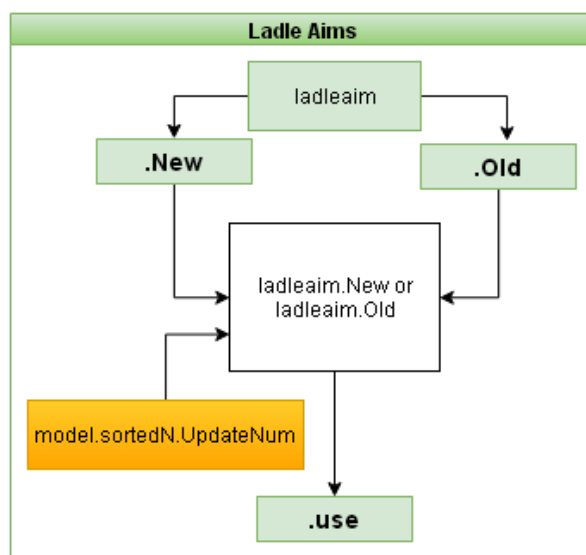
In the PSMET database, the COORD LINK table contains update times and program numbers for each every time the schedule is updated, essentially keeps track of grade changes.

The PI database is sued for the nitrogen flow rate, this is a value per second.

**Figure 4.2 – Table Showing All Of The Data Tables Used For Desulph System, From PSSUP, PSMET & PI Databases**

#### 4.1.2 Ladle Aims

This section of the system has been designed to handle the required aims within the process, but more importantly check for adjustments with these aims. As shown in Figure 4.3, there are two main initial sections, new and old, which both contain the same data. New comes from data read from the Sulphur\_Levels table, which has all the desulphurization treatment aims for retreating and direct charging. The old structure contains the same data but from the previous data run where it got saved to allow a comparison. The reason for doing this is to allow a direct comparison between the two, allowing both to be used depending on at what time the new values were updated, and what the start treatment times were for each individual heat, making the analysis more accurate.

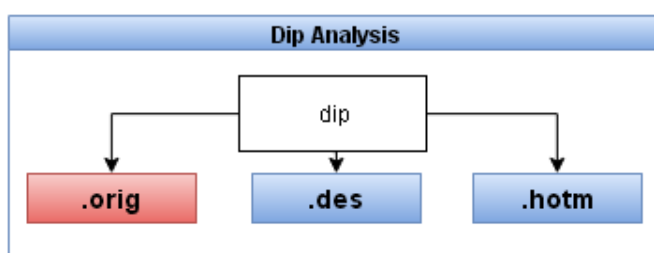


**Figure 4.3 – Data & Logic Used For The ladleaim Data Structure**

This is where the Use structure comes in, as based on the schedule update time from the Model data structure (yellow), it uses whichever treatment aims were applicable at the time of the treatment.

### 4.1.3 Dip Analysis

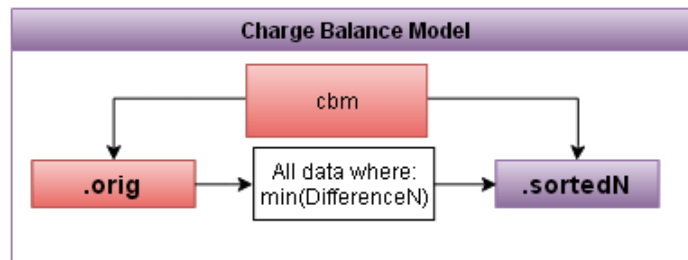
This section quite simply contains the HM analysis results from the Dip\_Result table, which contains T and S levels in the iron. To facilitate the use of the data for the outputs, there are 2 additional structures created from the orig structure, which contains the raw data shown in Figure 4.4; des and hotm. These contain the data for the desulphurisation station dip results, and the transfer ladle dip results respectively.



**Figure 4.4 – Data & Logic Used For The dip Data Structure**

#### 4.1.4 Charge Balance Model

The Charge Balance Model (CBM) as previously discussed, is used to calculate the required weights of HM, scrap and fluxes amongst other materials within the BOS process. What it additionally does is estimate the HM S based upon the Blast Furnace (BF) runner analysis for each torpedo of iron used for the given transfer ladle. This section contains the raw data for the CBM, and has a row of data every time the schedule is updated, as it is rerun every time this is done.

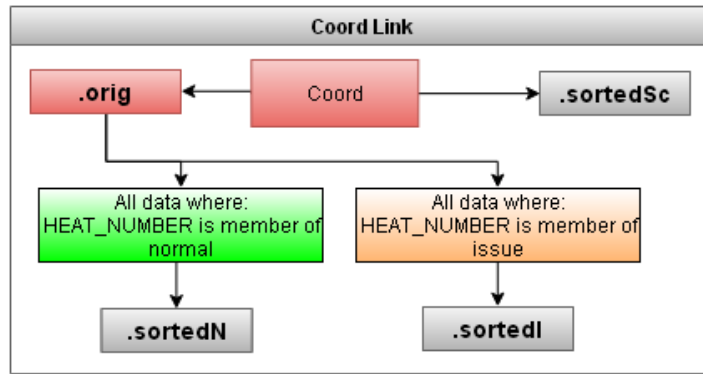


*Figure 4.5 - Data & Logic Used For The cbm Data Structure*

As Figure 4.5 shows however, this structure doesn't just contain the raw data in the orig structure, it also has a sortedN structure. This has a single row of data for each heat number that is based upon the update time and the start treatment time. The variable DifferenceN is the difference between model run time of the CBM and the start of treatment time for the given heat number. The minimum value only looks into heat where the CBM run is before the treatment time. Therefore the minimum value gives the closest model run to the treatment time, and the most applicable data to compare the treatment with.

#### 4.1.5 Coord Link

This section is similar to the charge balance model section, in that it contains all of the raw data from the Coord\_Link table, which as described in the previous chapter, contains a new set of data for each heat number every time the schedule is updated. Therefore, to make this data easy to use later on in the system when processing the outputs, it has been filtered and passed to a number of different structures with this section as shown in Figure 4.6.



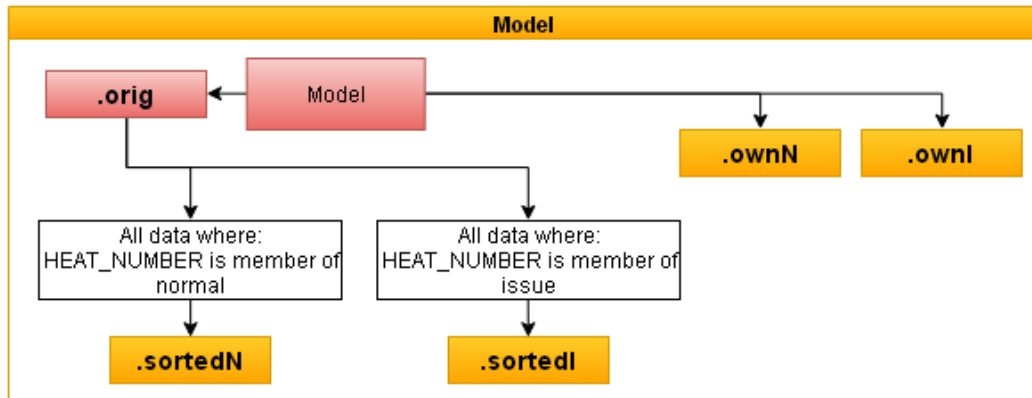
**Figure 4.6 - Data & Logic Used For The Coord Data Structure**

The data sections Normal and Issue are structures of data for single and multiple injection heats respectively. Therefore separate structures are created to contain relevant data for both, to allow proper analysis. The sortedSc structure contains data regarding scrap mix, as part of this system checks to see if there have been any scrap mix changes at the vessel, following an issue of a treatment change at the desulphurisation treatment stations.

#### **4.1.6 Model Data Structure**

In Tata Steel Port Talbot works, a computer model is used to calculate the required Mg and CaO quantities. The model is required to facilitate the operators in calculating material use, due to the level of variation within incoming process parameters. It makes process determinations based on incoming HM W, HM T and HM S, and the outgoing Aim S.

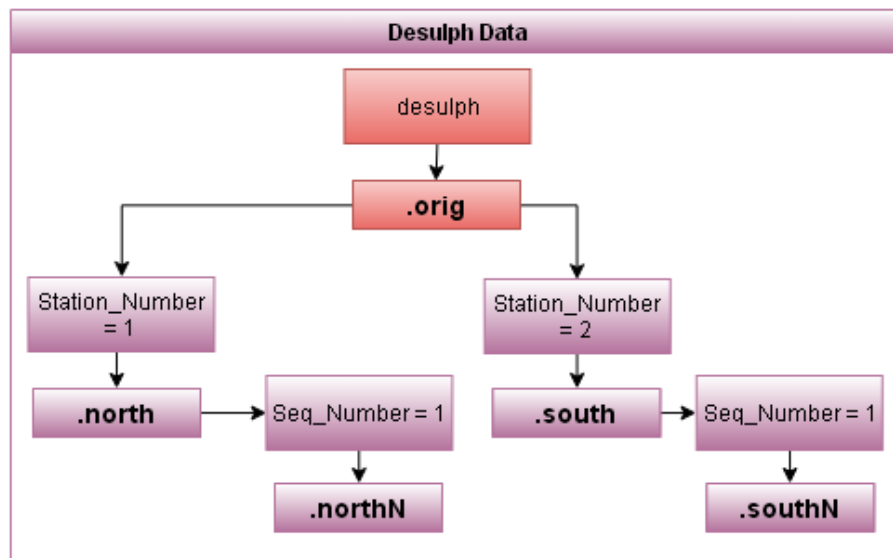
This model facilitates a higher level of process control, allowing for a more efficient treatment. The first section of the diagnostic system monitors plant model setup, calculating required Mg and CaO use, for each individual treatment. All of the data corresponding to actual model runs and simulated model runs performed by the system are stored in the data structure Model, as shown in Figure 4.7. The sortedN and sortedI structures contain data from the plant model for single and multiple treatments respectively. The ownN and ownI structures contain all model outputs and setup parameters from the simulated plant desulphurisation model built within this system which will be fully explained in the next section, for single and multiple treatments respectively.



**Figure 4.7 - Data & Logic Used For The Model Data Structure**

#### 4.1.7 Desulph Data Structure

This contains all of the raw data on the desulphurisation process extracted from the Des\_Treatment table, which range from injection weights to process times. As with all of the data structures so far in this section, this data is also processed and split into relevant structures, in this case between the two desulphurisation stations used for the process.



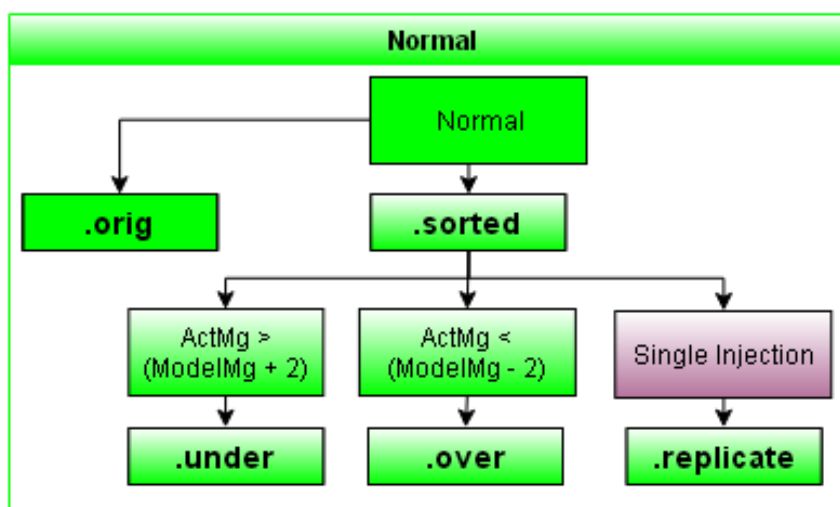
**Figure 4.8 - Data & Logic Used For The Desulph Data Structure**

As shown in Figure 4.8, a station number of 1 corresponds to the north station, and 2 to the south. An additional set of processing filters out all data for the first injection on all heats. Typically this is the only data, but for heats where there have been multiple injections, looking into the first injection can give a lot of insight into the cause of the problem.

#### 4.1.8 Normal Data Structure

As has been briefly described this structure is used to contain all of the relevant data for heats where there has been a single injection i.e. no issues with the process. This is done to facilitate the filtering of data elsewhere within the system, such as filtering of the model data mentioned previously.

Due to this the data in this section is more focused around the amounts of material being used, so two of the structures outlined in Figure 4.9 are for over and under treated heats, where too much or too little material has been injected respectively.



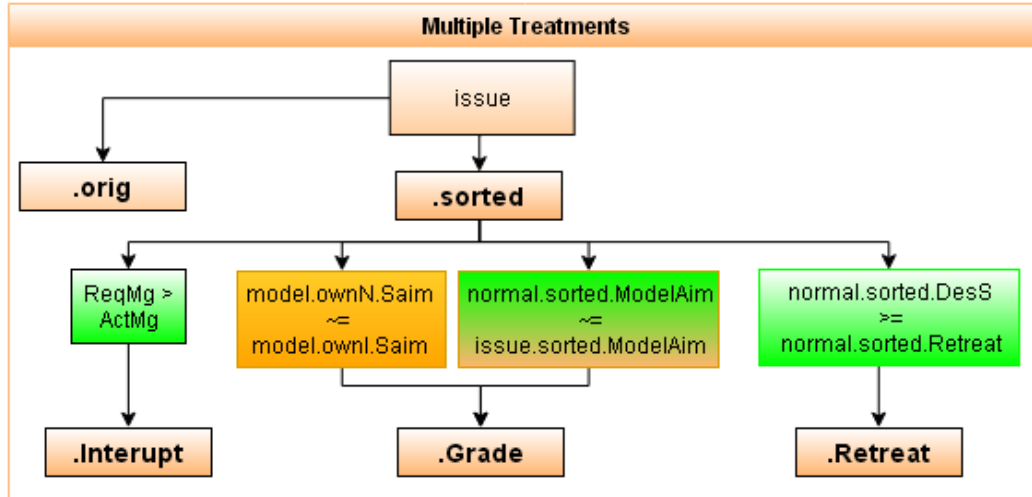
*Figure 4.9 - Data & Logic Used For The Normal Data Structure*

The final structure Replicate, will be explained in more detail later, but it contains data on all heats where the data is considered to be potentially incorrect due to a data recording error. Occasionally treatment data for a single heat gets recorded as the treatment data for two consecutive heats, this attempts to pickup these heats, to allow them to be dealt with correctly. This is done using data from the Desulph data structure, indicated in purple.

#### 4.1.9 Issue Data Structure

This section of the system is used to gather all of the data on heats that have had more than one injection. It is set up to monitor for process type issues and so the data structures within the issue data structure reflect this. The exact issues are considered in more detail later on in this chapter, but an interrupted treatment is one where an injection gets interrupted part way through the treatment. All data contained in this structure is relevant to helping diagnose

firstly what type of interruption occurred, and secondly how it affected the process. So to highlight these heats, it looks for heats within the normal data structure that have a required injected Mg weight higher than the actual injection Mg weight, as this is a good indicator.



**Figure 4.10 - Data & Logic Used For The Issue Data Structure**

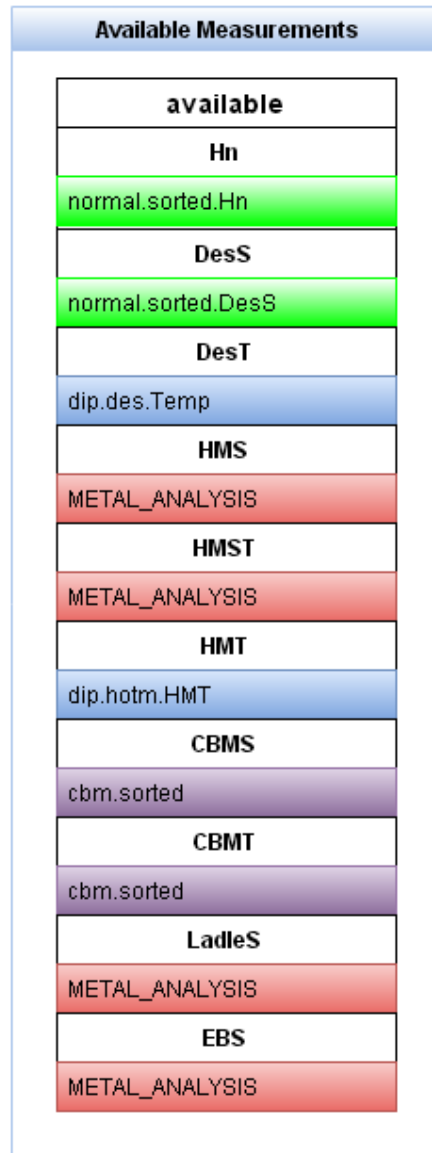
Another important structure is for grade related changes, as with any process in the steel plant grades and schedules can change at anytime, including part way through a treatment. This attempts to pick up if the operators have reacted to a scheduled grade change, which has caused them to carry out more than one injection.

The final structure is for retreated heats, which contains all relevant data on heats where the first injection removed insufficient quantities of S from the HM, and so needed to be retreated to further reduce the S level. This contains data to facilitate the diagnosis of the cause of this, as it isn't something that happens often.

#### 4.1.10 Available Data Structure

The purpose of this data structure is to collate all available data for the outputs of the system, housing commonly used sets of data, allowing additional code to search for relevant data to be reduced. The data contained is grouped into location typically, with analysis after desulphurisation treatment, HM analysis, CBM key parameters and finally vessel and ladle sulphur analysis. To facilitate in understanding the different data sources that the data is gathered from, in Figure 4.14, red is raw data direct from the plant databases, blue is from the Dip data structure, great from the Normal data structure, and dark purple is data from the CBM data structure.





*Figure 4.11 - Data Sources Used For The available Data Structure*

## 4.2 Desulphurisation Model

The aim of the research presented in this section was to establish a mechanism for monitoring the model setup to ensure, based on timings and available analysis, the operators use the optimum values for the model setup. This new approach means that the material use for each treatment can be well controlled. It also highlights increased planned material use in particular. The deployed model has embedded diagnostic capabilities allowing it to perform these tasks. A simulated desulphurisation plant model has been built into the diagnostic system, allowing all affects on material use to be quantified, from plant model adjustments. The system has been designed to check for a wide range of different situations, where the model setup has been altered.

### 4.2.1 Model Setup

The operators cannot adjust all four inputs into the plant desulphurisation model, with HM W and HM T being automatically set. In the case where the HM W is unknown, an automatic default value is obtained from a variable within the PSSUP1\_Logicals table in the PSSUP database. This means that only the correct Aim S and correct HM S need to be compared. The plant model setup screen that is used by the operators is shown in Figure 4.12.

**Figure 4.12 - Desulphurisation Model Intranet Information Screen, Showing Inputs Used For The Model Setup By The Operators**

#### 4.2.1.1 Aim S

This section of the system relies on being able to calculate what the Aim S was at the time of each treatment. This information is recorded within Port Talbot's databases against programme numbers. At every stage through a process, each batch of iron/steel (depending on how far through the process it has reached) is allocated a programme number, which only changes if there is a change to the grade/grades assigned to that batch. Every time the plant schedule is updated, the programme number and the update time are recorded to a table called Coord\_Link within the PSMET database. Along side this, a table called Program\_Analysis contains all of the program numbers and the relevant aims and limits for the different stages in the process route. Information held includes End Blow (EB) aims for C and T, ladle aims for C, T, S and so on.

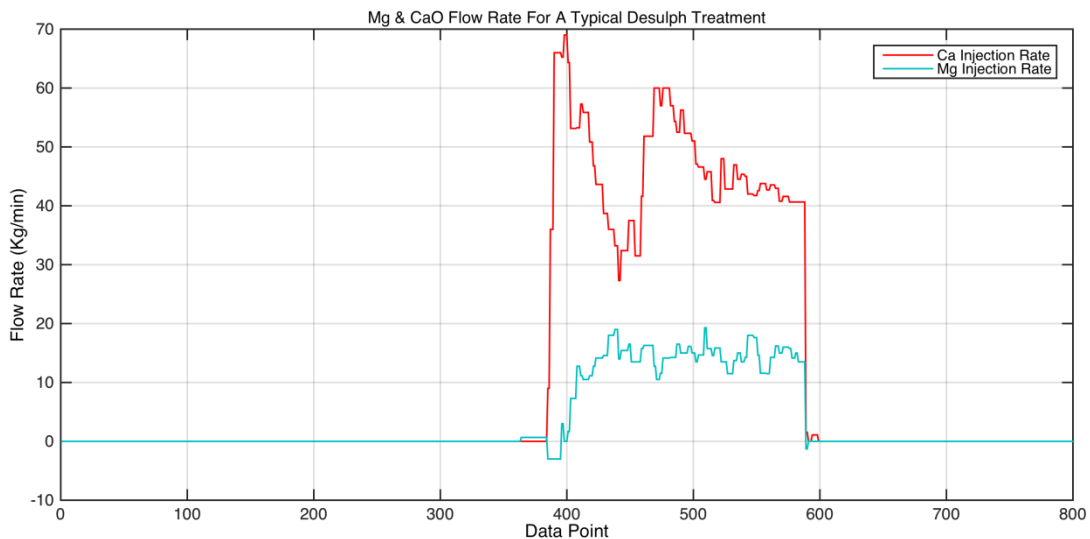
The start treatment time is not recorded in either the PSSUP or the PSMET databases. The start injection time was initially calculated from the finish time by using the CaO

injection weights. The CaO has a set flow rate of 60kg/min, so a relatively accurate estimated start time could be calculated by working out total injection time based on total weight over injection rate, shown by Equation 4.1.

***Equation 4.1 - Start Injection Time Based On CaO Weight***

$$\text{Start Injection} = \text{Finish Injection} - (\text{Injected CaO Weight} / 60\text{kg/min})$$

This proved to be generally acceptable, although occasionally if there were a lot of model runs prior to a treatment, and if the time was out by a few minutes due to injection issues, it resulted in the system comparing values against the wrong model setup. During the development of the EB C & EB T system, knowledge and programming experience was gained and applied to provide access within Matlab to the information contained in the Pi database. The Pi database contains continuous data traces for a wide range of parameters, including injection rates for Mg and CaO, as shown in Figure 4.13.



***Figure 4.13- Mg & CaO Flow Rate From The Pi Database For A Single Heat, Showing The Ratio Of CaO To Mg Weight Injected***

This allowed the accuracy of the start treatment time calculation to be significantly improved as the nitrogen gas flow starts earlier than the CaO flow and so gives a truer representation of the start treatment time.

In the deployed diagnostic system the start treatment time was found by finding the minimum time where the CaO flow rate rises above zero. This was determined using the Matlab code shown in Listing 4.1. There are occasions however where the incorrect station number is recorded, or an issue has occurred where a heat has been treated on both stations.

To ensure on these occasions the correct start time is also found, the system attempts to find the start treatment time for the assumed station. If however this process unsuccessful, the “if” statement loop checks on the other station to find a flow rate indicating a treatment, and find a start treatment time based on that trace instead. This ensures that the system is as robust as possible, as it needs to handle as many abnormal conditions as possible to ensure the system is useful to the plant.

```
% Open Pi Connection
picon = connpi();
picon.On;
% References to adjust pi tags
number = [0,1];
% Gas Flow A137 or A147
flowtag = strcat('GM10A1',num2str(3+ number(data.station(1))), '7');
flow = PiData('SELECT VALUE,TIME,STATUS FROM
PIINTERP',0,flowtag,data.d_start,0.05,data.d_finish);
flow.Data(picon.conn);
% Close pi connection
picon.Off
flow.Timenum('TIME','Time');
% assign the smallest time, with a flow above 0 to charge time
if isempty(flow.orig.Time(flow.orig.VALUE > 0))
    if data.both == 1
        stations = unique(data.station);
        picon.On;
        flowtag = strcat('GM10A1',num2str(3+ number(stations(2))), '7');
```

***Listing 4.1 – Matlab Code Used For Start Treatment Time Calculation Based On Pi Database Data Database Data***

The next step in working out if the model was setup correctly is cross referencing the start injection time, with the Coord\_Link table in the PSSUP database update times, to find which programme number related to the batch of HM at the time of treatment. The relevant programme number within Programme\_Analysis can then be used to find the ladle Aim S. This is the target S content of the steel when it is tapped at the end of the BOS process. The final step in this process is then to cross reference the ladle Aim S with the desulphurisation Aim S, which is based on ladle aims directly. When the system was originally built, this was simply part of a QA document, and was hard coded into the system.

**Table 4.1 Sulphur Aims Table From Port Talbot Intranet, Showing How Grade Aims Relate To Desulphurisation Aims**

Ladle Aim S	Desulphurisation Aim S	Scrap Type	Retreat Limit	Direct Charge Limit
0.040%	0.020%	Dirty	0.025%	0.030%
0.035%	0.016%	Dirty	0.021%	0.026%
0.030%	0.012%	Dirty	0.017%	0.022%
0.025%	0.009%	Normal	0.013%	0.016%
0.020%	0.005%	Normal	0.009%	0.010%
0.017%/0.018% I.F.	0.004%	Clean	0.008%	0.009%
0.015%	0.003%	Clean	0.007%	0.008%
0.012%	0.003%	Clean	0.006%	0.008%
0.010%	0.002%	X Clean	0.005%	-
0.008%	0.001%	X Clean	0.004%	-
0.006%	0.001%	X Clean	0.003%	-

The values in Table 4.1 were originally hard coded into the system, however in the interest of making the system more reliable and robust, it was suggested that these be saved to a table in the PSSUP database instead. These values were uploaded to a new table called SulphurAims in PSSUP, where they can be read by the system and when necessary automatically updated.

Most importantly, the technical department has access to adjust the values within this table, and their own plant model will now update itself automatically without any need for the hard coding to be adjusted. This was the case when the desulphurisation plant managers decided to introduce a new mix of Mg for the process, which affected the Mg efficiency for one, but also resulted in the desulphurisation aims being adjusted.

#### **4.2.1.2 HM Sulphur**

Torpedo ladles arrive on railway tracks into the BOS plant, where they are stopped on one of two weighbridges. With the use of the weighbridges, a set weight of HM is poured out of the torpedo ladle into a transfer ladle in the HM pit below. The capacity of the transfer ladle is typically higher than that of any one torpedo ladle, though the sizes will vary within the fleet, and so more than one torpedo ladle is typically used for the pour. During this process an operator takes a manual HM sample from the transfer ladle, which is passed onto the labs for analysis. Unfortunately due to the HM pouring area and desulphurisation

stations being in very close proximity to each other, there are occasions when the transfer ladles reach the desulphurisation stations for a treatment before the labs have performed the HM analysis. In such instances the actual HM S is unknown. In these cases the HM S is estimated from the CBM, these being based on the BF runner analysis for each of the torpedoes used to fill up the transfer ladle. There is a measured HM chemistry at the BF for each torpedo ladle of HM. Based on weights from each torpedo and their respective chemistry that has gone into the transfer ladle, an overall chemistry for the HM in the transfer ladle is estimated by the CBM, which is predominantly done with Neural Networks.

#### **4.2.2 Simulating the Plant Desulphurisation Model**

To quantify the effect on Mg & CaO use that the changes to incoming HM S and Aims S have, a simulated version of the plant desulphurisation model was built by the author within the system. This simulated version was then used in two main ways. It was initially deployed as a separate function that could be called from a script in Matlab. This was how the function was initially written. It provided an offline version of the plant model for use by the technical department overseeing the operation of the desulphurisation system. As progress with this system continued it was then also used as a nested function wrapped within a single desulphurisation system function, allowing this to be easily packaged into a standalone application for use within the actual system.

To allow adjustment of the plant model without having to adjust the actual code, a number of variables used within the model including constants, Mg efficiency and aim V ratio, were not hard coded. Instead these were included in a table in the PSSUP database, where they can be imported each time the model runs. The benefit of this approach is that the PSSUP1\_Logicals table in the PSSUP database, along with the Sulphur\_Levels table, can be edited by the technical department if they deem it necessary. This updated information can be accessed to adjust the model without modifying the code; the screen used to do this is shown in Figure 4.14. This made building a simulated model a lot easier, as it was built in the same manner as the plant model, so that it would automatically update if any of the values changed. The Matlab code generated in this research to achieve this is shown in Listing 4.2.

As Listing 4.2 shows, the desulphurisation model was designed using four inputs, HM S, Aim S, HM T and HM W. These are labelled in the first line in the listing as *sact*, *saim*, *hmtc* and *HM W* respectively. There are two main outputs, which are the required weights of Mg and CaO required for treating the incoming HM to the required levels.

```

function [Mg,CaO] = desulphmodel(sact,saim,hmtc,HM W)

...

% Make connection to PSMET database.
tic
conn = database('int_pssupl_ro','int_ro','xxx');
disp('PSSUP Started')
live = isconnection(conn);
if live == 0
    disp('PSSUP Connection Failed')
    pause(10)
    conn = database('int_pssupl_ro','int_ro','xxx');
    disp('PSSUP Started')
    live = isconnection(conn);
    if live == 0
        return
    end
end
end

```

***Listing 4.2 – Matlab Code Used To Simulate Desulphurisation Model Data Extraction***

The updateable values are extracted from the PSSUP database using the code in Listing 4.2. The remaining sections of the desulphurisation model were hard coded as shown in Listing 4.3. The vast majority of the calculations are done using anonymous functions, as it makes the code and the equations used a lot easier to understand, and a lot more reusable. The equations for this model were developed by Tata Steel's research and development department in Ijmuiden, and has since been rolled out across all of their European plants, however the replica model built within this system has entirely been programmed by the author as part of this project.

**PSSUP1 Constants Editor**

**Reblow**

**HM Desulph Model**

**Sulphox**

**Model Defaults**

**Adaption Limits**

**Misc Constants**

**Direct Tap Limits**

**Temperature Model**

**Endblow Carbon Aims**

**Endblow Temp Limits**

**Steel Ladle Limits**

**HM Ladle Limits**

PASSWORD (2) 
Your Name 
UPDATE

Parameter	Current Value	Update Value	Reason for change
HMDSM_LJMUIDEN_CONSTANT_1	0.1410010167	<input type="text" value="0.1410010167"/>	<input type="text"/>
HMDSM_LJMUIDEN_CONSTANT_2	-0.290309134	<input type="text" value="-0.290309134"/>	<input type="text"/>
HMDSM_MG_EFFICIENCY	0.77	<input type="text" value="0.77"/>	<input type="text"/>
HMDS_LIME_FOR_HIGH_AIM_SULPHUR	30	<input type="text" value="30"/>	<input type="text"/>
HMDS_LIME_FOR_LOW_AIM_SULPHUR	30	<input type="text" value="30"/>	<input type="text"/>
HMDS_LOW_SULPHUR_THRESHOLD	0.0012	<input type="text" value="0.0012"/>	<input type="text"/>
HMDS_MG_LIME_RATIO	2.25	<input type="text" value="2.25"/>	<input type="text"/>

**Figure 4.14 - Plant Desulphurisation Model Constant Update Screen From Port Talbot BOS Plant Intranet**

The portion of code shown in Listing 4.3 is split into three sections. The first adjusts the incoming values for Aims S, HM S, and HM T to the required format. The second section defines all of the equations that are required for the necessary calculations, all in anonymous functions. It would be possible to put all of the equations into a single calculation, however they were split up like this to make reading and understanding of the code for the calculations much easier. The final section is where the anonymous functions are called with the inputted values to calculate the Mg & CaO weights.

```

%% Mg
% Mg Data
sact = sact.*1e4; saim = saim.*1e4;
hmtk = hmtc+273.13;

% Mg Formula
hmc.eq = @(hmtc) 1.3+(0.00257.*hmtc);
ks1.eq = @(hmc,hmtk) 10.^(0.18-(0.11.*hmc) +(11839./hmtk));
ks2.eq = @(hmtk) exp((-404070+(169.21.*hmtk))./(8.314.*hmtk));
k.eq = @(ks1,ks2) ks1.*ks2;
etamg.eq = @(sact) (ijmuiden1.*log(sact))+ ijmuiden2;
predmg.eq = @(HM W,etamg,k,saim,sact) ((HM
W./(etamg.*1000)).*(k./saim)+((24.3./32.1).*(sact-saim)))./mgeff;

% Mg Calculation

```

**Listing 4.3 - Mg & CaO Weight Calculations Within Desulphurisation Model Shown In Matlab**



The code for the desulphurisation model function has been written in such a way to enable it to handle vectors as well as scalar values. This means the function doesn't need to be called individually for each heat that the system is checking. It can instead be called once, and populated with all of the data in the form of vectors. It is then able to calculate the required weights for multiple heats at the same time. This is important, as it makes the use of the code a lot quicker as it only needs to call upon the function once. It is also a lot more user-friendly, as it requires significantly less code to be able to analyse large numbers of heats. As is shown in Listing 4.4, the desulphurisation model function is called by passing it four inputs, and assigning two outputs. The inputs here, all part of the model.ownN data structure, as shown in line 2 and 3 of the listing, can be either single values or vectors. The "own" implies it is calculated by the replica model, and the "N" that is applies to normal heats.

```
%% Normal data desulph run
[model.ownN.Mg,model.ownN.CaO] =
desulphmodel(model.ownN.Sact,model.ownN.Saim,model.ownN.Hmt,model.ownN.HM W);
```

***Listing 4.4 - Use Of desulphmodel Function In Matlab Code***

### **4.3 Desulphurisation Expert System Outputs**

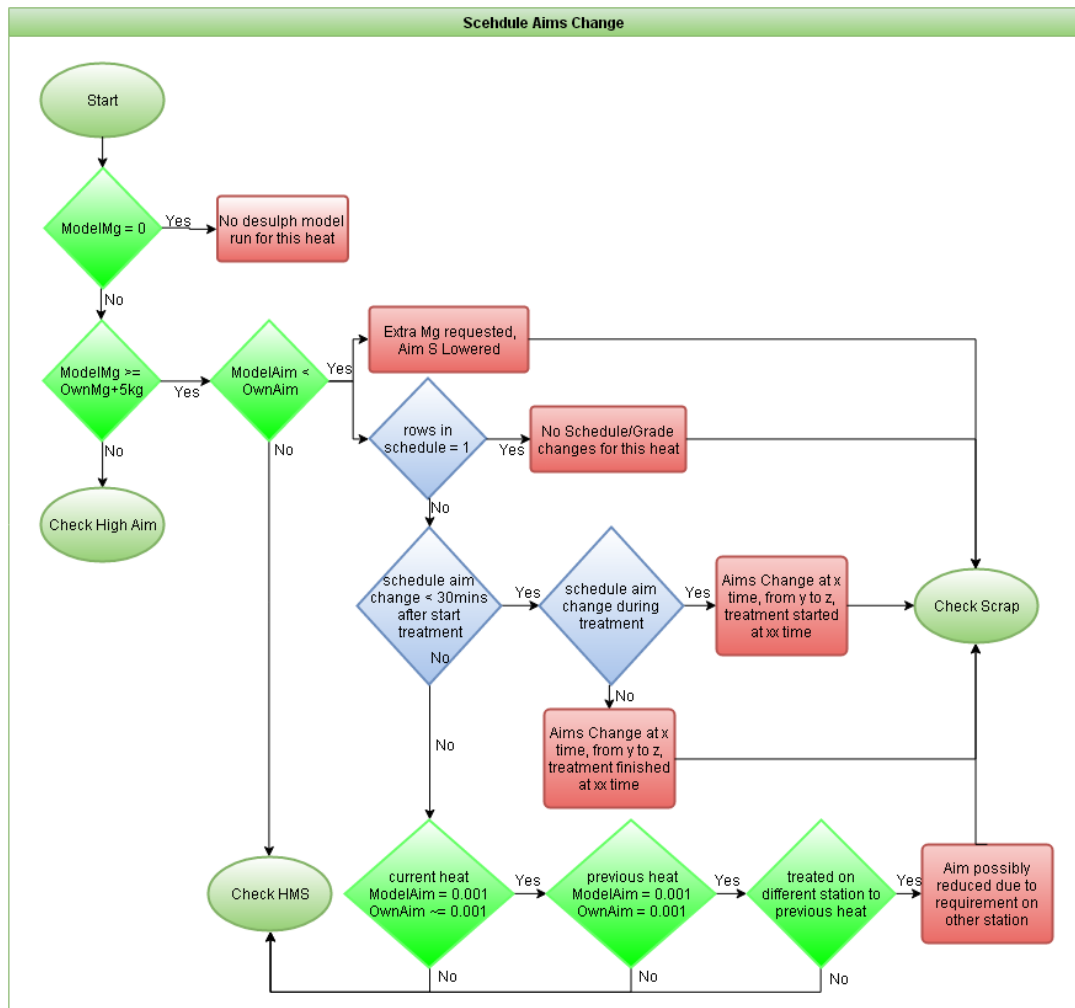
The first section of the system outputs to be covered are those related to the model setup, as the model setup is the first stage at which process issues or deviations can occur. The system outputs are focused on improving the operator performance, as it is at this stage that the operators can and do adjust the process, whether it is correct to do so or not.

#### **4.3.1 Aim Sulphur Adjustment Outputs**

There are four different shifts and on each shift a number of operators. There are wide ranges of adjustments that can arise with the model. Consequently the outputs for this section of the system are fairly extensive, given the fairly simple nature of the process itself. As there are two variables the operators can adjust, the HM S and Aim S, it is around these two that the outputs are based. Analysis of the actions taken allows the assumption that the operators will only ever adjust one of these at a time, allowing the outputs for each to be dealt with separately.

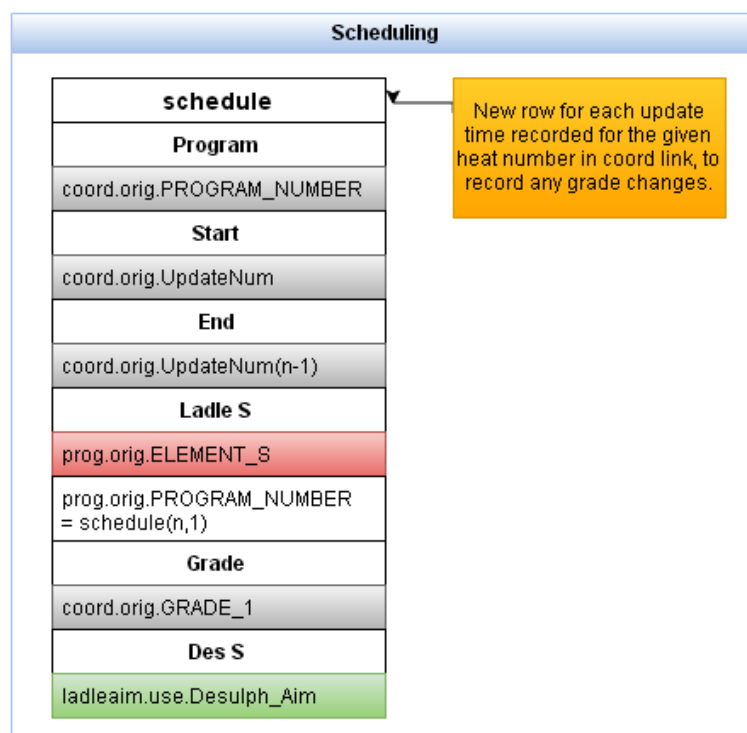
### 4.3.1.1 Schedule Aims Change

Before the system goes into checking if and how the model has been adjusted, it first checks to see if the desulphurisation model was actually run. Occasionally the operators will simply put in there own Mg & CaO values into the desulphurisation plant without getting the model to calculate the required values. When this does happen the system generates an output, an example of which is shown on row one of Figure 4.15.



**Figure 4.15 – Flow Diagram Showing Data & Logic Used For Schedule Aims Change Outputs**

There is a single variable within the system called “schedule”, which updates for every single heat individually, shown in Figure 4.16. It contains all the different programme numbers and update times assigned to that heat number between the HM pour station and the end of blow at the vessel, as shown in Table 4.2 the program can change very often.



**Figure 4.16 – Data & Logic Used For The Schedule Data Structure**

For each heat that is applicable, the system calculates within this schedule variable the time difference between the program number update time and the start and end treatment times. These times are shown in Table 4.2 as the Start and End columns, these being date strings converted to a number within Matlab, to facilitate the calculation and comparison. The system additionally calculates this difference within thirty minutes of the start treatment time as well. Occasionally before the schedule gets changed, typically a maximum of thirty minutes in advance, the schedule coordinator can ring the desulphurisation station to advise the operators to adjust the Aim S, as there is going to be a grade change for that specific heat by the time it reaches the BOS vessel.

**Table 4.2 Schedule Variable Built Within Matlab**

Program	Start	End	Ladle S	Grade	Des S
683	736207.5	736208.2	0.02	3046	0.007
681	736208.2	736208.5	0.02	3063	0.007
132	736208.5	736208.6	0.005	3154	0.0015
681	736208.6	736208.8	0.02	3063	0.007
131	736208.8	736208.9	0.005	3154	0.0015
683	736208.9	736208.9	0.02	3046	0.007
377	736208.9	736209	0.02	3190	0.007
368	736209	736209.2	0.02	3190	0.007

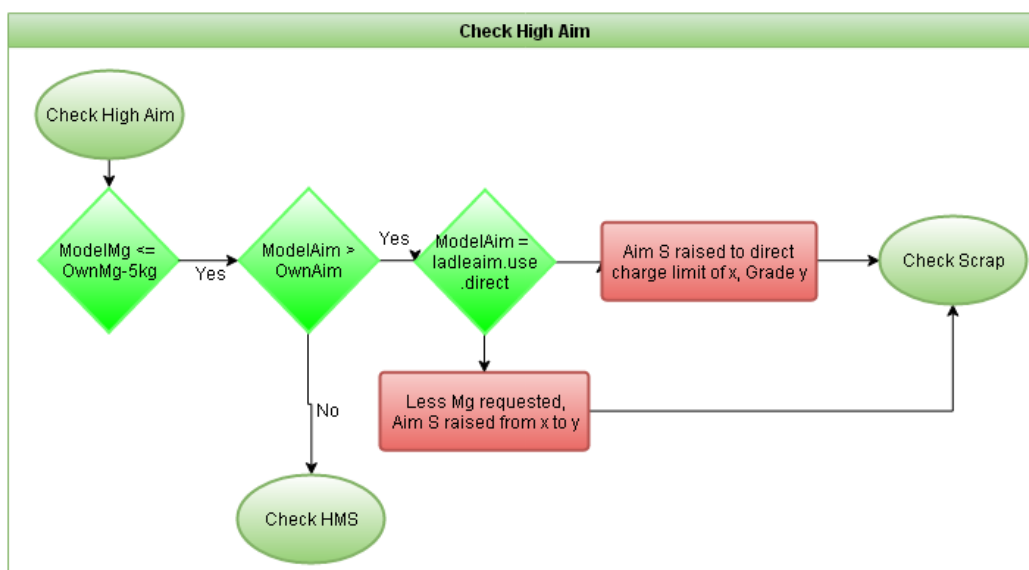
In situations where a schedule change has occurred, the system checks that the nature of the change is the same, i.e. that both Aim S have either been raised or lowered. If they have both been lowered, the system will additionally mention the change in Aim S and their respective grades, and specifically highlight the timings, if it occurred prior or during the treatment, as shown in Figure 4.15.

If the system is unable to find a valid grade change to justify the reduction in Aim S, it checks the grade of steel being made on the opposite station. If there is a low S grade, typically Aim S of 0.0011, and it is considered a special or trial grade, the operators will occasionally treat both stations down to the low S aim. This is not a procedure that has been put in place by management, as it should not be necessary, but the operators themselves perform it. The operators carry this out to provide a backup ladle if there is an injection issue on the station initially allocated the low S treatment, regardless of the actual aim on the 'back up' station.

To make this section of the analysis as robust as possible, the Aim S values have not been hard coded into the system. They are instead uploaded from the Sulphur\_Levels table in PSMET each time the system runs. The initial step is for the system to check if the Aim S has been lowered to or below the lowest aim in this table. If this is the case, then it will check to see if the aim for the treatment on the opposite station at the time of treatment was also at or below the lowest aim. When this is applicable, the system will create an output, highlighting that this is likely due to demand on the other station, quoting the relevant grade numbers. The logic for this is depicted in Figure 4.15, with this output being in the bottom right hand corner of the diagram.

#### **4.3.1.2 Check High Aim**

If the operator has raised the Aim S, the first thing the system checks for is whether the Aim S has been raised to the direct charge limit. Direct charging is when a HM ladle is charged directly into the BOS vessel without a desulphurisation treatment. For a given grade of steel, there is target chemistry for the steel ladle at the end of the BOS process. Based on this, the desulphurisation treatment aims for S are set, as well as a limit on S for HM to be direct charged into the vessel.



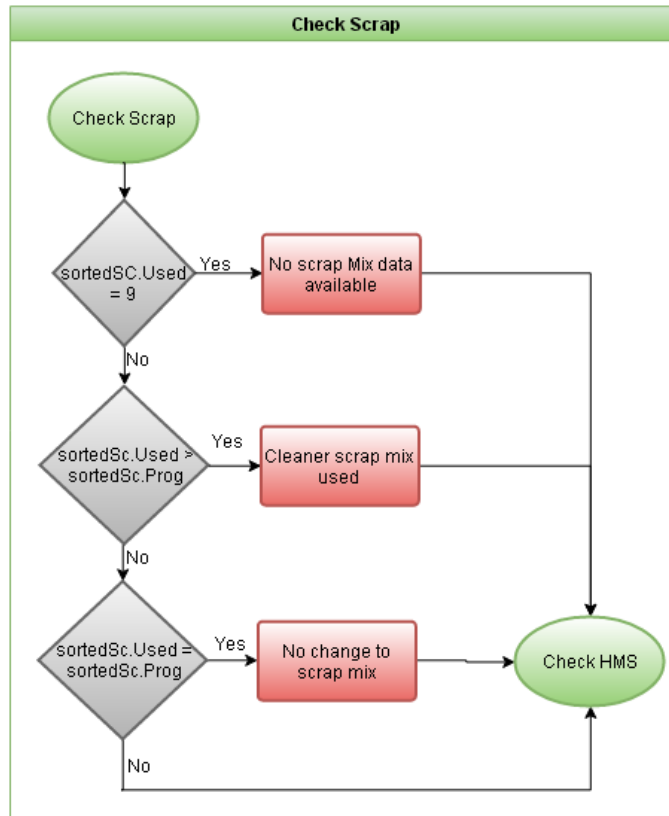
**Figure 4.17 - Flow Diagram Showing Data & Logic Used For Check High Aim Outputs**

The BF keeps producing iron regardless of any issue within the BOS plant or casters. This can result in a large number of full torpedo ladles stacking up outside of the BOS plant. The level of such HM that is ready but cooling outside of the BOS plant is known as standage. If there is a lot of HM available, it is known as high standage. This is an issue, as it will be cooling down and so the speed of work will need to be increased accordingly. If this is the case, to reduce treatment times within the desulphurisation plant, the heats will be treated as little as possible, to the direct charge limits for the aim grade being made. This is done, as at full capacity the desulphurisation stations are a bottleneck within the steel plant at Port Talbot. In order to be as useful to the shift managers as possible, this type of output contains the applicable direct charge limit and the grade of steel being made. The system also checks if the scrap mix being used at the vessel changed. Typically, when speed of work increases and the heats are treated to the direct charge limits, a cleaner scrap mix is used. This maintains the S balance within the vessel, by offsetting the increase in S from the HM with a decrease in S coming from the scrap, avoiding a negative impact of the steel chemistry. The first row in Figure 4.17 shows the logic used to generate the output for raising the Aim S to the direct charge limit. If the Aim S has been increased, however not to the direct charge limit, then the system has been designed to highlight the effect on Mg weight requested by the desulphurisation model for the treatment, the used Aim S and correct Aim S, and the grade being made at the time, which is shown as the second output in Figure 4.17.

#### 4.3.1.3 Check Scrap

As shown in Figure 4.15 and Figure 4.17, if certain outputs within these sections are used, the scrap mix used at the vessel is also checked within the Check Scrap section, shown in Figure 4.18. This is done to add additional information to the output, as often an adjusted

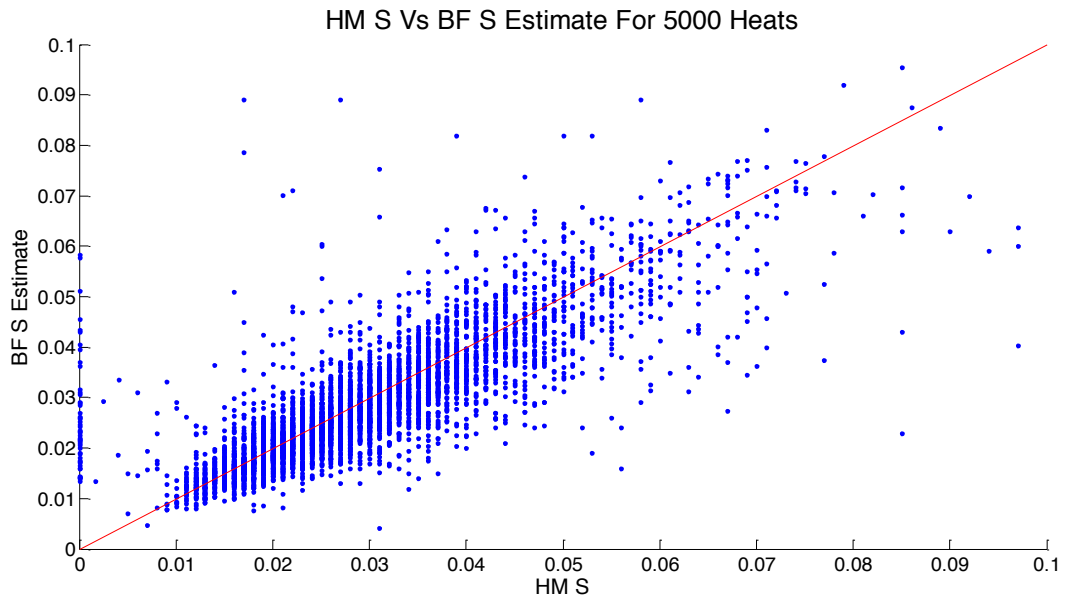
treatment at the desulphurisation station means changing the scrap mix at the vessel, to maintain the total S burden of the total charge. The sortedSc.Used and sortedSc.Prog depicted in Figure 4.18 come from the coord link data structure that has previously been described in Figure 4.6, and is depicted by the grey colour to represent this.



**Figure 4.18 - Flow Diagram Showing Data & Logic Used For Check Scrap Output**

#### 4.3.1.4 Check HMS

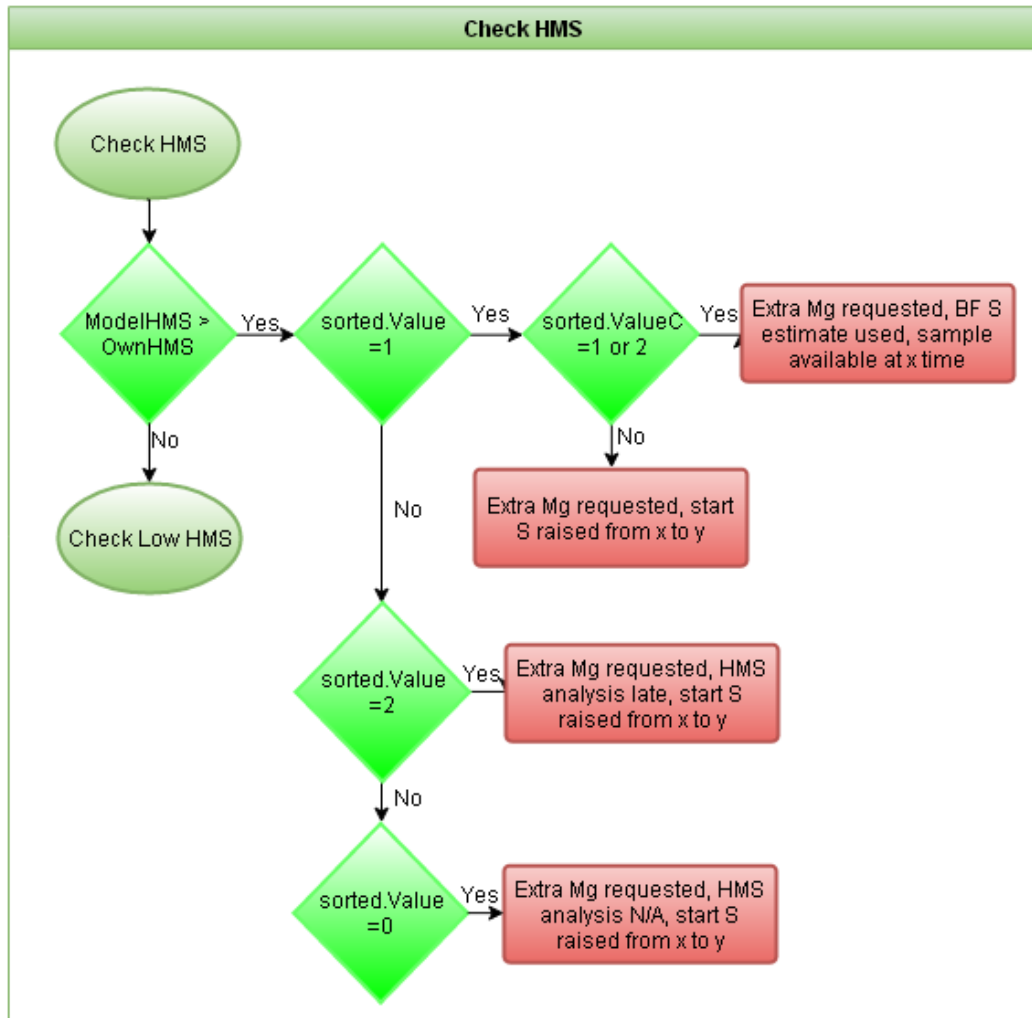
The second parameter the system monitors is the HM S value used by the operator. The initial processing steps are first to check the availability and secondly the timing of the HM analysis. There are set procedures in place to allow the operators to use estimated values, based on BF runner analysis, if the samples are either received too late for the process or are unavailable. If the HM analysis is late or unavailable, the operator should use the CBM estimated HM S value as a replacement HM S value. As shown by Figure 4.19, the estimate shows good correlation with the actual analysis, and so provides a good backup for late or unavailable analysis.



***Figure 4.19 - HM S Analysis Vs CBM Estimated S, The Data Points Follow The Red Line Indicating The BF S Estimate Can Model The HM S***

There are 2 sets of outputs for this section of the expert system, one when the HM S has been raised, increasing the requested Mg weight, and another when it has been lowered. The following outputs will be discussed in respect to raising the HM S as this is the most common occurrence.

In situations where the used HM S value doesn't align with the value the system has calculated should have been used, the system first checks if the HM S analysis was late based on sample timings. When this is the case and the CBM S has been used no output is generated by the system, this is the correct procedure to take. The system has been designed to highlight however when the CBM S estimate has been ignored in favour of an operators own higher estimated value, as this has a detrimental effect on material use, this is depicted as the third output in Figure 4.20. The sorted.Value variable referenced in the diagram comes from the Normal data structure shown in Figure 4.9, which is why it is highlighted in green. It has 3 values, 0, 1 and 2 which correspond to available, late and not available respectively to the HM S analysis.



**Figure 4.20 - Flow Diagram Showing Data & Logic Used For Check HMS Outputs**

As with late samples, when the analysis is completely unavailable, if the CBM S estimate is used, then no output is generated, as this is correct. However in cases where the CBM S estimate hasn't been used, the system generates an output highlighting this issue, along with the CBM estimated S and the used HM S value. This allows a comparison to be easily made by the manager about the issue. The logic used and the output is shown as the final output in Figure 4.20.

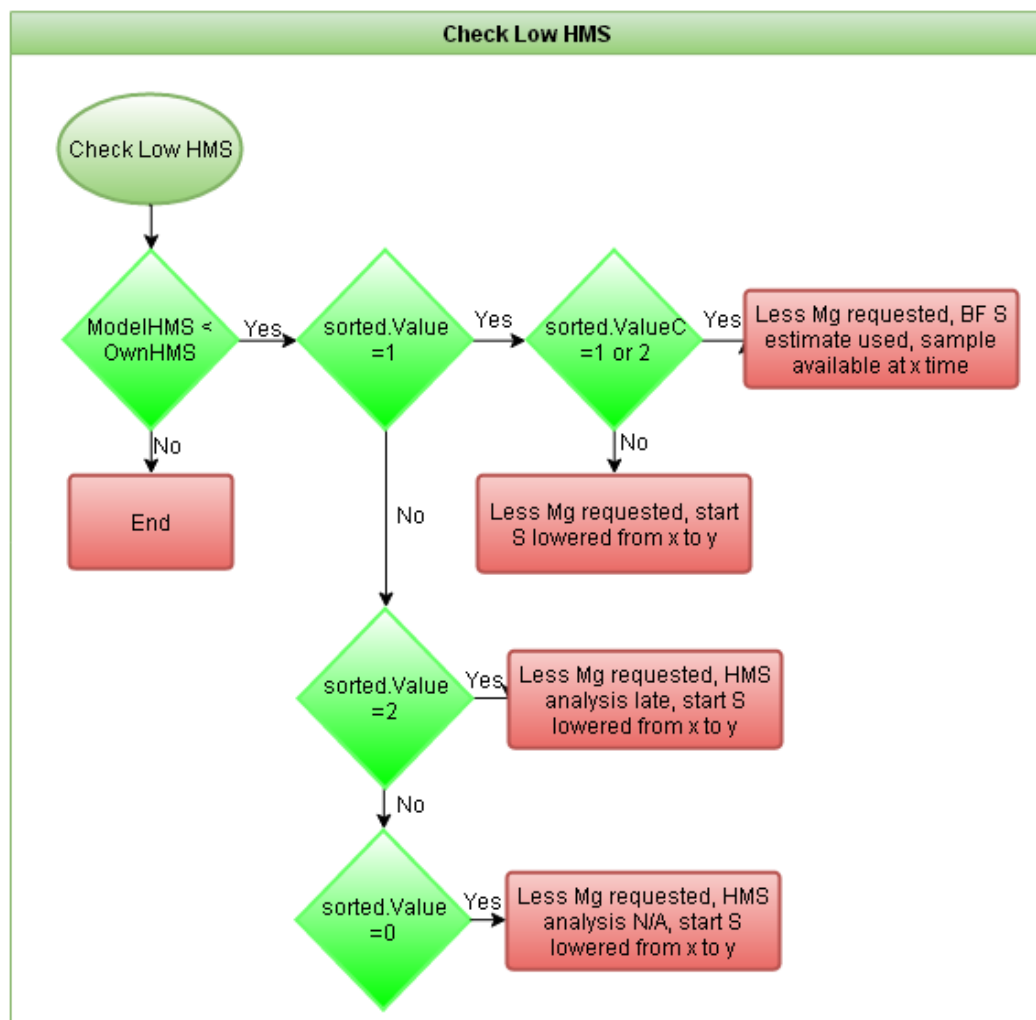
If the HM S is available, but this value wasn't used, the system initially checks to see if it was the CBM S value that was used. If that is the case, the system generates an output highlighting that the CBM S value was used when the HM S was available. This is the case where the Normal.sorted.ValueC is equal to 1 or 2, shown by the first output in the figure above. Additionally the difference in requested Mg weight and relevant timings for sample availability and start of treatment are quoted as shown.



When the CBM S isn't used either, meaning the operator has decided on their own value, there is no need to highlight the timing's as all samples were available. Instead the change in requested Mg weight, along with the used and correct HM S values are displayed, as shown by the second row in Figure 4.20.

#### 4.3.1.5 Check Low Hot Metal Sulphur

The alternate scenario where the HM S has in fact been lowered is shown below for reference in Figure 4.21. As can be clearly seen the outputs are almost identical in nature to those shown in Figure 4.20, however the initial criteria differ, where the used HM S is checked against the calculated HM S.



**Figure 4.21 - Flow Diagram Showing Data & Logic Used For Check Low HMS Outputs**

### **4.3.2 Normal Desulphurisation Process Outputs**

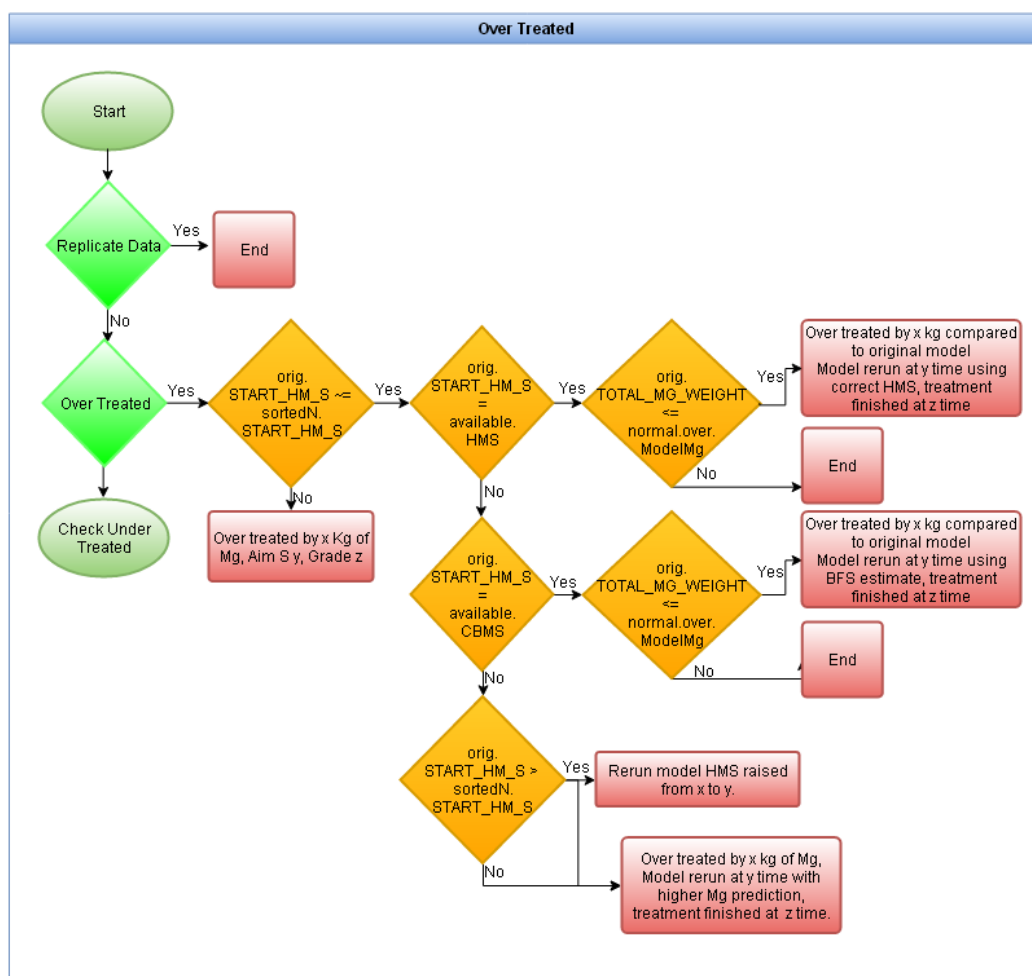
The primary focus of the process section of the diagnostic system is process performance. This is considered in terms of the number of injections per treatment and material use. This involves monitoring lance issues causing interrupted treatments, over and under treatments, and diagnosing causes of occasional re-treatments. Where appropriate these issues are quantified in terms of deviation from the aim end point chemistry, as this is considered a key process indicator.

To better represent the state of the process, all calculations of under and over treatments are based upon the model run using the values of HM S and Aim S used by the operator. It is a measure of how closely the model has been followed, in contrast to the model section, which looks into how well the model was setup.

#### **4.3.2.1 Over Treated**

The system has been designed to monitor for over and under treatments. In addition to affecting process cost this can also be an indicator of a process issue. This is an important section of the desulphurisation diagnostic system, as a great deal of development has gone into the plant desulphurisation model, to improve the efficiency of material usage during the treatments. Clearly, if this model isn't being followed, there will be detrimental effects on the capability of the technical department to refine and improve the state of the model. Therefore the main focus of this section of the system is to try and diagnose why this model isn't being followed, and whether this is due to the operator or the equipment.

An outline of the outputs for this section are shown below in Figure 4.22, where the green diamonds correspond to the Normal data structure shown in Figure 4.9, and the yellow diamonds correspond to the Model data structure shown in Figure 4.7. The first check the flow diagram shows is checking if the heat is considered potentially to have replicate data from the previous heat. If this is the case this section of the outputs is abandoned, as they are potentially misleading. A separate section of outputs are designed later on page 120 to handle this instance, but it is separate from this set of outputs at this stage.



**Figure 4.22 - Flow Diagram Showing Data & Logic Used For Over Treated Outputs**

There are a number of occasions when the operator reruns the desulphurisation model during the treatment, meaning they need to adjust the amount of Mg and CaO used during the treatment accordingly. This section of the system has been designed to initially check for model reruns during the treatment. All data corresponding to this type of issue has been built into the Model data structure to facilitate the investigation and generation of relevant outputs.

The first output generated in this section is if the HM S used is the same as the calculated correct HM S, as shown in Figure 4.22. If this is the case, the heat has simply been over treated without an obvious cause. Occasionally this is down to the grade being made, if it is a low S grade, occasionally the operators feel the need to over treat as a preventative measure, and so the grade and aim S is highlighted for this reason.

If the original model run was performed with an estimated HM S value this would be either an operators own estimate or CBM S. If then during the treatment the model is rerun using the correct HM S value, the system checks to see if both the used weights and the

newly calculated weights are the same. If this is the case, the system then generates an output, commenting on the difference in Mg weight from the original model run, along with the relevant timings for the new model run and the end treatment time, as shown by the top output in Figure 4.22.

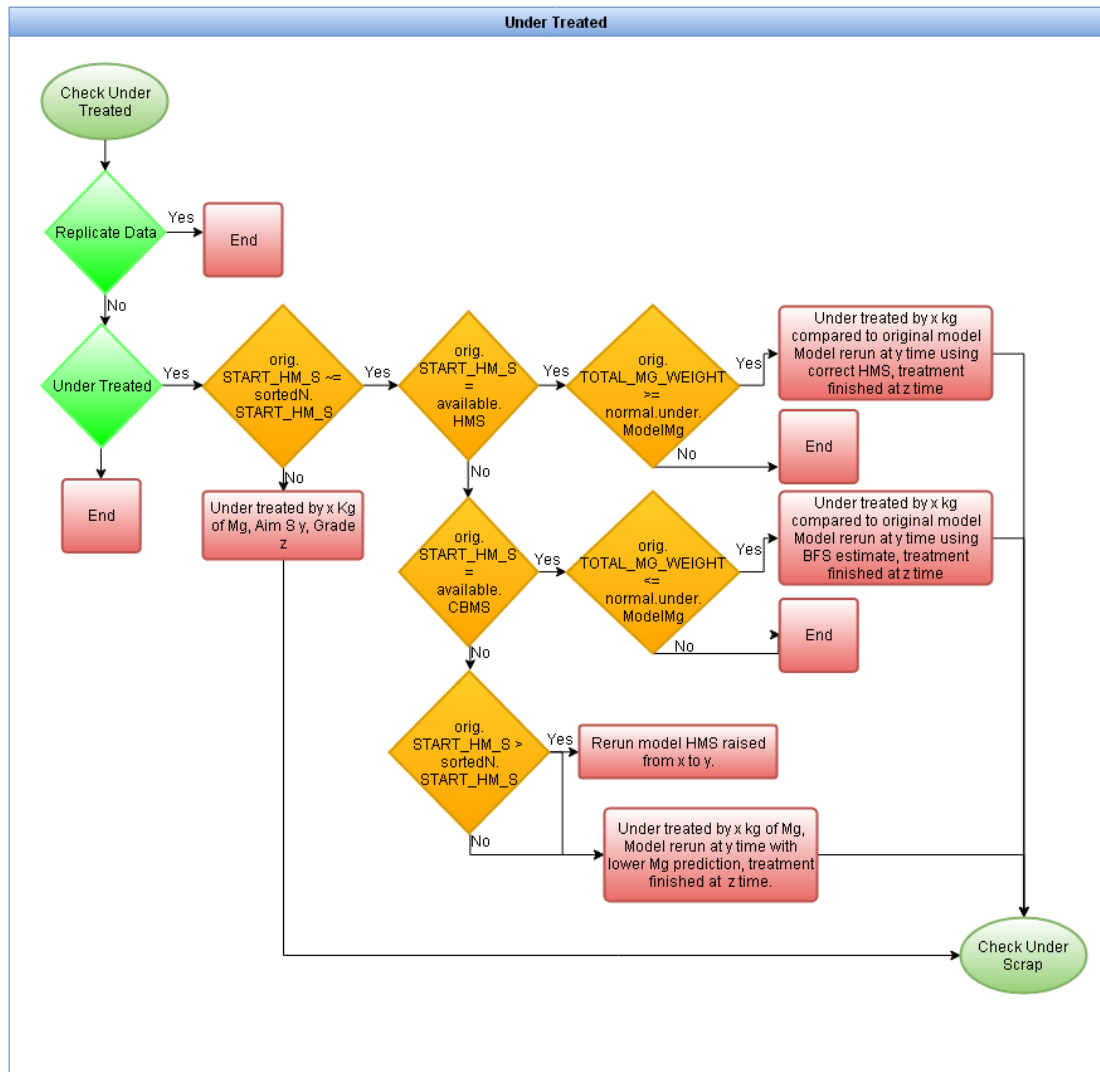
There are occasions however where the operator decides to rerun the model during the treatment, replacing the available HM S with the CBM S, and proceed to adjust the end used Mg weights accordingly. The only situation where this would be appropriate would be if the incoming HM S is obviously too high or low; based on experience the operators will know roughly what the incoming HM S value should be. However this isn't normally the case when this situation is monitored by the system, it is done to simply over treat the ladle, as shown by the second row output in Figure 4.22.

There are unfortunately occasions where the operators decide to rerun the model during the treatment with their own estimate for HM S. This will typically involve increasing the total Mg used to avoid a potential re-treat, shown by the final group of outputs in Figure 4.22.

The final section of the outputs arising from model reruns is associated with aim adjustments. The author intended to specify what the adjusted Aim S values were, to enhance the level of detail available, but after consulting key members within the technical department, the additional detail was considered unnecessary. Due to this, if the Aim S has been changed within the new model run, the system generates an output only detailing a few values, this is the final output generated in this section. The final check is to see if the HMS value has been changed, if it hasn't the only other adjustment must be the aim.

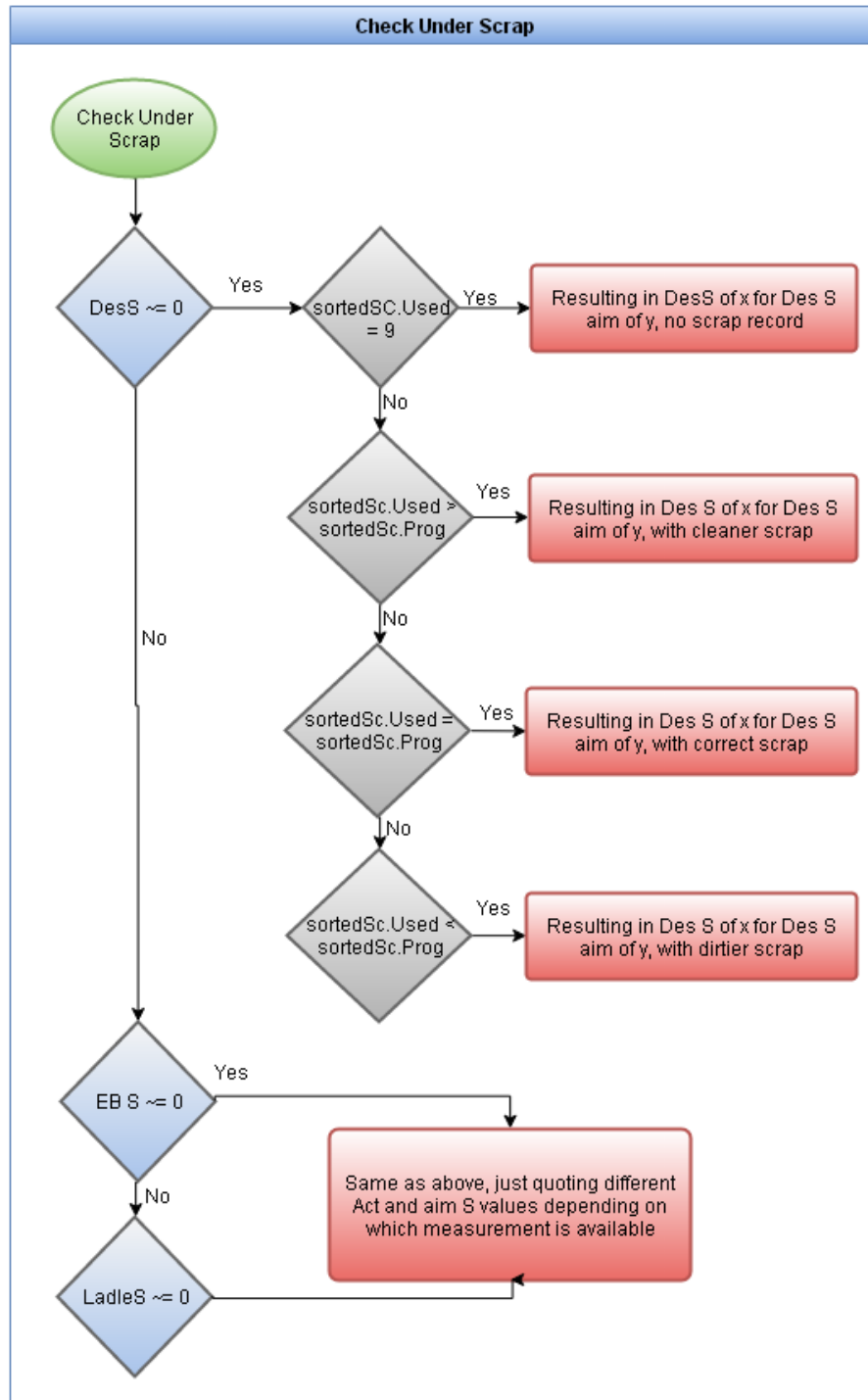
#### **4.3.2.2 Under Treated**

As with previous output sections, this section is equivalent to the over treated section of the outputs, all that differs is the actual Mg weight compared with that actually used. As can be seen below in Figure 4.23, the main structure of the outputs is identical.



**Figure 4.23 - Flow Diagram Showing Data & Logic Used For Under Treated Outputs**

There is one key difference however, if any of the outputs in this section are triggered, there is an additional section of outputs checked through call Check Under Scrap shown below in Figure 4.24.



**Figure 4.24 - Flow Diagram Showing Data & Logic Used For Check Under Scrap**

The light blue diamonds of data here correspond to the Available data structure shown in Figure 4.11, and is primarily designed to contain useful data for the outputs. The grey diamonds represent the coord link data structure as previously discussed in Figure 4.6, with the sortedSc structure in particular containing relevant data on scrap mix selection.

Where a treatment has been under injected for Mg, it was determined to be beneficial for the system to monitor the end point chemistry. If a treatment is under injected, this should imply that insufficient S has been removed from the HM, which would have an adverse effect on the S balance at the vessel, potentially causing a downgrade further along the process route. It is important to note, that if a ladle is re-treated, then it is no longer classed simply as under treated, and this section of the outputs will be bypassed. However for treatments that are simply under treated without a re-treat, the system will attempt to analyse the effect the reduced injection has had on the chemistry, at the first point of measurement.

There is a sampling point in the procedure before the HM ladle is transferred and poured into the BOS vessel. This analysis will involve S and T measurements; however a sample isn't always taken. If there is a need to increase speed due to high standage, there is often no desulphurisation HM sample taken. To complicate matters, occasionally no EB analysis is taken either, although there is always ladle analysis, as this is exceptionally important for secondary steel making.

The system will systematically attempt to find the first point of measurement, as close to the end of treatment as possible. This will initially involve checking for a desulphurisation HM sample, this is the purpose of the Available data structure as this search is always carried out as part of the data processing, and only needs to be done once. If this isn't available then the next point is EB analysis. If there is high standage, or single vessel operations for some reason, then quick tap models are used based on IB lab analysis and so EB analysis isn't always available. A quick tap model, based on steel chemistry at the IB point in the process, and additions made since the IB point, will estimate the EB chemistry. If there is a requirement for speed of work to increase, relying on this estimated EB analysis, is quicker than waiting for any lab analysis to arrive. When this arises, then the ladle analysis is used to assess the effect on S levels.

When the nearest analysis is found, the system creates an output outlining the relevant S analysis, along with the Aim S for that specific point in the process as shown above in Figure 4.24.

### **4.3.3 Non-Normal Desulphurisation Process Outputs**

As with any batch process, if specific properties aren't obtained during the process, then the batch is occasionally reworked, or in this case re-treated. In the case of the desulphurisation process, if the end point S chemistry isn't reached, then the heat if necessary is re-treated.

This can also happen if there has been an Aim S change due to re-scheduling, to a lower S grade specification.

There is a similar situation to a re-treat called an interrupted treatment, where the treatment gets interrupted part way through, typically due to an injection flow issue. The key difference is that a dip has been taken; the operators only take a dip if they consider the treatment to be finished. The operators will not take a dip every time the treatment gets interrupted, as the treatment is not finished. But if a heat is under treated because the operator thinks it can be, they will take a dip as it is considered a finished treatment. If after the dip has been taken, the operators decide to reduce the S level further, it is considered a re-treat.

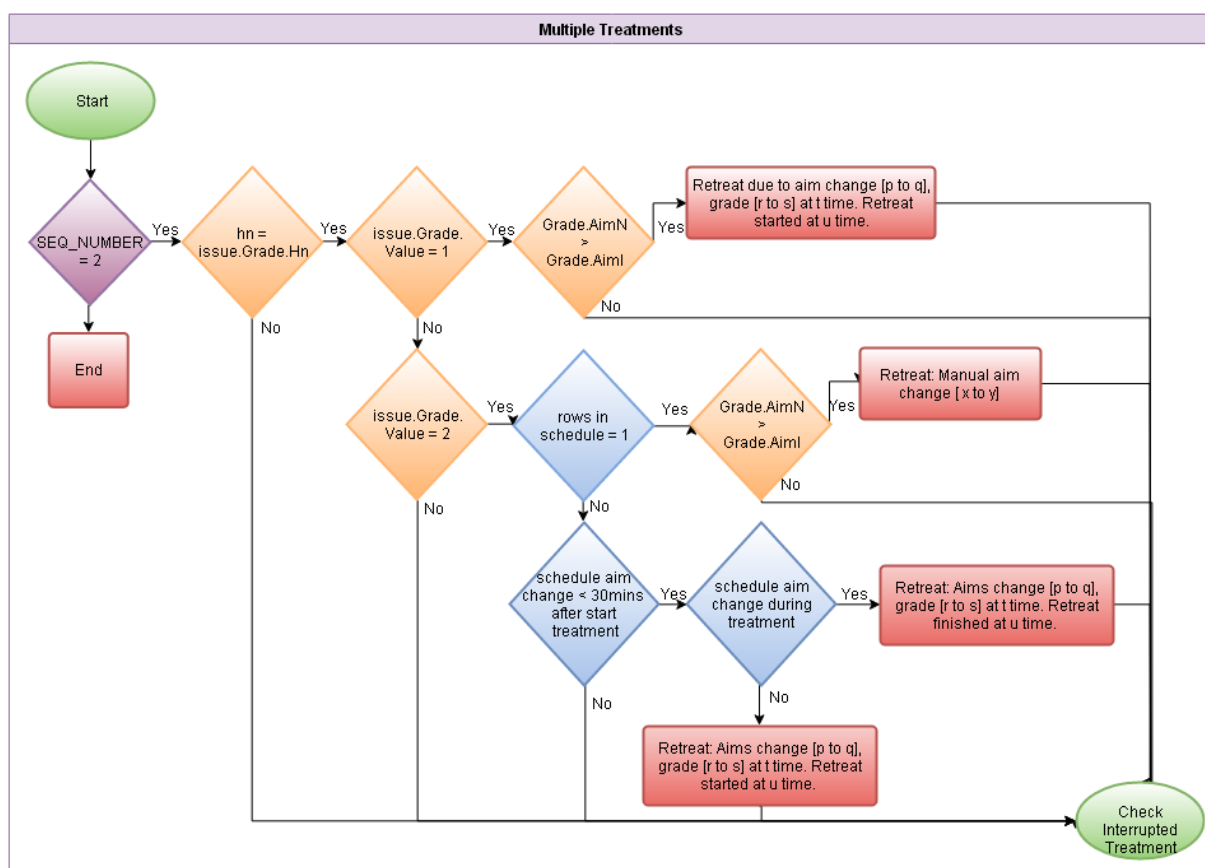
#### **4.3.3.1 Aim Sulphur Change**

As previously mentioned, there can be cause for a re-treat due to schedule changes affecting the grade assigned to the batch being treated. If this batch is initially assigned to a high S grade, but after the schedule change, it has been assigned to a low S grade, then it is necessary to re-treat the batch to ensure the new target chemistry is obtained.

The system starts by checking if the re-treated heat has had a scheduled Aim S change, between the start of the initial treatment and the end of the re-treat that matched the new Aim S used in the re-treat model run. The time frame checked is quite wide, but this is necessary as previously mentioned, due to the schedule coordinator occasionally notifying the desulphurisation pulpit in advance. As previously discussed, this is done within the Schedule data structure, which is referred to in Figure 4.25 with light blue diamonds, the orange diamonds correspond to the Issue data structure.

If the scheduled Aim S change has taken place before the re-treat began, then the system output contains the new and original Aim S values, along with the relevant grade numbers and appropriate timings, as shown by the first row in Figure 4.25. If the schedule change occurred during the re-treat, the system generates an output highlighting the timings of the schedule update time, and the end treatment time, along with the relevant Aim S and grade number changes, as shown above. The timings in both of these instances are highlighted to allow the manager to fully understand the timescale involved, which furthers their understanding of the operator's actions.





**Figure 4.25 - Flow Diagram Showing Data & Logic Used For Multiple Treatment Outputs**

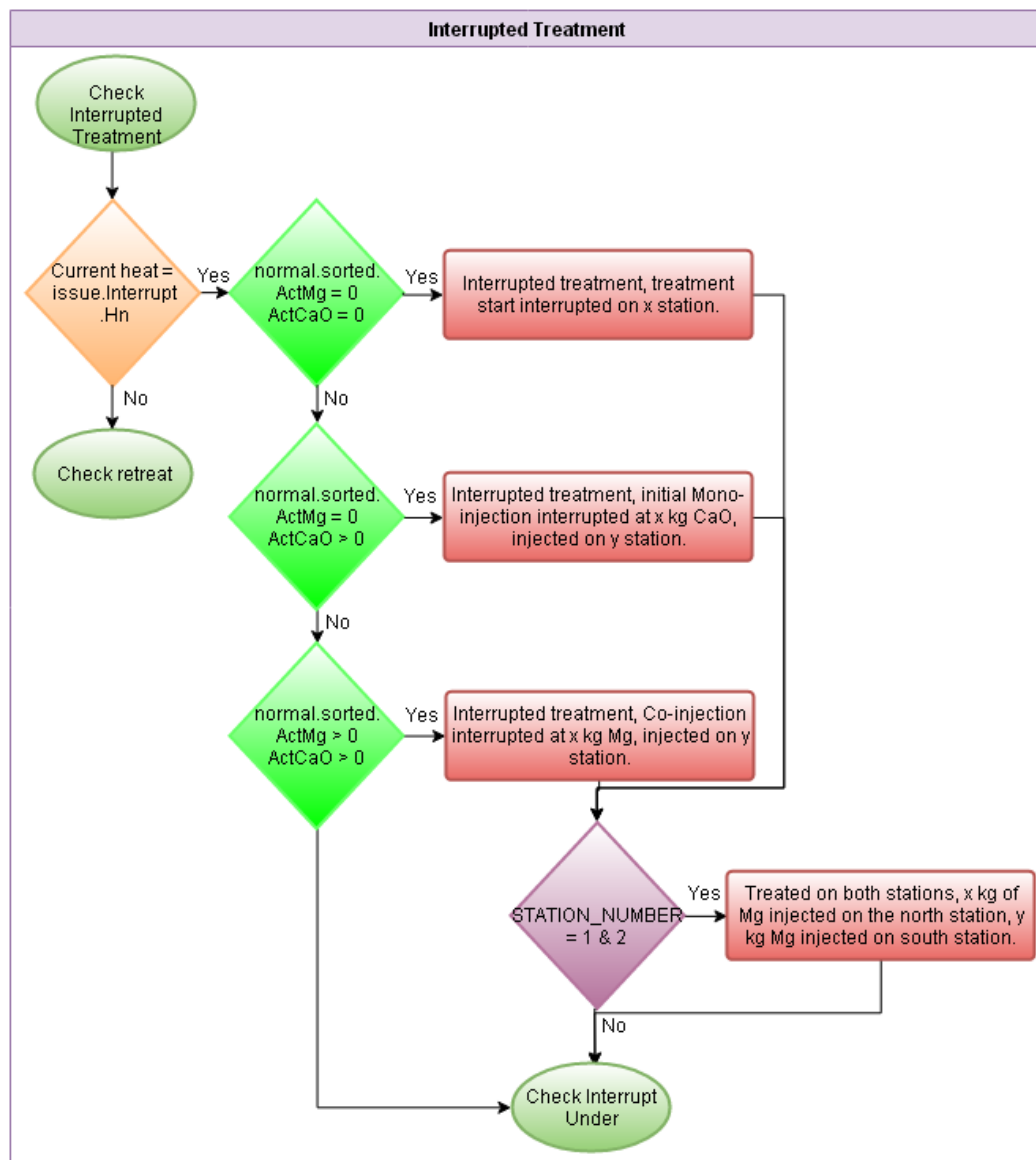
The final situation that the system monitors, involving Aim S changes for re-treated heats, is whether the batch was re-treated for an adjusted Aim S that was defined only by the operator and not by a valid schedule change. As with a lot of occurrences within the desulphurisation process, it is not possible with the available data to diagnose the exact reasoning for the operator's actions. To assist the managers however, all relevant data is added to the output, so an exact cause can be easily discussed with the operators if deemed necessary. The output mentions the re-treat was due to a manual Aim S change, and contains the new and original Aim S. This logic and output used for this issue is shown in row two of the diagram in Figure 4.25.

#### 4.3.3.2 Interrupted Treatment

The desulphurisation process involves lowering a nitrogen lance into the HM, where powdered CaO and Mg are added into the nitrogen stream, and transported into the HM. There are three steps to this process involving the lance flow, first the flow of nitrogen begins, once this is steady the valve from the CaO bunker is opened and CaO is added to the nitrogen flow. Once the flow again becomes steady, then the valve to the Mg bunker is

opened, and the Mg powder is added to the flow. This then continues until the required Mg is injected, and the process finishes. These three stages of injection are known as start injection, mono-injection and co-injection respectively, and are highlighted if and when they occur, as the cause of a delay to the process.

The flow diagram in Figure 4.26 shows the logic used to determine the separate injection issues. As can be seen 3 data structures are used in this case, orange from the Issue structure, green from the Normal structure, and purple from the Desulph structure.



**Figure 4.26 - Flow Diagram Showing Data & Logic Used For Check Interrupted Treatment Outputs**

Start injection issues are classified as happening between the start of the nitrogen flow starting, and before the CaO powder is added to the flow. When the system finds a heat

where this occurs, there isn't a great deal of detail that can be given with the available data, other than the total number of times the treatment was interrupted, and on which station this occurred. As shown by row 1 in Figure 4.26, this is determined by looking for heats with 0kg CaO and 0kg Mg injected weights for an injection record.

When an issue occurs during the addition of CaO to the nitrogen flow, but before the Mg is added, it is known as a mono-injection issue. This typically occurs due to an unsteady flow rate, which can cause the lance to block. For heats where this is applicable, the system generates an output similar to that for a start injection issue. However in this case the weight of CaO injected before the issue occurred is also detailed, as this is considered useful for possibly highlighting recurring issues. As shown above in row 2, this issue is determined when the injected weights of CaO from the Normal data structure are above 0kg, the Mg weight is still 0kg.

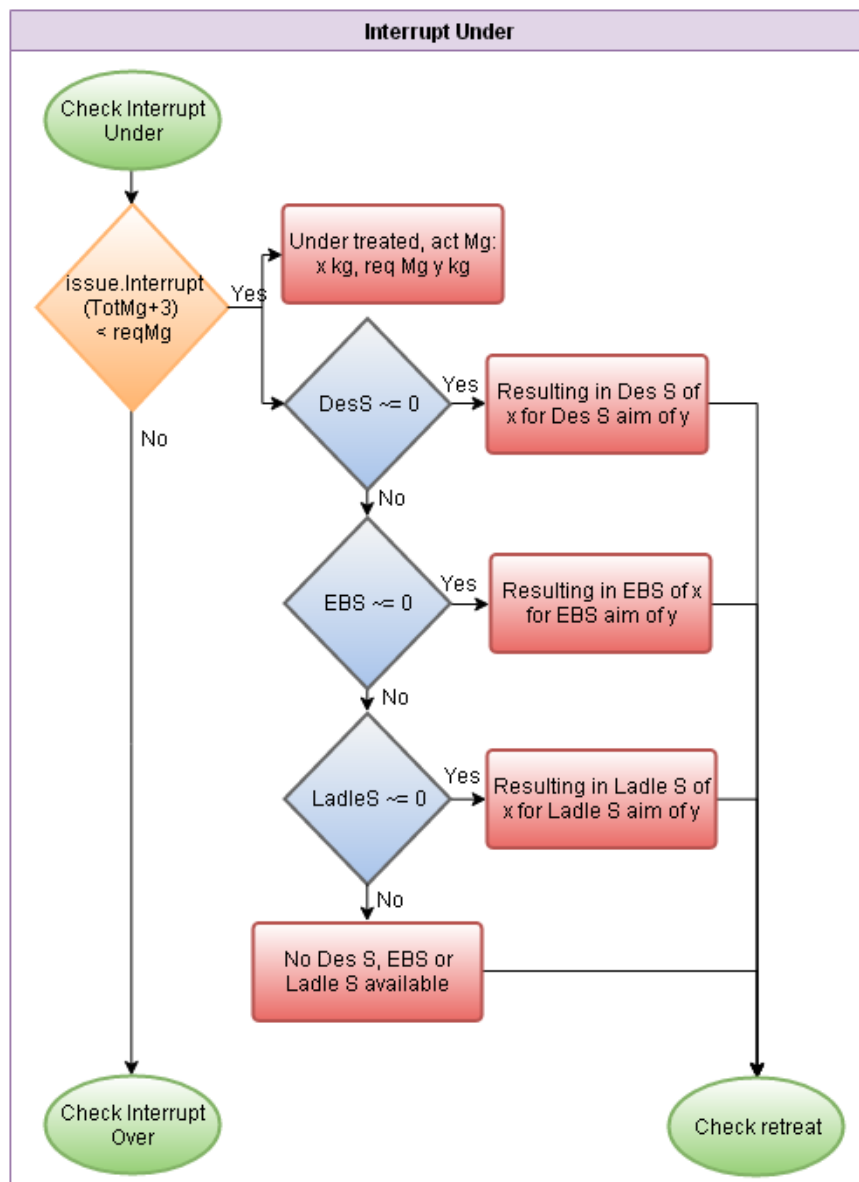
The final section involving the lance flow is a co-injection issue. This is where the flow becomes unsteady and the lance blocks whilst both the powdered CaO and Mg are being simultaneously added to the nitrogen flow within the lance. This type of event doesn't occur particularly often. However if it does occur, it's often the case that a lot of issues will arise within the same shift. Due to the nature of the issue, it was seen as useful to detail only the amount of Mg that was injected before the first issue arose with a particular heat, but unnecessary to additionally mention the CaO weight, as it may help to indicate a recurring issue on a particular station. As with the previous 2 categories of injection issues, the CaO and Mg injection weights once again determine this, however in this case it is when both have an injection weight above 0kg shown by row 3 in Figure 4.29.

There are rare occasions when a treatment on one of the desulphurisation stations completely fails, after a number of interrupted injections, and the ladle is transferred to the adjacent station to finish the treatment. This type of output has been designed to supplement the output describing the type of injection issue, as it has been designed to be a second line output. This is shown as the final output in Figure 4.26, as if an output is used, this is automatically checked for. Checking the Desulph data structure for the station number treated on figures, which will have 2 different values if both stations used, does this.

#### **4.3.3.3 Interrupt Under**

As with the treated on both stations script, this type of output has been designed to supplement, if applicable, the injection issue output. This section has been designed to inform any deviation from the model, due to interrupted treatments, and if under treated, any affect this has had on the end point chemistry.

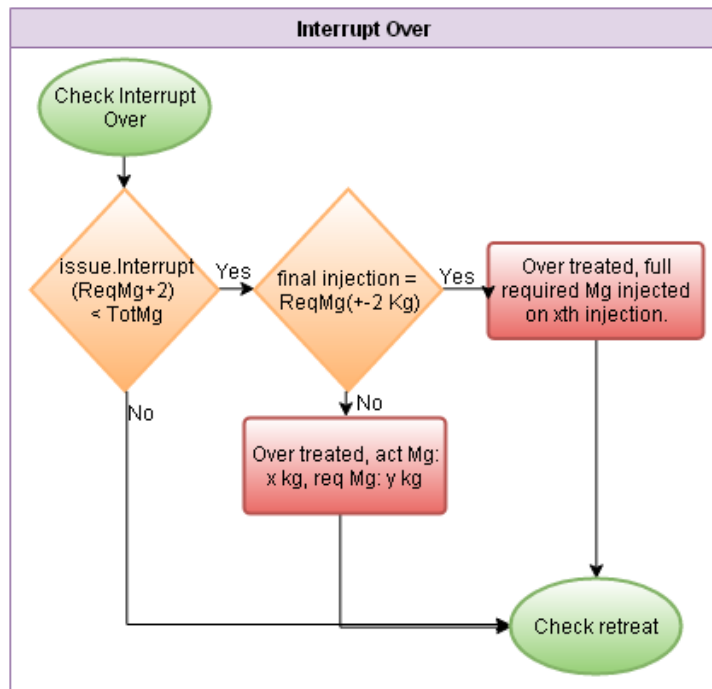
This issue can be down to a speed of work issue, if there's not time to fully treat the heat after a number of interrupted injections for example. This section uses data from 2 sources, Available data structure shown in blue and the Issue data structure shown in orange. When this occurs, the system generates an output commenting that an under treatment has occurred, highlighting the required and actual injected Mg weights, allowing the extent of the under treatment to be seen. As with a normal under treated heat, the system also checks for the nearest S analysis after the treatment, and the respective Aim S to show if this had a major effect on the HM S shown in Figure 4.27.



**Figure 4.27 - Flow Diagram Showing Data & Logic Used For Interrupt Under Outputs**

#### 4.3.3.4 Interrupt Over

Where an over treatment has occurred, the system checks to see if the required Mg weight was fully injected on the final injection, regardless of previous attempts. There are occasions, where there are significant issues with the lance during a treatment, where only 5-10kg of Mg are being injected before the treatment is interrupted due to flow issues. Under these circumstances the operators often try to inject the required Mg in one treatment, ignoring the generally small weights previously injected whilst there were flow issues. If this is the case, the system highlights that the full required Mg weight was injected in the final treatment, highlighting the total number of interrupted treatments that occurred before the full treatment, as shown by the first row in Figure 4.28.

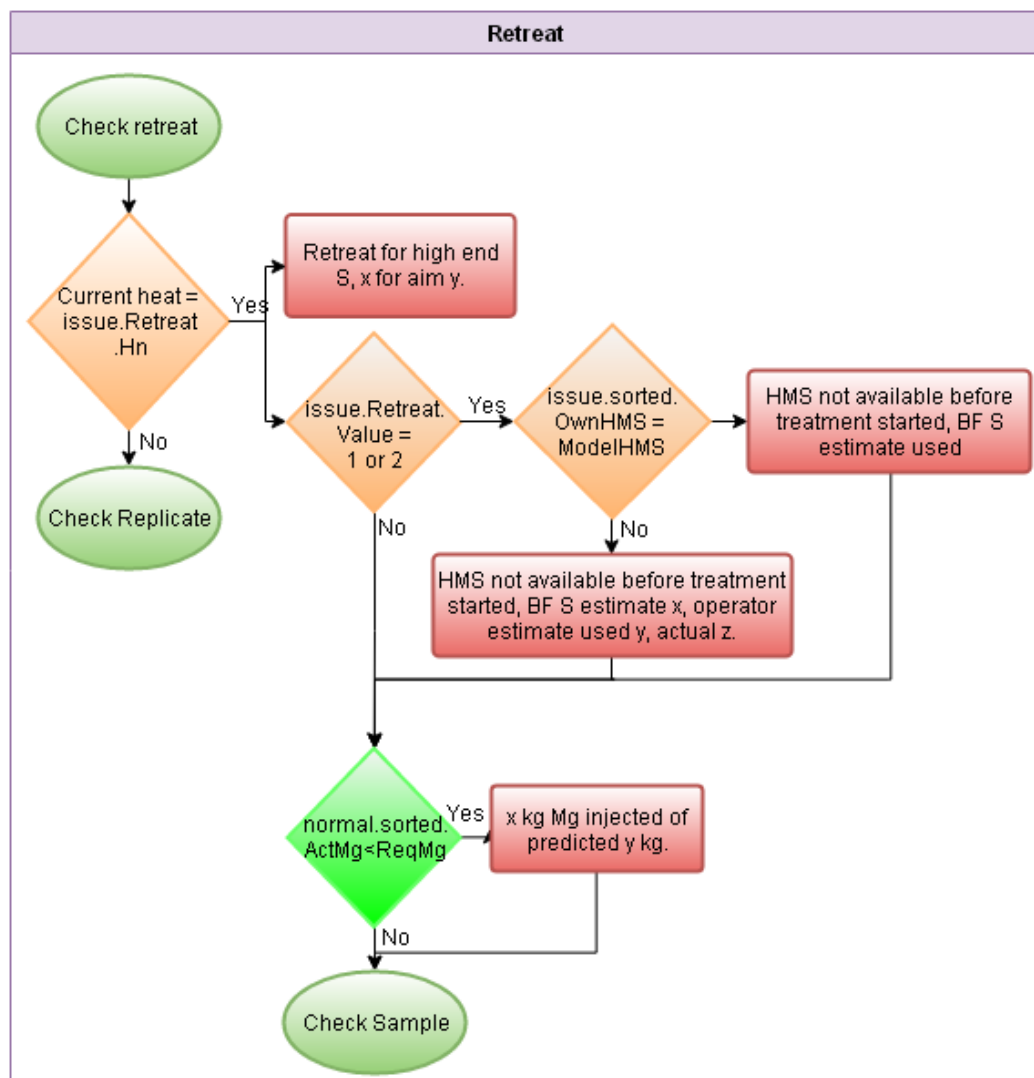


**Figure 4.28 - Flow Diagram Showing Data & Logic Used For Interrupt Over Outputs**

If however the operator over treated the heat, and the final injection weight didn't tie in with the required weights, the system generates an output commenting that the heat was over treated, highlighting the required and actual Mg weights, as shown by the second row output in Figure 4.28.

#### 4.3.3.5 Retreated

The other reason for a re-treat to occur, other than an aim change, is if the original treatment didn't deliver the required level of S removal from the HM. This means that the end treatment S chemistry was too high and out of specification despite the required amounts of CaO and Mg being injected. The system has been designed to systematically work through all plausible situations that may cause this to occur. This can mean looking into the model setup and assessing factors such as the unavailability of HM analysis before the treatment started, to validating the end point analysis, ensuring that the high end point S is actually correct. All outputs for this section are shown below in Figure 4.29, where data from the Issue and Normal data structures are used, shown in orange and green respectively.



**Figure 4.29 - Flow Diagram Showing Data & Logic Used For Retreat Outputs**

The system looks into three areas to find the cause of the high end point S: model, treatment and sampling. The model section checks if assumptions made whilst setting up the

model were correct, and determining if HM analysis wasn't available, were the estimates used realistic. The treatment section simply checks to see if the required Mg was actually injected before the treatment was finished and a sample was taken. The sampling section checks the validity of the desulphurisation S and HM S. The desulphurisation S is validated against the EB S level, and the HM S is validated against the CBM S.

The system generates a common output for all heats where the end point S was above the re-treat level for the grade of steel being made, indicating the end point and Aim S chemistry, as shown by the first output in Figure 4.29. The system then adds additional lines to this output, depending on whether it can determine a cause or not.

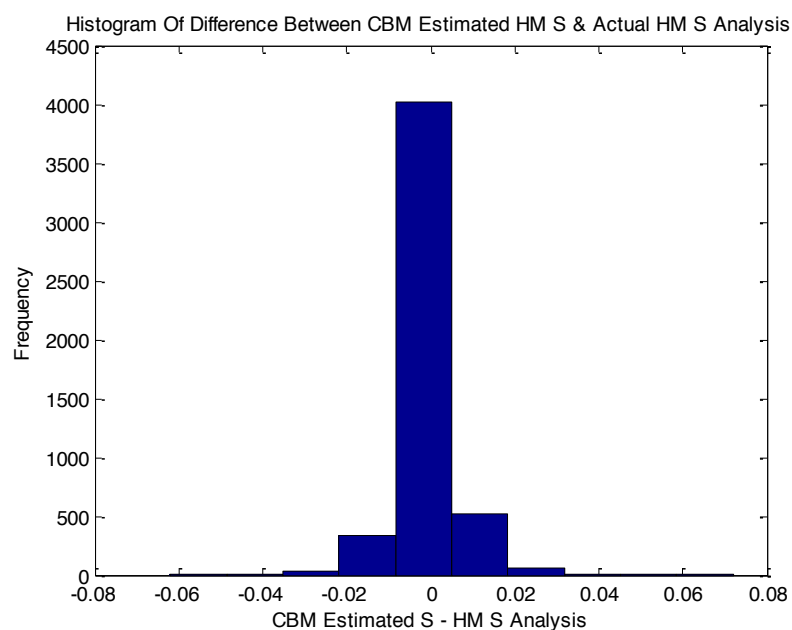
The model aspect of the re-treat analysis is focused on the HM S value used within the desulphurisation model for the treatment. This is only for looking into heats where the HM analysis was late, as the quality of the HM S is checked as part of the sample analysis as described on page 117. The system initially checks to see if it was the BF estimate that was used by the operator. This is only applicable if the CBM S is lower than the late HM S. This is because a lower incoming HM S value would cause the model to calculate a reduced level of S removal and reduced injection weights. If this is the case an output is generated suggesting that this estimate may have been the cause, as a lower value for HM S would cause the model to underestimate the required Mg weight to remove the S, resulting in high end point S in the HM. How this is decided within the system is shown by the second row of decision points in Figure 4.29.

If however the CBM S was not used, then this would imply that the operator used their own estimate, which is not advisable. This may however be considered the correct approach if the CBM S has been significantly wrong for a number of heats. The CBM S calculation has been designed to adapt, by using running means based on the level of accuracy for previous heats that adjust the values accordingly. This means that if the estimate is significantly inaccurate, typically it will improve, though this is very rarely an issue. If the operator has used their own estimate, and it is lower than the late HM S, then the system generates an output highlighting the used and actual HM S values as a possible cause for the high end point S, as with the previous output. The operators approach is typically to overestimate the incoming HM S, as they would prefer to over treat a ladle, rather than need to re-treat it. The logic and data used for this are shown above, with the output being shown on row 3 of Figure 4.29.

The treatment aspect of the re-treat analysis focuses entirely on the Mg weight injected, assessing the difference between the requested and actual injection weights before a dip was taken. The key difference between this and looking at interrupted treatments is that a dip has been taken, so the system checks to see if a dip was taken between treatments, and if the initial treatment was under treated. For heats where the initial injection was undertreated, the system generates an additional line below the re-treat script, detailing the actual and required injection weights prior to the dip, as shown by the final output in Figure 4.29.

#### 4.3.3.6 Check Sample

The sampling aspect of the re-treat analysis focuses on two values, the incoming HM S, and the outgoing desulphurisation S. The system checks to see if it's possible that either the incoming HM S was too low or the desulphurisation S was too high, causing the need for a re-treat. The system checks the HM S first, by comparing this against the CBM S, as typically this is an accurate estimate to the incoming HM S, as shown in Figure 4.33.

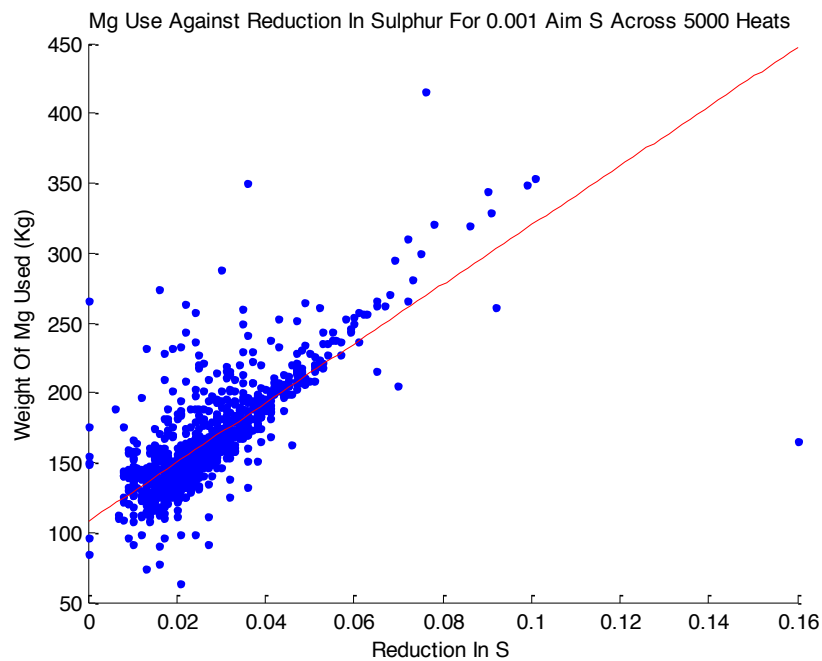


***Figure 4.30 - Histogram Of CBM Estimated S Against HM Analysis, Indicating The Values Typically Match, Due To High Frequency Of Values At 0***

Statistical analysis was undertaken for the HM S chemistry compared with the CBM S value over 5000 heats. This analysis showed an average deviation of 0.00064, and a standard deviation of 0.0074. It was decided that if an estimated value had a deviation from the actual analysis of more than one standard deviation from the calculated mean that this should be

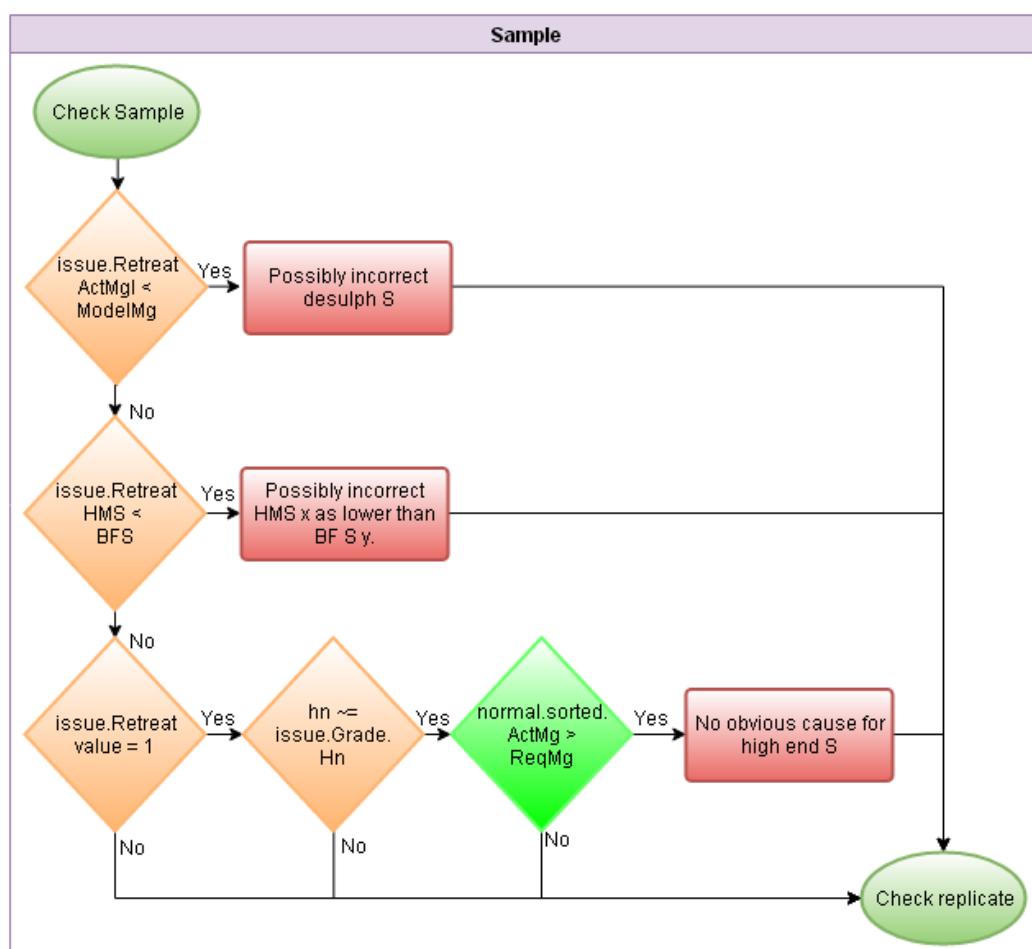


highlighted as a potential cause for the high end point S. Assuming an Aim S of 0.001, with a HM T of 1380°C and a HM W of 280 tonnes, a difference of 0.0074 in HM S content equates to a 25kg difference in Mg weight requested by the desulphurisation model. This is shown to be a significant amount by Figure 4.34. The figure shows the calculated Mg weights for heats with an Aim S of 0.001, as these have the highest injection Mg weights. As can be seen, 25Kg equates to between 10 - 25% of the total injection weight, which increases for heats with lower Aim S and injection weights.



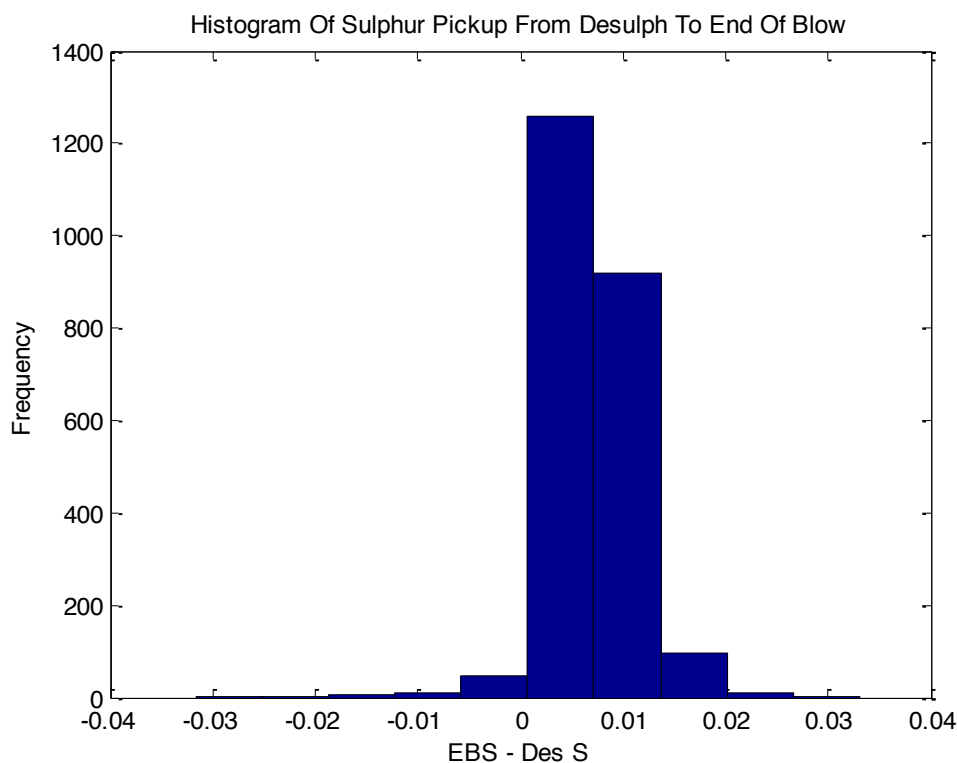
**Figure 4.31 - Mg Use Against S Removed For 0.001 Aim S Heats**

The heats where this analysis is applicable and where the HM S analysis is more than one standard deviation below the CBM S, the system highlights this as a possible cause showing the HM S, as well as the CBM S as shown by the second row in Figure 4.32.



**Figure 4.32 - Flow Diagram Showing Data & Logic Used For Sample Outputs**

The system next checks the desulphurisation S, by comparing it to the EB S. This analysis requires more calculation than the HM S analysis, as a dip is taken at the end of the first treatment to assess the HM chemistry, but not after the re-treat. Due to this, the system has been designed to calculate the required Mg weight to get from the desulphurisation S value from the initial dip to the EB S value. This value is then compared to the actual Mg weight injected; if the actual Mg weight is lower than that calculated, then it is highlighted that the Desulphurisation analysis was potentially incorrect. Analysis of S pickup between the desulphurisation analysis and EB analysis was done over 5000 heats; a histogram of the analysis is shown in Figure 4.33.



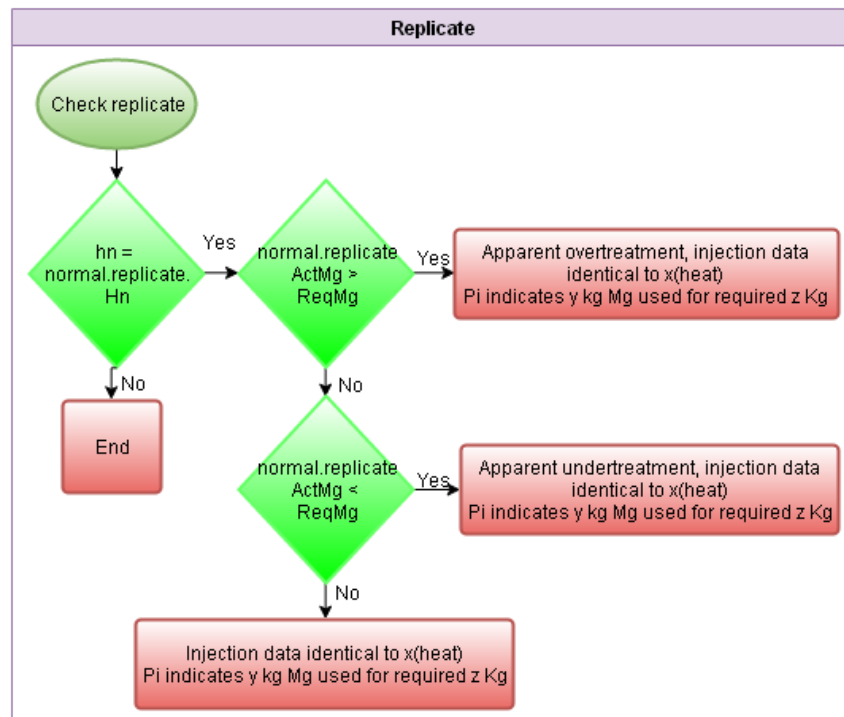
***Figure 4.33 - Histogram Of S Pickup From Desulphurisation To End Of Blow, Showing That S Pickup Is Generally Between 0 & 0.01%***

As can be seen in Figure 4.36, the majority of heats will have very little change in S levels, with the highest frequency being seen between 0 and 0.01%. The value of S pickup for the data used was a mean of 0.0069 with a standard deviation of 0.0041. By calculating the required Mg to get from the desulphurisation S value to the EB S value, this will provide an underestimate of the required Mg, as the S level would have been on average 0.0069% lower when it left the desulphurisation station. Therefore, if the actual injected Mg is still lower than this underestimate, then it is highly likely the desulphurisation S analysis was wrong, and not that the process has suddenly gained a level of efficiency. The calculated Mg value is stored within the Issue structure, and is referred to in Figure 4.32 as ModelMg, on the first row, where this output is generated.

#### **4.3.3.7 Replicate Data**

Within the PSMET database used on plant occasionally the treatment data is recorded incorrectly. Here the system stores the previous treatment data as the current heat, which if not detected can appear as a heat that has been either heavily under or over treated.

Thankfully this is only an issue with heats on the same station, no data gets incorrectly stored for a heat from the opposite station to that being analysed.



**Figure 4.34 - Flow Diagram Showing Data & Logic Used For Replicate Data Outputs**

The system initially splits the heats into their separate stations and systematically goes through checking if firstly there are any consecutive Mg values that are the same, which happens occasionally under normal circumstances, and secondly the used CaO weight. The CaO weight is the main indicator, as it typically isn't monitored. The CaO is simply injected until the required Mg weight is fully injected, and then additionally depending on the grade, a set weight is added post Mg injection as a rinse to further facilitate S removal. Due to this, it is very rare to have two heats where the CaO weights are identical, and even rarer that the Mg weights are also identical. So when this does occur, the system comments whether the heat appears to be over or under treated, and highlight the original heat, and the heat with the suspected replicate data, as shown by the first 2 rows of outputs in Figure 4.34.

This section of the system was additionally developed once the Pi database had become accessible within Matlab. It is somewhat useful to indicate if the system has found a replicate heat, as generally this would appear as an additional over or under treated heat. It is very useful however if the actual injection weights can be added to the information available.

Within the Pi database there is data indicating the bunker weights, both during and between treatments. The bunkers are pressurised units containing either Mg or CaO, and are only refilled after a treatment has occurred, that are above the stations. There is however a continuous measurement available of the weight of material within these bunkers, that can be used to calculate the injected weight of each material by monitoring the bunkers during the period of the injection.

```
function [weights] = MaterialUse(Hn)
weights =
table(Hn,zeros(numel(Hn),1),zeros(numel(Hn),1),'VariableNames',{'Hn','Mg','CaO'});
for n=1:numel(Hn)
    data = Times(Hn(n),2);
    picon = connpi();
    picon.On;
    % References to adjust pi tags
    number = [0,1];
    if data.both == 0
        % Gas Flow A137 or A147
        flowtag = strcat('GM10A1',num2str(3+ number(data.station(1))), '7');
        flow = PiData('SELECT VALUE,TIME,STATUS FROM
PIINTERP',0,flowtag,data.d_start,0.05,data.d_finish);
        flow.Data(picon.conn);
        % Mg Injection Display Weight A138 or A148
        mgitag = strcat('GM10A1',num2str(3+number(data.station(1))), '8');
        mginj = PiData('SELECT VALUE,TIME,STATUS FROM
PIINTERP',0,mgitag,data.d_start,0.05,data.d_finish);
        mginj.Data(picon.conn);
        % CaO added in here if want it in future
        % CaO Injection Display Weight A135 or A145
```

#### ***Listing 4.5 - MaterialUse Function For Treatments On A Single Station***

The code shown in Listing 4.5 extracts the data for the nitrogen gas flow, as well as the injection display weights for both the CaO and Mg bunkers. This data is then filtered to only show the weights during the treatment, when the nitrogen flow is above zero. The function then simply works out the difference between the maximum and minimum weights to calculate the total weight of material injected.

An additional section of code, outlined in Listing 4.6, is required for heats that are treated on both stations. For this the system extracts the bunker weights for both stations during the time of treatment on each station individually, and records the data into separate columns. The same procedure is then used for each column, filtering the data to only show

that relevant when the flow rate of the nitrogen was above zero. As there are two weights, one for each station, the calculated injection weights are then simply added together to find the total injection weight. This allows the outputs from the system for this type of incident to be significantly more useful to the managers, as it indicates precisely the injection weights of Mg, despite this data being unavailable in either the PSMET or PSSUP when there is a databases record error.

```

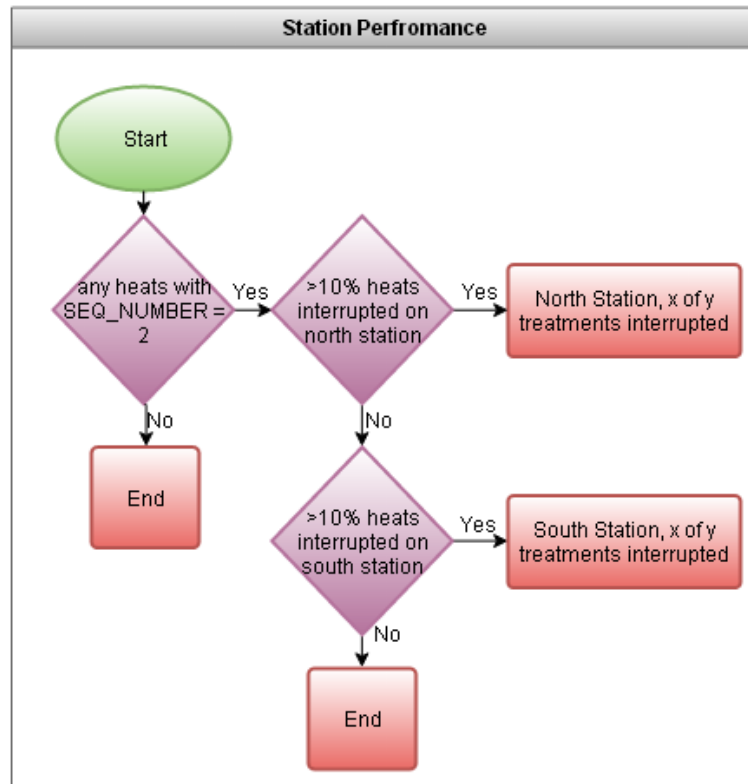
else
    stations = unique(data.station);
    % References to adjust pi tags
    for m=1:2
        % Gas Flow A137 or A147
        flowtag = strcat('GM10A1',num2str(3+ number(stations(m))), '7');
        flow = PiData('SELECT VALUE,TIME,STATUS FROM
PIINTERP',0,flowtag,data.d_start,0.05,data.d_finish);
        flow.Data(picon.conn);
        % Mg Injection Display Weight A138 or A148
        mgitag = strcat('GM10A1',num2str(3+number(stations(m))), '8');
        mginj = PiData('SELECT VALUE,TIME,STATUS FROM
PIINTERP',0,mgitag,data.d_start,0.05,data.d_finish);
        mginj.Data(picon.conn);
        % CaO added in here if want it in future
        % CaO Injection Display Weight A135 or A145
        caitag = strcat('GM10A1',num2str(3+number(stations(m))), '5');
        cainj = PiData('SELECT VALUE,TIME,STATUS FROM
PIINTERP',0,caitag,data.d_start,0.05,data.d_finish);
        cainj.Data(picon.conn);
        picon.Off
        %% Weights Used

```

***Listing 4.6 - MaterialUse Function For Treatments On Both Stations***

#### 4.3.4 Recurring Station Issue

This section has been designed to highlight if a particular station has had more than 10% of the treatments during the last 24hr period interrupted, as this would indicate a potential engineering issue that should ideally be resolved quickly. This particular output is set to be output at the very end of the treatment section, after all analysis and other outputs have finished, as it is there as an overview. The output itself is very simple, simply containing the station, the number of total treatments and number of interrupted treatments that occurred. As can be seen in Figure 4.35 below, this section only uses data from the Desulph data structure shown in purple, with the SEQ\_NUMBER representing the injection number for each heat. Any value above 1 indicates a multiple injection treatment.



**Figure 4.35 - Flow Diagram Showing Data & Logic Used For Station Performance Outputs**

#### 4.3.5 Sample Availability Outputs

The data availability section of the desulphurisation system primarily focuses on the availability of the HM and desulphurisation T and S analysis, so it monitors the percentage of samples being taken over the 24hr period. Discussion with shift managers confirmed that the monitoring of the CBM S and CBM T to ensure that the estimates are correctly adapting and adjusting in line with the process would be helpful, so this function was also added. All analysis within this section uses statistical process control based on a binomial distribution to highlight which levels of deviation or sampling is normal or not. Statistically relevant deviations can then be communicated via the report to the shift managers.

This section considers the availability of the HM and desulphurisation S and T analysis. Capture and analysis of these allow the performance of the desulphurisation process to be monitored and evaluated. The initial challenge was to work out under what circumstances the shift managers would want to be made aware of a lack of sampling. This is because there isn't a push to improve the level of sampling in the desulphurisation process in particular, as there are a number of outside influences that can affect the time available to sample. The

HM analysis typically is very reliable already, as it is used in the CBM calculations at the BOS vessel. It was therefore decided that the system should enable shift managers to be made aware if the sampling rate was significantly low compared to the normal operating conditions.

Data analysis based upon the application of statistical process control was implemented, as it is a quick and effective way of isolating abnormalities within large data sets. The size of the data set was also another consideration, as the dataset needed to be big enough to be representative. A further consideration was market forces, as there are annual fluctuations in the production of steel throughout the year due to these, and so these factors also needed to be accounted for. As there is a number of years' worth of data within the PSMET database for a wide range of variables, including sampling, a dataset comprising of 12 months of production data was decided upon. A smaller representative sample size could have been calculated and implemented, but given that the data was already available, and time to allow the program to run was not a constraint, it was considered unnecessary and potentially less informative than using the full 12 month's worth of data.

The final consideration regarding the dataset was ensuring that it would stay representative, as the process and product mix does vary, and so the level of sampling may change as the grades of steel ordered change. Due to this the system was built to rerun the analysis every 30 days, and update the dataset using a rolling 12 month period of data.

#### **4.3.5.1 Calculation**

The first part of the calculation involves the system counting the number of heats that were treated on either of the desulphurisation stations over a 24-hour period. Then going from the data within the Metal\_Analysis and Dip-Result tables within the PSMET database, the system counts the number of samples taken over the 24 hour period, counting the HM and desulphurisation, T and S analysis in separate columns.

Due to the nature of the process, and the data, it is necessary to standardise the data so that it can be appropriately compared. This is done because missing samples for 5 heats on a day with 60 treatments is not directly comparable to missing samples for 5 heats on a day when there were only 20 heats. The data is standardised using Equation 4.2, which simply divides the difference in heats and samples available by total number of heats.



**Equation 4.2 - Data Standardisation**

The system then calculates  $z = \frac{N_{Heats} - N_{Samples}}{N_{Heats}}$  the mean and standard deviation of the standardised data based on a binomial distribution, as shown in Equation 4.3.

**Equation 4.3 - Mean & Standard Deviation**

$$\bar{x} = \frac{\sum x}{N}$$

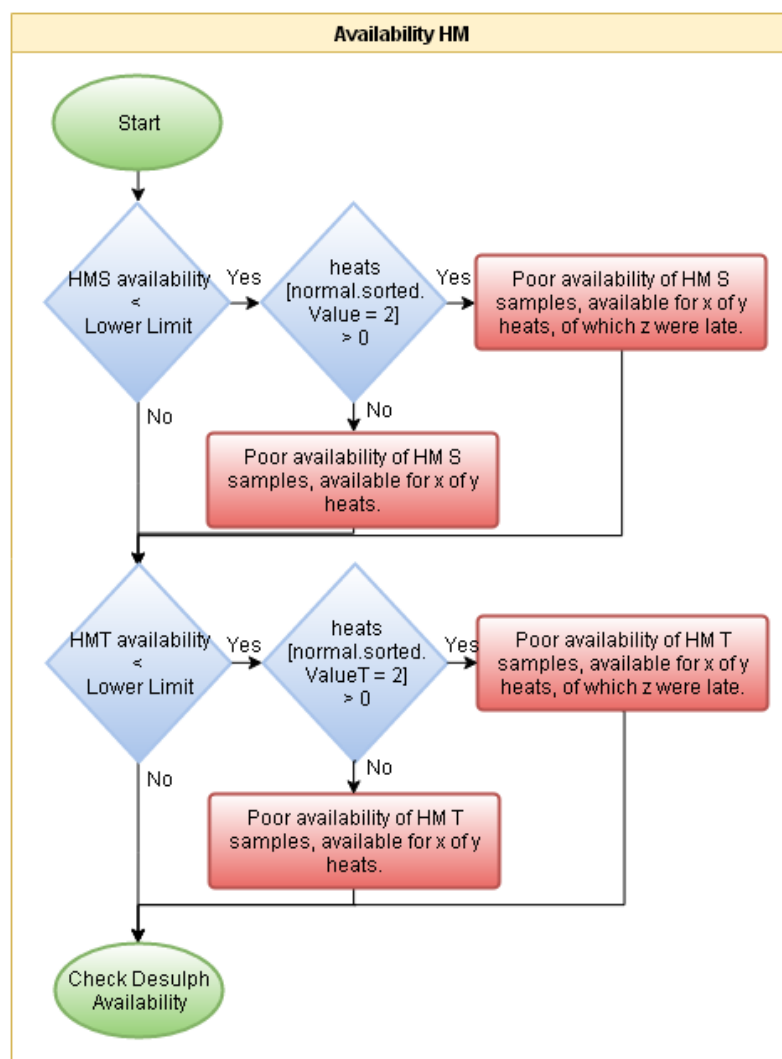
$$\sigma = \sqrt{\frac{\bar{x}(1 - \bar{x})}{\sum x}}$$

Variations in sampling rates were not of interest if the level of sampling was above what was expected, only if they were lower. So it was only necessary to calculate the lower control limit, by subtracting 3 standard deviations from the mean as shown in Equation 4.4.

**Equation 4.4 - Lower Control Limit**

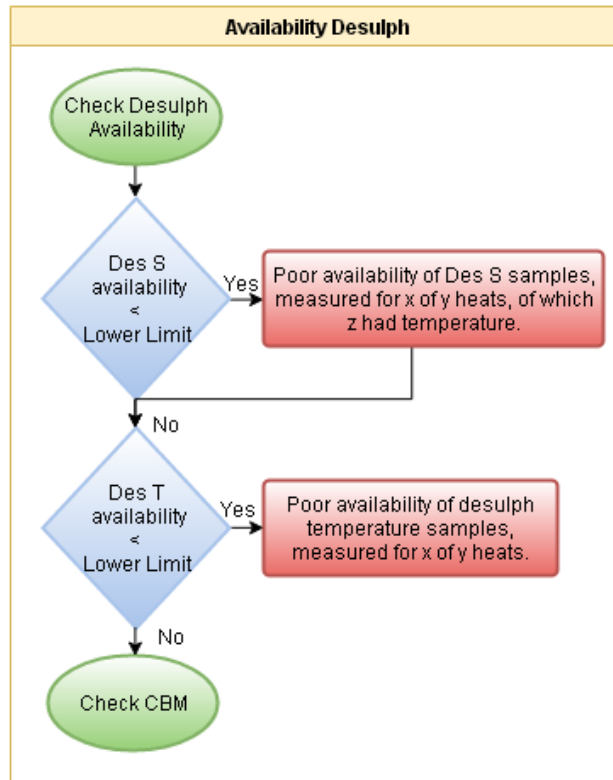
$$LCL = \bar{x} - 3\sigma$$

The final stage is to then apply the same method and calculations to the last 24 hours heats, and compare this to the lower control limit defined in Equation 4.4. If this sample falls below the control chart limit, then the system generates an output, highlighting the number of heats and the number of samples available for the specific measurement that is abnormally low. All of the outputs relating to HM sample availability and timing are shown in Figure 4.36.



**Figure 4.36 - Flow Diagram Showing Data & Logic Used For HM Availability Outputs**

There are slight differences between the outputs generated for the HM sampling rates in Figure 4.36 and the Desulphurisation sampling rates in Figure 4.37, as it was considered useful to also mention additional information for both. The HM sampling output also mentions the number of samples that were late; as for the desulphurisation this is equivalent to the samples not being available. The desulphurisation sampling output for the S sampling rate in particular, also comments on how many of the available desulphurisation samples had successful T measurements.



**Figure 4.37 - Flow Diagram Showing Data & Logic Used For Desulph Availability Outputs**

#### 4.3.5.2 Programming Within Matlab

The “dataanalysis” application of the sampling availability code within the desulphurisation system was written as a nested function, as it allows this to be easily packaged with the rest of the desulphurisation system code. The function itself is split into a number of sections. The first section is partially shown in Listing 4.7. This is where all of the heat numbers are extracted from the HEAT\_PSSUP table within the PSMET database. This contains the dates of all the heat numbers that have been used within the steel plant, and can be used as a reference point if trying to extract data over a particular time period, which in this case is 12 months.

As shown in Listing 4.7 after the heat numbers and associated dates have been extracted from the database, the system determines the highest heat number for the previous day, and the lowest heat number for the current day, 12 months previously. This then gives the range of heat numbers that data is required for the data analysis to be undertaken.

```

function [means,cbmsu,cbmsl,cbmtu,cbmtl] = dataanalysis(~,~)

% Make connection to PSMET database.
tic
conn = database('PSmet_read','odbc_ro','xxxx');
disp('PSMET Started')
live = isconnection(conn);
if live == 0
    disp('PSMET Connection Failed')
    return
end
% Heat number data
hs = exec(conn,'SELECT DISTINCT HEAT_NUMBER,DAY_NO,WEEK_NO,YEAR_NO FROM HEAT_PSSUP');
%psup apparently best place for heat numebr extraction
hs = fetch(hs);
close(hs)
psup = hs.Data;
% close(conn)

```

***Listing 4.7 - dataanalysis Heat number Extraction Code***

The next stage in the process is to use the heat number range found for the requested time period, and to get all relevant data from the tables within PSMET. The code used is shown in Listing 4.8.

```

% metal analysis
metal.s{1} = {'SELECT DISTINCT
HEAT_NUMBER_SET,HEAT_NUMBER,MATERIAL_CODE,LOCATION_CODE,SULPHUR FROM METAL_ANALYSIS
WHERE (MATERIAL_CODE = 29 OR MATERIAL_CODE = 30) AND (LOCATION_CODE = 43 OR
LOCATION_CODE = 44) AND HEAT_NUMBER BETWEEN '};
metal.s{2} = strcat(first.s,{' AND '},last.s);
metal.s{3} = strcat(metal.s{1},metal.s{2});
metal.s{4} = char(metal.s{3});
metal.d = exec(conn,metal.s{4});
metal.d = fetch(metal.d);
close(metal.d);
metal.orig = metal.d.Data;

% direct charge data
desulph.s{1} = {'SELECT DISTINCT HEAT_NUMBER,CHARGE_TIME,INJECTION_DURATION FROM

```

***Listing 4.8 - dataanalysis Data Extraction Code***

The final stage within the data analysis function is to organise the data that has been extracted into a structure called ‘data’, and using Equation 4.2 and Equation 4.3 to

standardise the sampling rate, and calculate the mean values for each of the sample types. These mean values can then be used within Equation 4.4 outside of the data analysis function to calculate the standard deviation, as shown in Listing 4.9.

```
% counting the number of samples available and numebr of treatments for each day
z = zeros(numel(unique(datad.Date)),8);
z(:,1) = unique(datad.Date);

for n = 1:numel(z(:,1))
    % how many treatments were there
    z(n,2) = numel(datad.Hn(datad.Date == z(n,1)));
    % how many HM S samples were there
    z(n,3) = numel(datad.HM S(datad.HM S ~= 0 & datad.Date == z(n,1)));
    z(n,4) = numel(datad.DesS(datad.DesS ~= 0 & datad.Date == z(n,1)));
    z(n,5) = numel(datad.HMT(datad.HMT ~= 0 & datad.Date == z(n,1)));
    z(n,6) = numel(datad.DesT(datad.DesT ~= 0 & datad.Date == z(n,1)));

end

z(1,:) = [];

%% caluclating the difference between the treatments and samples
bimod = zeros(numel(z(:,1)),4);
bimod(:,1) = (z(:,2) - z(:,3))./z(:,2);
bimod(:,2) = (z(:,4) - z(:,5))./z(:,4);
bimod(:,3) = (z(:,6) - z(:,5))./z(:,5);
bimod(:,4) = (z(:,6) - z(:,4))./z(:,4);
```

#### ***Listing 4.9 - dataanalysis Data Processing & Calculation Code***

The dataanalysis function has no inputs, as it can extract all necessary data from the PSMET databases without being given any other data. It does however have five outputs; means, cbmsu, cbmsl, cbmtu and cbmtl, as shown by the first line in Listing 4.7. The ‘means’ output contains the mean values for the S and T sampling rates for both the HM and end treatment analysis. The last four outputs correspond only to the CBM estimates, indicating upper and lower limits for the CBM S and T values respectively.

The values for the mean standardized sampling rates are then used within the main desulphurisation system function as shown in Listing 4.10. The mean values are used to calculate the lower control limit value, which is defined in Equation 4.2 as the mean minus 3 standard deviations, and labeled as ‘ucls’ in the listing. This lower control limit is then compared against the calculated distribution values for the current shift, labeled as ‘samples’ in the listing. If the current sampling rate is lower, the system will work through the if statement, and generate an output line within the output matrix ‘exdata’.

```

%% Data Availability Scripts
% ucls/samples = [HM S, Des S, Hm T, Des T]
ucls = zeros(1,4);
% ucl = mean+3sd, where sd = sqrt[(mean*(1-mean))/number treatments]
ucls(1) = means(1) + 3.*sqrt((means(1).*(1-means(:,1)))./numel(normal.sorted.Hn));
ucls(2) = means(2) + 3.*sqrt((means(2).*(1-means(:,2)))./numel(normal.sorted.Hn));
ucls(3) = means(3) + 3.*sqrt((means(3).*(1-means(:,3)))./numel(normal.sorted.Hn));
ucls(4) = means(4) + 3.*sqrt((means(4).*(1-means(:,4)))./numel(normal.sorted.Hn));

samples = zeros(1,4);
% binomial distribution : (N - available)/N
samples(1) = (numel(normal.sorted.Hn) - nnz(available.HM
S))/numel(normal.sorted.Hn);
samples(2) = (numel(normal.sorted.Hn) -
nnz(available.DesS))/numel(normal.sorted.Hn);
samples(3) = (numel(normal.sorted.Hn) - nnz(available.HMT))/numel(normal.sorted.Hn);
samples(4) = (numel(normal.sorted.Hn) -
nnz(available.DesT))/numel(normal.sorted.Hn);

```

***Listing 4.10 - Using dataanalysis Function Outputs In Desulphurisation System***

#### **4.3.6 CBM HM Estimates**

The final function of the data availability section of the system is the monitoring of the CBM HM estimates. The CBM calculates an estimate of the HM S. This calculated value is then adjusted using factors based on running means. The difference between the previous heats estimate and actual analysis is used to adjust these factors, by taking 10% of this calculated difference. The figure of 10% is used by the plant, as it was considered large enough to affect the running mean sufficiently, but small enough to not cause significant deviations from an outlier measurement. If the previous estimate was higher than the actual measurement, then the adjustment factor will be lowered, to reflect the over estimating of the analysis, with the opposite occurring for an underestimate. The adjustment factor is added to the raw calculated CBM estimate for the given measurement, to adjust it appropriately.

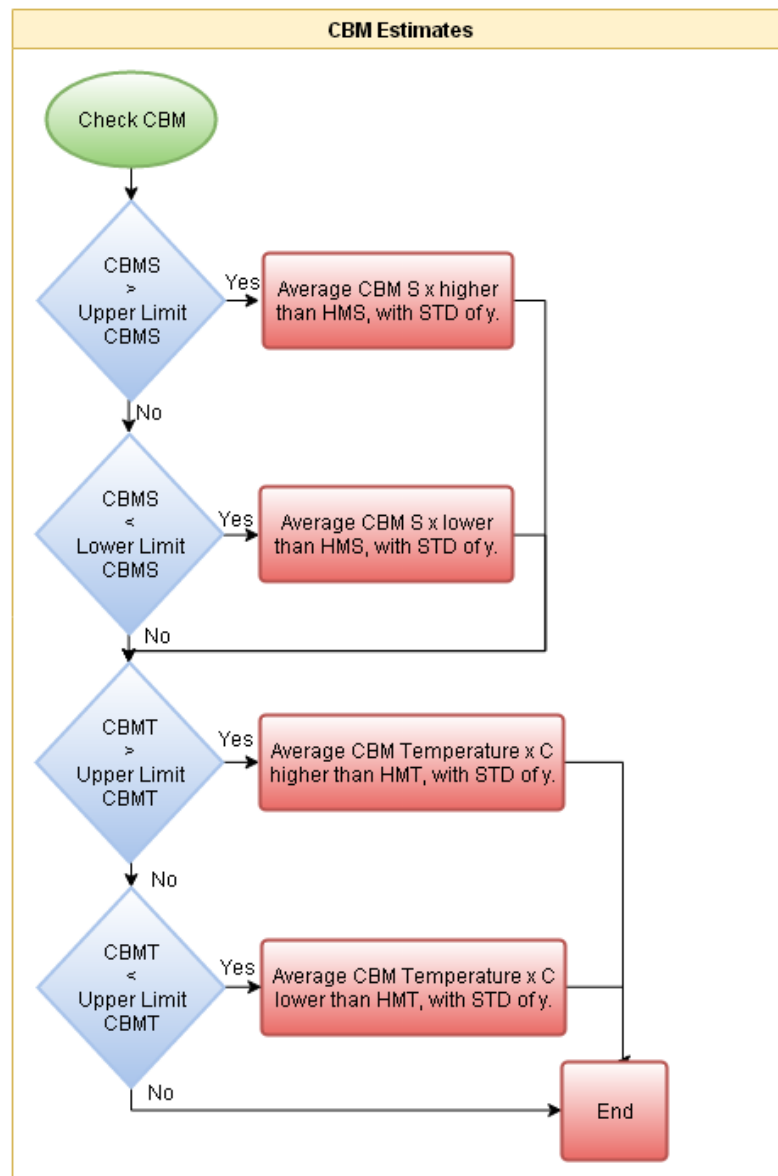
For the CBM analysis, as with the sampling availability outputs, it was decided that attention would be drawn only if the estimates were exceptionally high or low compared to normal operating conditions. Due to this the use statistical process control was also applied, however due to the nature of this adjustment, it can be assumed that the data is normally distributed, and so calculation of the mean and standard deviation of the data was much easier, as the data also didn't need to be standardised.

#### **4.3.6.1 Calculation Of CBM Estimate Accuracy**

The calculation of the CBM estimated accuracy initially requires the calculation of how accurate the estimate has been over the previous year, on a 24-hour basis. Since these estimates can and do get recalculated if the HM has been treated at the desulphurisation stage, this first requires the system, based upon update times, and desulphurisation model run times, to determine which CBM estimate of the HM S and T was applicable at the time of each treatment.

Once the system has acquired the appropriate estimates for each of the heats, it filters out all heats that didn't have HM analysis available. Next it groups the heats based on the date of the model run, into 24-hour periods. Finally the system calculates the mean difference over each 24-hour period, between the CBM estimated HM S and T compared with the actual analysis. Then the mean and standard deviation of the 24-hour based calculated means is calculated, to give an overall analysis of the CBM estimates for a 24-hour period. These values are then used to calculate an upper and lower control limit, by adding and subtracting 3 standard deviations from the mean respectively.

Finally the system applies the same method to the 24-hour period in question, calculating the mean deviation between the CBM estimate and actual HM analysis. If this mean is either above or below the upper or lower control limits respectively, the system generates an output, as shown below in Figure 4.38. This highlights the mean difference, and standard deviation for the particular variable, either CBM S or T estimate.



**Figure 4.38 - Flow Diagram Showing Data & Logic Used For CBM Estimate Outputs**

#### 4.4 Summary

A diagnostic system has been designed and implemented at Tata Steel's Port Talbot works to generate a report every morning, on the state and operation of the desulphurisation plant, which considers the past 24hours of production. The system monitors the model setup by operators, allowing better control of material use for the desulphurisation treatments. The performance of the process is monitored, highlighting interrupted treatments and re-treatments. The system supports the diagnosing of possible causes for these. Particular attention is paid throughout to highlight deviations in material use and the effects this has on end point chemistry. This system has allowed a detailed overview of the process to be easily available to all personnel on plant, allowing the state of the process to be better understood, and the control of the process and material usage to improve.

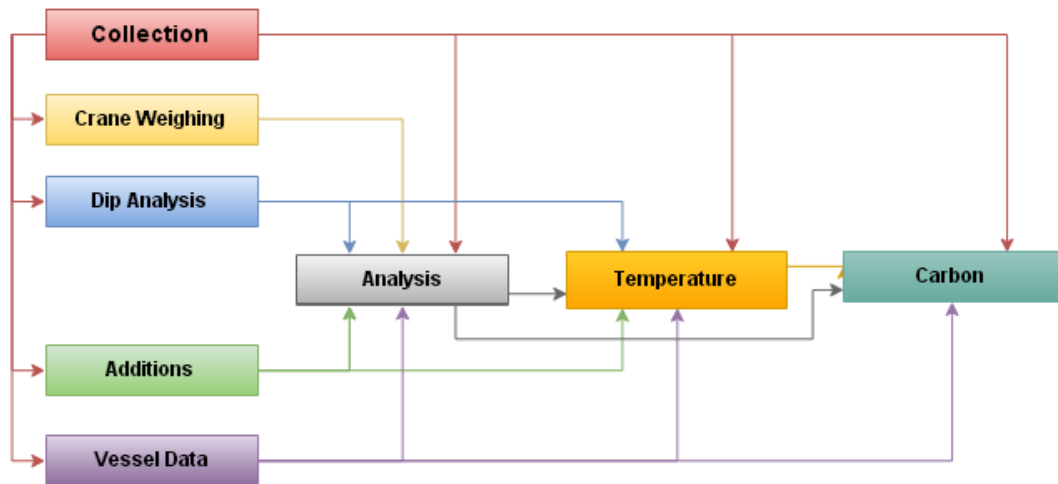


## **5 End Blow Carbon & Temperature Deviation**

The End Blow (EB) Carbon (C) & EB Temperature (T) deviation system is built to focus entirely on the Basic Oxygen Steelmaking (BOS) process as a whole, diagnosing issues based on the end point parameters of the process. Where previous systems have focused on the inputs into the BOS process, with the scrap adherence looking into the quality and mix of scrap being charged, and the desulphurisation system looking into the removal of Sulphur (S) from the Hot Metal (HM) being charged into the vessel, this system focuses on the outputs of the BOS process. During the development of this system there has been consideration as to the most informative sources of data available. This has included the application of the static data sources such as the PSMET and PSSUP databases and the utilisation of the continuous data sources found within the PI database. Improvements in programming techniques applied have allowed the author to make better use of the Object Oriented Programming (OOP) capabilities of Matlab. This has been predominantly in the application of creating classes of objects to handle specific tasks, such as data extraction and standard processing tasks.

### **5.1 Expert System Overview**

An overview of the expert system developed is shown in Figure 5.1, showing the key sections of data built within this expert system. Each of these sections, and their interconnectivity will be explained in more detail. The next stage after the above system overview is the outputs, which will be covered within the relevant diagnostic modules later on in this chapter. The reason all of these data structures have been built is to facilitate the generation of the outputs of the expert system, with the output section of system being able to simply locate the required information within the organised data structures. A fully expanded view of these modules is contained within Appendix E.



**Figure 5.1 - EB C & EB T System Overview**

The programming developments that have been made during the engineering of this system, outlining examples of classes of objects created and their application are now described. The diagnostic modules that have been created are presented. These are designed to be modular in nature. Finally the data processing, programming and logic behind the modules and the scope with which the outputs are generated is described.

### 5.1.1 Collection

The collection section of the system, as with previous expert systems, is where the data extraction from the plant databases occurs. As Figure 5.1 shows, data from the Collection section of the system is used in every other data structure built within this system, as it contains all raw data used within the system. As with the previous expert system on the desulphurisation process, this system has been designed to use data from all available data sources. The tables used from the PSSUP and PSMET databases are shown in Figure 5.2. The data shown under the Pi database tab in the figure, only shows the areas that the data extracted covers. Further detail on the exact data being used is shown in a fully expanded view of this section of the system within the Appendix E. Detail is also given on the type of data extracted from the Pi database, although a fully expanded view can be seen in the Appendix E.

Collection		
PSSUP	PSMET	Pi
HEAT_ALL_TIMES_VIEW	EXPERT_ADHERENCE	Tuyere
PSSUP1_LOGICAL	SUBL	Sub Lance
CBM_VESSEL_RM	META_ANALYSIS	Off Gas Analysis
HM_LADLE_TRIP	HEAT_PSSUP	Oxygen Lance
EBM_VESSEL_RM	MAT_CHARGED	Skirt
	DIP_RESULT	
	CBM_DISPLAY_ANALYSIS	
	CBM_ADAPT_FACTORS	
	CRANE	
	LG2_CONVERTERS	
	COORD_LINK	
	PROGRAM_ANALYSIS	
	EBM_DISPLAY	
	SLAG_ANALYSIS	
	HEAT_BOSMET	

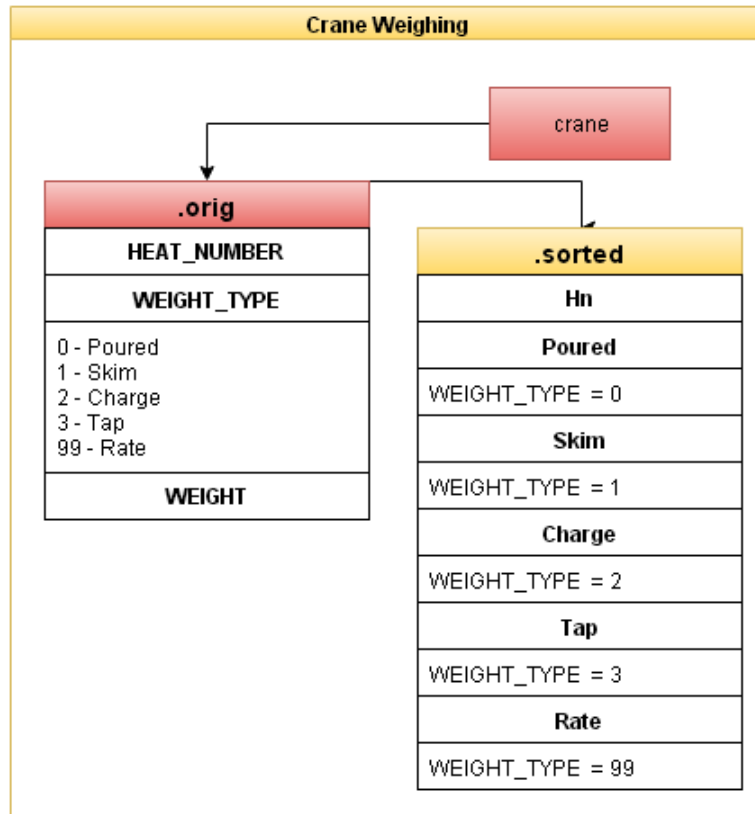
**Figure 5.2 - Collection Overview**

Within the PSSUP database, the new tables used within this system are Heat all times view, CBM VESSEL RM, HM LADLE TRIP and EBM VESSEL RM. The heat all times view table contains data for all timings associated with the BOS process. CBM VESSEL RM contains values for all of CBM model running means used, this is the same for EBM VESSEL RM which relates to the EBM model.

Within the PSMET database, there are a number of new data tables used within this system. Expert adherence is where all outputs from all expert systems are written to. SUBL contains sublance analysis results, so this will be C & T measurements. The CBM display analysis & adapt factors contains more data relating to the CBM model, specifically how the running means have affected the oxygen and coolant figures. Crane contains data of the crane weights, so this will be charged and tap weights for example.

### 5.1.2 Crane Weighing

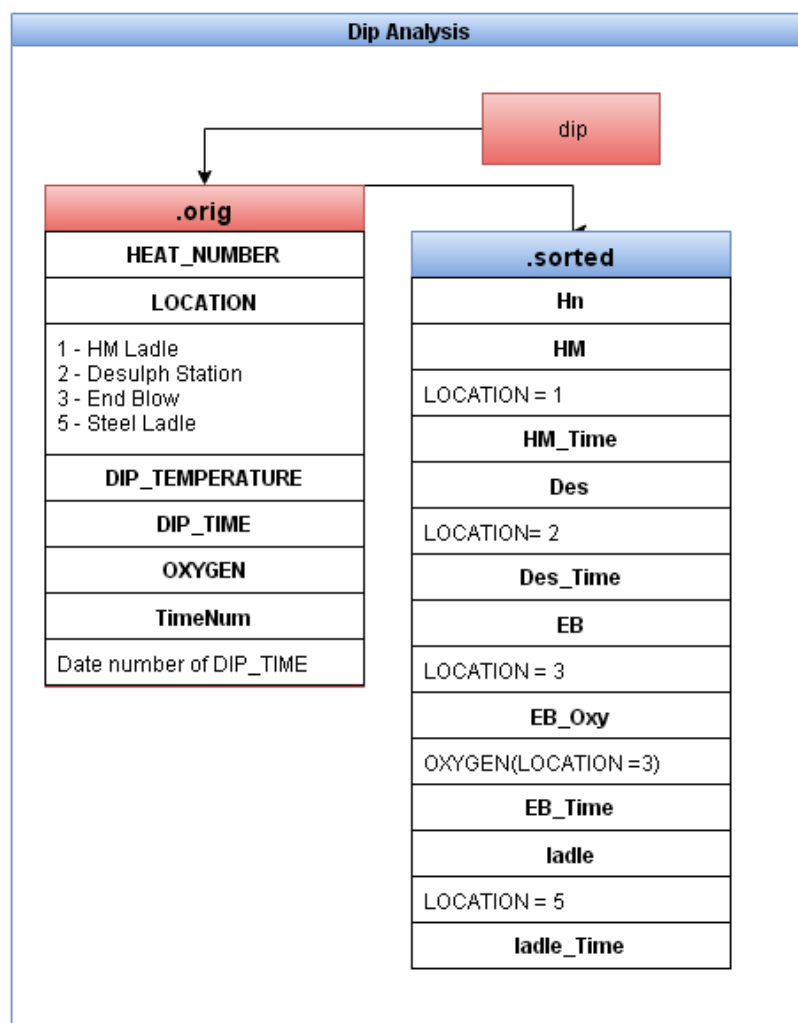
The data structure Crane is used to manage all of the weighing data used within the expert system, shown in Figure 5.3. The .orig structure contains the raw data from the CRANE table from the PSMET database, and the .sorted structure is used to sort this data to facilitate data analysis elsewhere within the system. The sorting is done by filtering the Weight\_Type column of data appropriately. Although the weighing data is used extensively throughout the system, this data structure is only directly referenced when building the Analysis data structure.



*Figure 5.3 – Overview of the Data & Logic Used Within the Crane Data Structure*

### 5.1.3 Dip Analysis

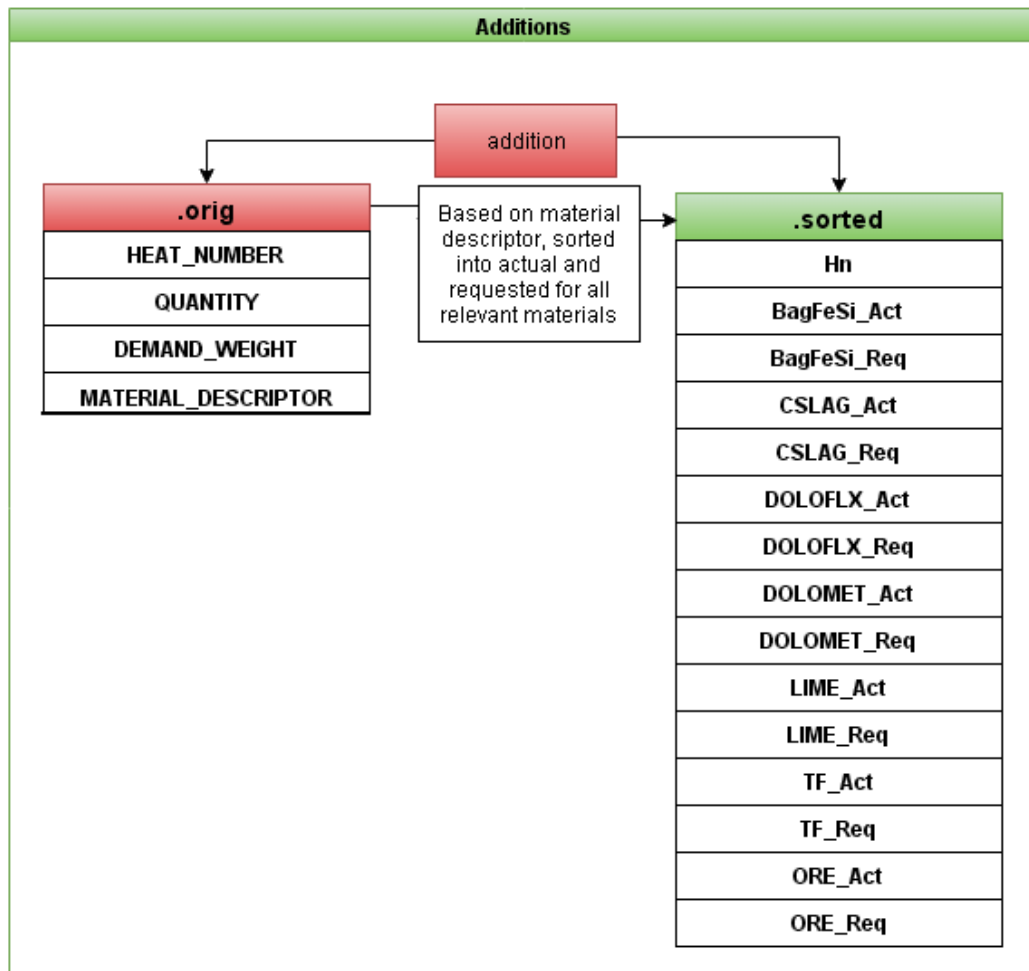
This data structure initially contains the raw data extracted from the DIP\_RESULT table, which as shown in Figure 5.4 contains the temperature and oxygen content from the metal sampling at various points in the process, filtered by LOCATION code. The HM, Des and EB columns shown within the .sorted data structure, contain the temperature measurement at the respective process locations. As shown in Figure 5.1, this data structure is used to build the Analysis and Temperature data structures, which will be explained in more detail further in the following sections.



**Figure 5.4 - Overview of the Data & Logic Used Within the Dip Analysis Data Structure**

#### 5.1.4 Additions

This data structure contains data on all fluxing and coolant materials that are charged during the BOS process, gathered from the MAT\_CHARGED table in PSMET. All materials used are shown in Figure 5.5, with the .sorted structure containing sorted data for demand and charged weights for each of these.



**Figure 5.5 - Overview of the Data & Logic Used Within the Additions Data Structure**

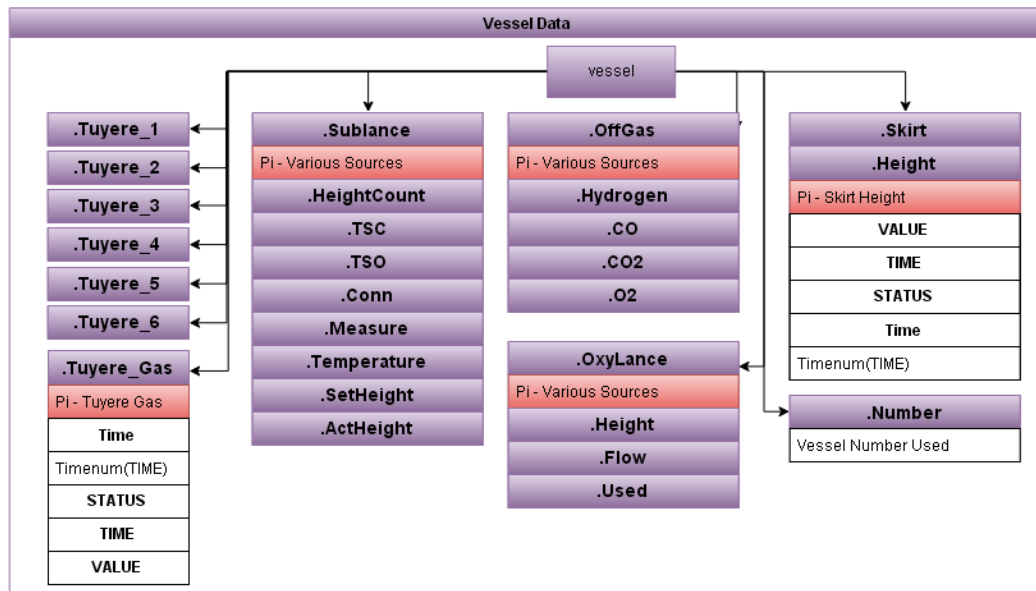
To assist in understanding the names used within the Additions data structure to separate the various materials used, Table 5.1 contains some of the names used within the Additions structure along with a brief description of which materials the names apply to.

**Table 5.1 - Overview of Additions Data Structure Names**

Name	Description
BagFeSi	Bags of Ferro Silicon (FeSi)
CSlag	Recycled BOS Slag
TF	Trickle Feed Additions, typically WOBS
ORE	Iron Ore

### 5.1.5 Vessel Data

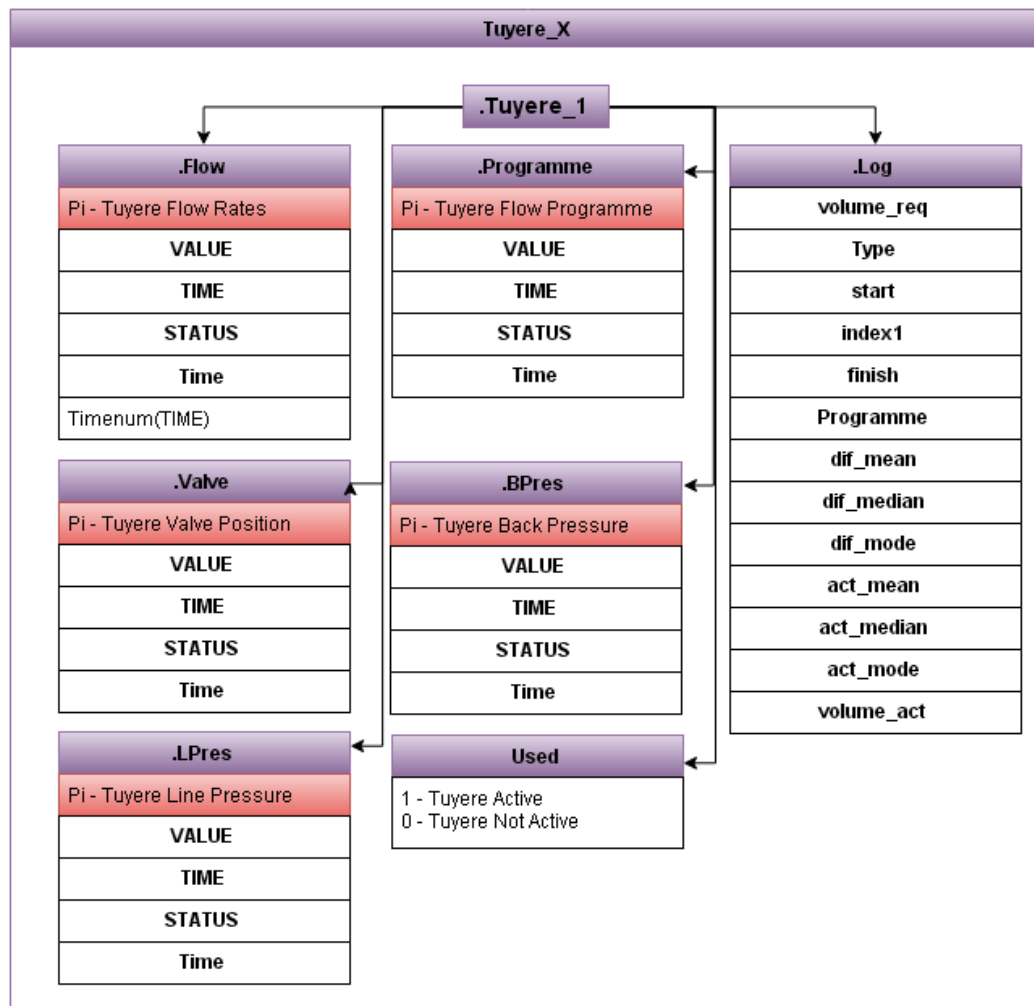
This data structure is used to organise all of the Pi data required for this expert system, and so contains a large number of structures within the main Vessel structure, to ensure the data is sufficiently sorted and easily accessed. An overview of the complete data structure is shown in Figure 5.6.



**Figure 5.6 - Overview of the Data & Logic Used Within the Vessel Data Structure**

As can be seen, this structure is used to contain data for all aspects of the process split into 5 different areas. These are the Tuyeres, Sublance, OffGas, OxyLance and Skirt. A fully expanded view of this structure is shown in the Appendix E if further clarification is required. The Time column contains a number which represents the time stamp stored in the TIME columns of the relevant data structures, these are converted from a time stamp to a number using a method call Timenum. To further explain the data contained within this structure, Figure 5.7 is an overview of the .Tuyere\_X data structure shown above for each tuyere, as these contain all relevant data for the each individual tuyere.

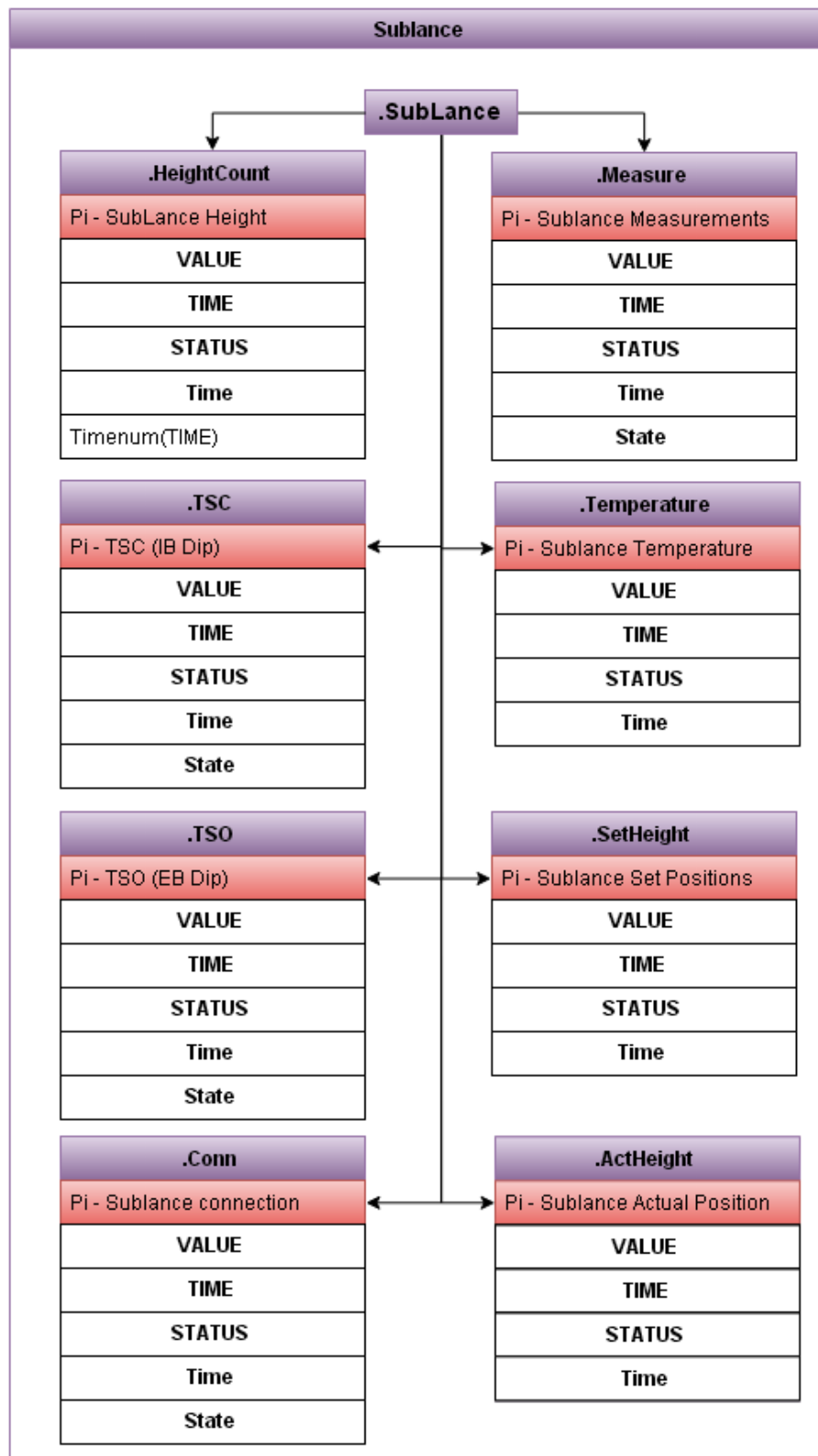
As can be seen this structure contains extensive data on the condition of each of the tuyeres. The associated data will be used later on within the expert system to infer any process issues. It contains flow rates (.Flow), valve position (.Valve), line pressure (.LPres), requested flow rate profiles (.Programme), back pressure (.BPres) and a log (.Log) which will be explained later on, which is used to assess the performance of the tuyere's during each blow.



**Figure 5.7 - Overview of the Data & Logic Used Within the Tuyere Data Structure**

To assist in understanding the other aspects of the data shown in Figure 5.6, one of these, Sublance, has been expanded to show all data that it contains in Figure 5.8. The data contained within the overall data structure Vessel, is used to build the Analysis, Temperature and Carbon data structures. These are then used to generate the relevant outputs from the expert system.

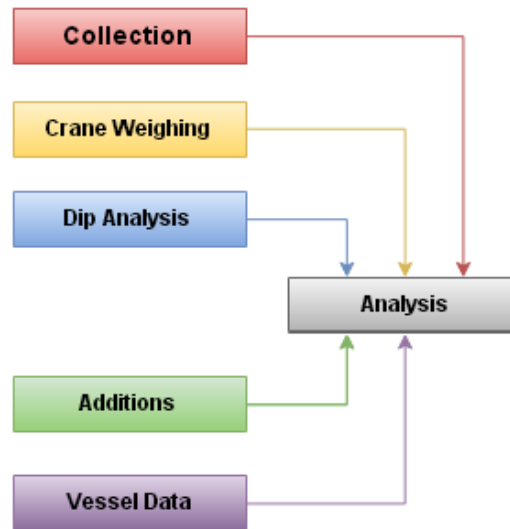




**Figure 5.8 - Overview of the Data & Logic Used Within the Sublance Data Structure**

### 5.1.6 Analysis Data Structure

This data structure is used to assess the overall state of the process, and contains various structures to facilitate in the diagnosis of a number of different issues that can affect the EB T and EB C control within the BOS process. To help understand the data that is used within this section, Figure 5.9 shows the data structures that feed into this section.



***Figure 5.9 - Analysis Data Structure Inputs, Showing Data Is Input From 5 Different Modules Within The System***

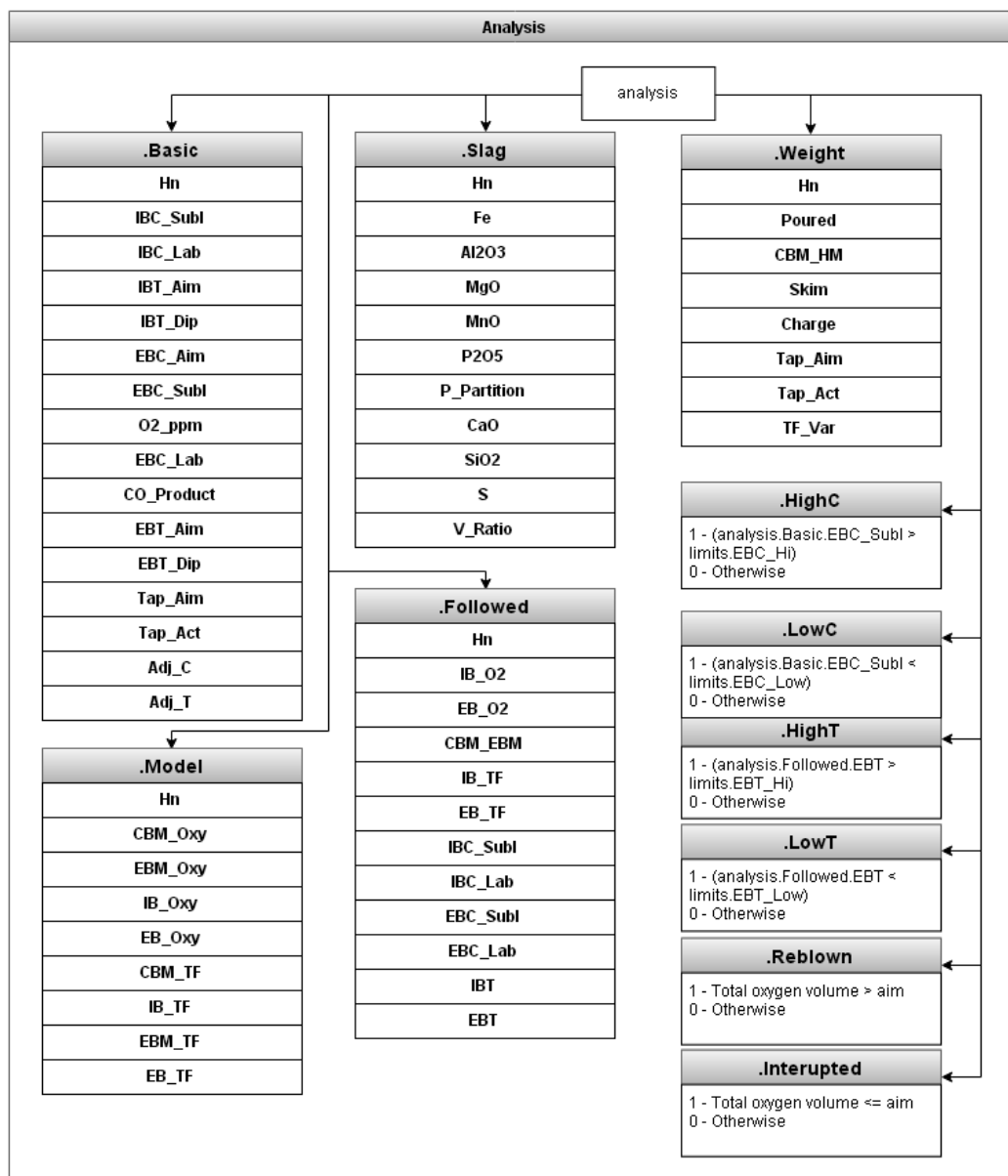
Figure 5.9 shows five different sections of the system feed into this section of the system, 4 processed sections of the system detailed previously along with raw data (red). The various structures this data is split into is shown in Figure 5.10. This contains a wide array of different aspects of the process, a fully expanded view of this is available within the Appendix E. Briefly considering each element:

The .Basic structure is used to gather basic data on the process, including IB and EB measurements from the subblance and labs, along with process aims for T and weight. The .Model structure contains data from the CBM and EBM models as the aim values, and then additionally contains the actual figures used for oxygen and TF additions.

The .Slag structure contains all relevant data for the BOS slag analysis, primarily from the SLAG\_ANALYSIS table in PSMET, with some values being calculated. The .Followed structure contains data that is calculated from the differences between the .Basic and .Model structures, to assess if the model has been followed by the operators.

The .Weight structure primarily contains data from the Crane Analysis data structure, as well as model aims from the CBM and .Basic data structure.

Finally the remaining 6 structures contain a 1 or a 0 depending if the condition is true or not respectively, and are used as part of initial checks when the outputs are generated to see which analysis routes are appropriate for the given heat. These are shown in the bottom right of Figure 5.10.

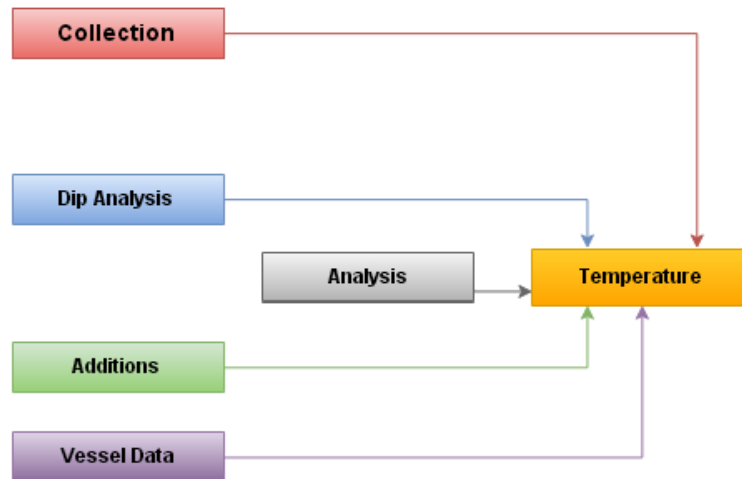


**Figure 5.10 - Overview of the Data & Logic Used Within the Analysis Data Structure, Data Within This Structure Is Extensive As Shown**

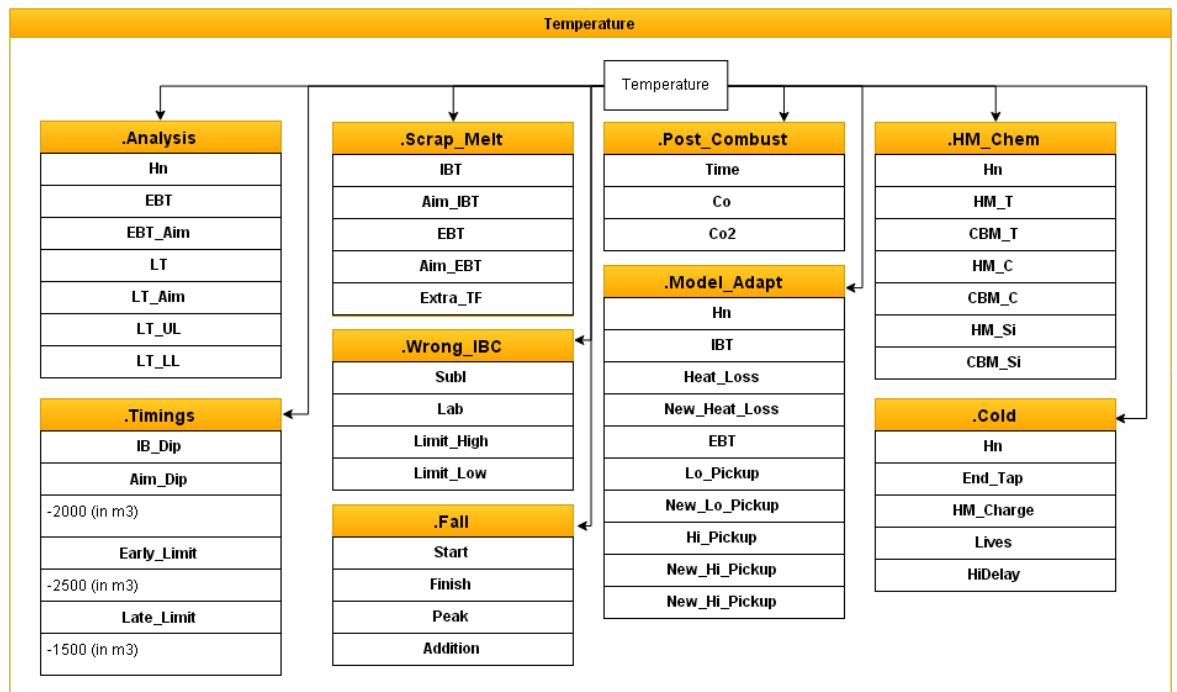
### 5.1.7 Temperature Data Structure

This data structure has been created to contain data covering all process issues that can cause a deviation in the EB T. As can be seen in Figure 5.11, this data structure acquires data from a wide array of data sources to allow it to gather all relevant information. As shown in Figure

5.12, there are a large number of data structures contained with the Temperature structure. All of the structures shown will be explained in more detail within the relevant output modules discussed later on in this chapter. This data structure, as well as being used to generate the outputs, also feeds into the Carbon data structure, which will be discussed in the next section.



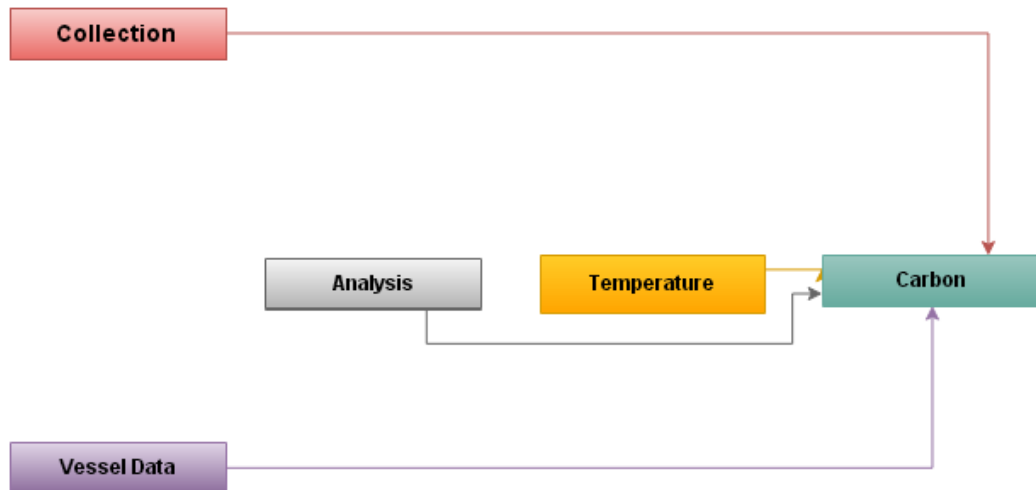
**Figure 5.11 - Temperature Data Structure Inputs, Showing That This Uses Data From 5 Data Structures Within The System**



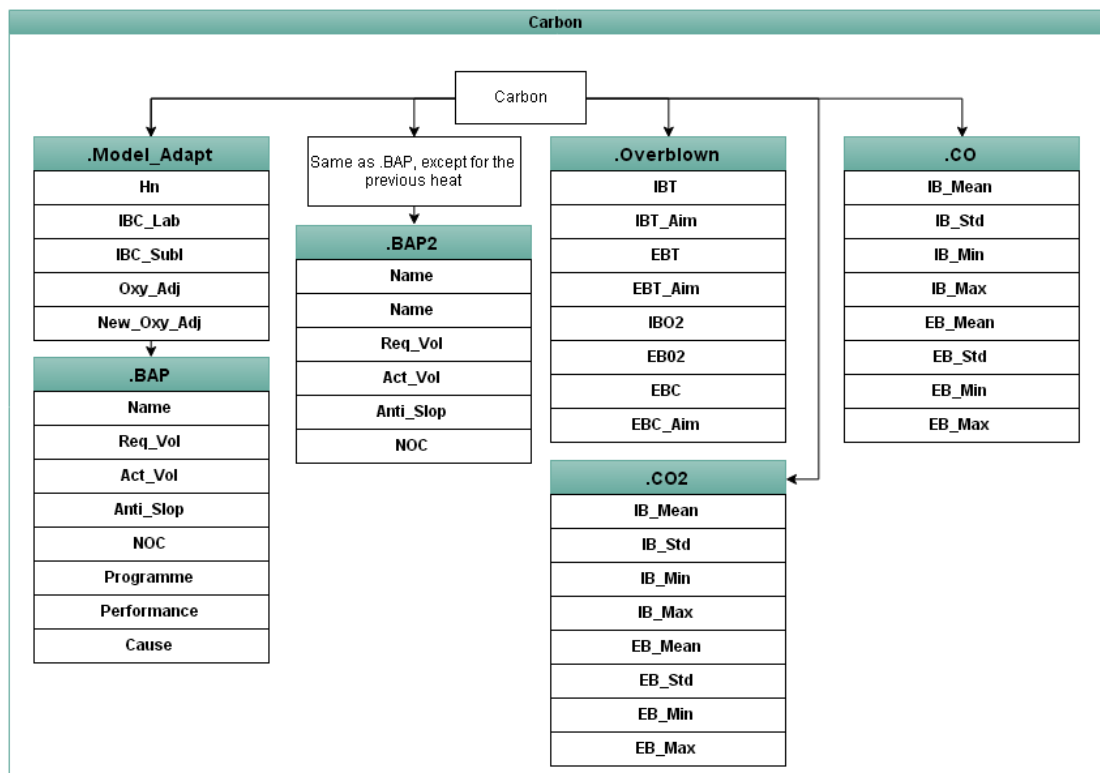
**Figure 5.12 - Overview of the Data & Logic Used Within the Temperature Data Structure**

### 5.1.8 Carbon Data Structure

As with the previous section covering the Temperature data structure, the Carbon data structure has been created to gather all relevant data for issues that relate to C issues within the process. As shown in Figure 5.13, this section of the system is fed by data from the Vessel data, Analysis and Temperature data structures, along with some raw data to allow it to gather all relevant information. An overview of the Carbon data structure is shown in Figure 5.14,



**Figure 5.13 - Carbon Data Structure Inputs, Showing the 4 Data Structures Used To Populate This Structure**



**Figure 5.14 - Overview of the Data & Logic Used Within the Carbon Data Structure**

As can be seen in Figure 5.14 the Carbon data contains 6 separate structures covering a number of issues relating to EB C deviation, facilitating the diagnosis of exact causes. All of these structures will be explained in more detail within the relevant diagnostic modules where they are used later on in this chapter. A fully expanded view of the Carbon structure showing data sources for each column of data is shown in the Appendix E.

## **5.2 Object Oriented Programming Development**

Object Oriented Programming (OOP) has been used throughout the development of the systems presented in this thesis. The techniques used have developed with experience. They've grown from initial steps using basic structures to help organise data and variables within the different systems, to the development of objects designed for specific reusable tasks, available across a number of systems.

Within the Port Talbot Steel Works BOS Plant all continuous data measurements are stored within the Pi database. Unlike the PSMET & PSSUP databases the Pi database is not configured to utilise set tables where specific data is housed. Instead each individual measurement has its own reference, or "tag". This is used to identify the particular measurement being retrieved. This means that, instead of using heat numbers, it is necessary to utilise timestamps to retrieve the required section of data.

To facilitate the extraction of data and improve the quality of coding used within the expert systems a number of objects were created to facilitate data extraction from the Pi database. This approach was used, as it provided a very efficient way of re-using code. This was a very important consideration as a separate data extraction is required for each individual measurement requested from the Pi Database. As with the code developed for data extraction from PSMET this supported the engineering of a tool that is useful, both for future expert system developments for this project, but also within TATA as an additional tool within Matlab.

### **5.2.1 Create & Open Pi Database Connection**

To enable data extraction the following set procedure was established using the database toolbox within Matlab. As shown in Listing 5.1 this was written using an Object called `connpi()`. This was designed using three methods: the "constructor" method to create the Object, "On to" to open the connection to the database and ".Off" to close the connection to the database when not in use.

```

classdef connpi<handle
    properties
        link = {'Pi'}; % read access link for psmet
        user = {'pidemo'}; % user name for read access psmet database
        password = {''}; % password for read access psmet
        % ... other properties ...
    end
end

```

***Listing 5.1 - connpi Object Properties, Shown In Matlab***

The code is used to setup the connpi object with objects. Unless a variable is defined within the properties section of the code, it cannot be used. This means all of the variables required within connpi must be defined. The first method defined is the constructor method, which is simply used to create an Object with the predefined properties, under the variable named in the code as shown in Listing 5.2.

```

methods
    % constructor
    function obj = connpi()
    end
end

```

***Listing 5.2 - connpi Constructor Method***

Once the connection has been created another method “.On” is deployed to open the connection. This is shown in Listing 5.3 and has been designed to retry the connection if it has failed, which can happen occasionally if the server cannot handle a connection request. The method attempts to create the connection 10 times if there is an issue. It also has had a number of outputs built into the code, to provide information on the state of the connection to the user. When the connection works it displays ‘Pi Open’, else it displays information on each attempt to create the connection, and finally ‘Pi Connection Failed’ if after the re-attempts this has not worked.

```

% opens up the database link
function On(obj)
    % database(link,user,password)
    obj.conn = database(char(obj.link),char(obj.user),char(obj.password));
    % checks if connection has worked
    obj.live = isconnection(obj.conn);
    if obj.live == 0
        for n=1:10
            % Wait 10s
            pause(10)
            % Rebuild connection
            obj.conn = [];
            obj.conn = database(char(obj.link),char(obj.user),char(obj.password));
            % If its live, break for loop
            if obj.live == 1
                disp(strcat('Attempt ',num2str(n),' PI Open..... Finally'));
                break
            else
                % else if 10 attempts and no luck
                if n == 10
                    disp('Pi Connection Failed')
                    return
                end
            end
        end
    end
end

```

***Listing 5.3 - connpi.On Method***

### 5.2.2 Data Extraction From Pi Database

The reason for writing the .On code was to create and make a connection to the Pii database. Within the EB C & EB T system, applying the code in Listing 5.4 uses these objects to first create and then open the connection to the database.

```

picon = connpi();
picon.On;

```

***Listing 5.4 - Code Required To Create & Open A Pi Database Connection***



## methods

```
% Constructor
function obj = PiData(string,condition,tag,start,timestep,finish)
    % Summary Of PiData (string,condition,tag,start,timestep,finish)
    % string - 1 for piinterp, 2 for picomp
    % condition - 0 if none applied, else string of condition, e.g.
    % 'STATUS = 81175' to find all values with a heat number of 81175
    % tag - PiTag
    % start - Start Time, in format dd-mmm-yyyy HH:MM:SS
    % timestep - Timestep wanted as a decimal, 1 - 1 minute....
    % finish - Finish Time, in format dd-mmm-yyyy HH:MM:SS

    % checks how inputs have been used
    % PiData(string,condition,tag)
    if nargin == 3
        args{1} = string;
        args{2} = condition;
        args{3} = tag;
        % PiData(string,condition,tag,start,timestep,finish)
    elseif nargin == 6
        args{1} = string;
        args{2} = condition;
        args{3} = tag;
        if strcmp('NaN',start,3)
            args{4} = char(datestr(denum(finish) - denum(0,0,0,45,0),'dd-mmm-yyyy HH:MM:SS'));
        else args{4} = start;
        end
        args{5} = timestep;
        args{6} = finish;
        % PiData(string,condition,tag,start,timestep)
    elseif nargin == 5
```

### *Listing 5.5 - Pi Constructor Method*

The section of the process shown in Listing 5.4 was written using an object called PiData, which has inherited methods and properties from the object called Pii. The constructor method for PiData has been outlined in Listing 5.5. This method has been designed to be very robust; ensuring it can work with a varying number of input variables. This is achieved by using ‘*if nargin ==*’, as this checks to see exactly how many inputs have been given, and

takes appropriate action. There are also checks to determine if the start time is Not a Number ‘NaN’, which indicates that there is no numerical value for this variable. Where possible, if this is the case, the system assumes a start time of 45 minutes prior to the finish time provided. Once the variables have been formatted accordingly, the constructor passes the inputs to another object called Pii in ‘*obj = obj@Pii(args{:});*’. This is applied since Pii is a parent object where all the original development was intended to create the SQL code required for the data extraction.

```
elseif nargin == 6
    if ~isnumeric(string)
        obj.string = string;
    else
        % pinterp on 1
        if string == 1
            obj.string = 'SELECT VALUE,TIME,STATUS FROM PIINTERP';
            % picomp on 2
        elseif string == 2
            obj.string = 'SELECT VALUE, TIME, STATUS, FLAGS, SVALUE FROM PICOMP';
        end
    end
    obj.condition = condition;
    obj.tag = tag;
    obj.start = start;
    obj.timestep = timestep;
    obj.finish = finish;
    obj.s{1} = obj.string;

    if isnumeric(obj.condition)
        if obj.timestep == 0
            obj.s{2} = strcat(obj.s{1},{ ' WHERE TAG = '},obj.tag,{ ' AND (TIME > {ts'},obj.start,{ '
AND TIME < {ts'},obj.finish,{ '})'});
            obj.s{3} = char(obj.s{2});
        else
            obj.s{2} = strcat(obj.s{1},{ ' WHERE TAG = '},obj.tag,{ ' AND (TIME > {ts'},obj.start,{ '
AND TIME < {ts'},obj.finish,{ '}) AND TIMESTEP = '+'},num2str(obj.timestep),{'m'});
            obj.s{3} = char(obj.s{2});
        end
    end
```

**Listing 5.6 - Excerpt From Pii Constructor Method**

As shown in Listing 5.6, the constructor method for Pii checks the number of input arguments and alters the SQL it is generating accordingly. It is important to note that within the Pi database there are two different sources for the data:

Piinterp is a continuous set of data that includes an interpolation of the actual data based on the time step given. If the raw data has a value at 2 second intervals, but the SQL requests data at a 1 second interval, this database interpolates the data to output data at 1 second intervals, as per the SQL request, which is the data source that has been predominantly used, for that reason.

Picomp is the raw data feed. As there are instances of missed data use of this source was avoided where possible.

The constructor methods used have been designed to do as much of the SQL code generation as possible, to make using Objects as simple as possible. The SQL code required to select either of these is identical apart from the name used. This function was therefore added as an input to the constructor as the variable 'string'. If the string had a value of 1, the SQL code for piinterp was used, and if it had a value of 2, then the SQL code for picomp was used. After this first part of the SQL is created, the conditions are added. These take into account the Pi Tag for the data required, the time step between data points and the timestamp range given, use of this is shown in Listing 5.7.

```
audio = PiData(1,0,'MVLAUDIOA_PV', '01-01-2015 07:30:00',0.05, '01-01-2015 08:30:00');
```

***Listing 5.7 - Example Using PiData Object***

This code then generates the SQL code shown below in Listing 5.8.

```
SELECT VALUE,TIME,STATUS FROM PIINTERP WHERE TAG = 'MVLAUDIO1_PV' AND  
(TIME > {ts'01-01-2015 07:30:00'} AND TIME < {ts'01-01-2015 08:30:00'}) AND TIMESTEP =  
'+0.05m'
```

***Listing 5.8 - SQL Code Generated By PiData In Example***

To facilitate the automation of this section of code it was necessary to automate the generation of the timestamps as it would be impractical to have to re-type new timestamps into the code for each diagnosis run. The automation of the timestamp generation was

achieved using an object called ‘Times’, which is shown in Listing 5.9 and was developed to generate the times of all important stages in the BOS plant from a single heat number.

```
classdef Times < handle
    % Times    Summary Of Times
    % Time has been designed to pull out the timings for various events
    % within primary steel making, to make life a little bit easier. Based
    % on an inputted heat number, and a required format, PSMET or PI
    %
    % Times    Properties:
    % d_start - Time ladle enters desulph station
    % d_finish - Time ladle exits desulph station
    % station - Desulph station treated on
    % both - 1 if treated on both stations, 0 otherwise
    % d_start2 - Time ladle enters second station if applicable
    % d_finish2 - Time ladle exits second station if applicable
    % charge - Charge Time For BOS Vessel
    % tap - Tap Time for Bos vessel
    % start - Start blow time for vessel
    % finish - End blow time for vessel
    % Vessel - vessel number, 1 or 2
    %
    % Times    Methods:
    % Times - Takes a heat number and a format request, and outputs the
    % required times into a structure defined by user
```

An important consideration when designing the Times Object was that it needed to

#### ***Listing 5.9 - Properties Of The Times Object***

be made as simple as possible to use, ideally from only a heat number, as this would make the code firstly a lot more robust, and secondly a lot easier to program for all of the required data extraction from Pi. It also needed to format the outputs depending on the application. The format of the time stamps is different depending on whether they are needed to add into the SQL code for data extraction from either PSMET or PSSUP or from the Pi database. To meet this consideration two input variables were required for the Times Object, the heat number for the treatment and a database number. To distinguish between them 1 was assigned for PSMET or PSSUP and 2 to Pi. As shown in Listing 5.10, the initial steps of the constructor method is to extract data from HEAT\_PSSUP, which contains timings for stages

within the BOS process, and DES\_TREATMENT, which contains end treatment time and station number.

```
methods
function obj = Times(hn,database)
% Times(hn,database)
% hn - Heat Number Requested
% database - 1 for PSMET, 2 for PI
% Depending on required format, as PMSET and PI differ, it
% formats all timings accordingly, base don required heat
% number
%
% Open psmet connection
smet = connpsmet();
smet.On;
% Extract relevant data from heat_pssup table
heat = PTData('SELECT DISTINCT
HEAT_NUMBER,ACTUAL_CONVERTER,START_SCRAP_CHARGE_TIME,START_FIRST_BLOW_TIME,END_LAST_BLOW_TIME,END_TAP_TIME FROM HEAT_PSSUP',0,hn,hn);
```

***Listing 5.10 - Initial Section Of Constructor Method For Times Object***

Unfortunately, due predominantly to data quality and availability it was not possible to rely on all of the timings extracted from these databases, if the system was to be made sufficiently robust. Since accurate timings were required for the data analysis of data from the Pi database, further calculations and analysis was undertaken. This was initially applied to the data relating to the BOS vessel extracted from HEAT\_PSSUP. As Listing 5.11 shows, the tap time, vessel number and charge time are simply formatted accordingly before being assigned within the object. This section of code shows the formatting for a database value of 2, which is for use within Pi database extraction.

The start and finish blow times, are based on analysis of Pi traces for the oxygen flow rate, as shown previously in Figure 1.9. The timings used for this initial data extraction are 20 minutes prior to the charge time and the tap time.

```

if nargin == 2
    if database == 2
        %% Vessel
        % Tap time
        obj.tap = datestr(heat.orig.END_TAP_TIME{1}, 'dd-mmm-yyyy HH:MM:SS');
        % Vessel Number
        obj.vessel = heat.orig.ACTUAL_CONVERTER;
        % Charge Time
        if strcmp('NaN', heat.orig.START_SCRAP_CHARGE_TIME{1}, 3) == 1
            obj.charge = datestr(heat.orig.START_FIRST_BLOW_TIME{1}, 'dd-mmm-yyyy HH:MM:SS');
        else
            obj.charge = datestr(heat.orig.START_SCRAP_CHARGE_TIME{1}, 'dd-mmm-yyyy HH:MM:SS');
        end

        % Start/Finish Blow Time
        % Create & open Connection
        picon = connpi();
        picon.On;
        % For Pi Tag
        number = [1, 2];
        % Flow Tag
        flotag = strcat('GM0', num2str(1 + number(obj.vessel)), 'H451');
        % Adjust Charge Time ensure have start blow time
        charge = datestr(denum(obj.charge) - denum(0, 0, 0, 0, 20, 0), 'dd-mmm-yyyy HH:MM:SS');
        % Extract Data
    end
end

```

***Listing 5.11 - Section Of Times Constructor Method Related To BOS Vessel Timings***

To get accurate start and finish blow times the system analyses the flow rate trace and finds the first point where the flow rate is above zero. The timestamp for this point is then recorded and adjusted by 20 seconds to ensure the precise start isn't missed. This point is then configured into the required format before being assigned to the 'start' variable. The finish blow time is obtained using the same approach, but finding the largest time where the flow rate is above zero. This approach is taken as it ensures that reblows and interrupted blows will be identified and contained within the time frame being calculated. Once again the finish time is adjusted by 20 seconds to ensure the end of blow isn't missed. It is then recorded under the 'finish' variable. This approach was necessary as it was initially found

when using the start and finish blow times from HEAT\_PSSUP that the start and any reblows or interrupted blows were occasionally overlooked within the time frame recorded. Therefore to ensure robustness within the system, this approach was taken to manually calculate an accurate start and end blow time. A similar approach was taken with the desulphurization process start and finish treatment times as there is no start treatment time recorded within any of the databases.

Within the Pi database there is a Tag that contains the value 1 when there is a ladle within the desulph stations, which are designated in this case as 'X\_HEAT\_NORTH\_DESULPH' and 'X\_HEAT\_SOUTH\_DESULPH' for the north and south stations respectively. The first and last values are used to estimate the range within which an accurate start and finish time is to be calculated. This is achieved by using this time frame to monitor the lance flow rate for the particular station in question. Using the same approach as with the BOS vessel flow rates the start is calculated as first point where flow rate is above zero and the finish is final point where the flow rate is above zero.

An extra loop is required around this code however as occasionally a ladle is treated on both stations if there has been an issue with the initial treatment. If this is the case the code shown in Listing 5.12, calculates the start and finish time twice, once for each station and stores the times separately. For the start, this will be under 'd\_start' and 'd\_start2' for the first and second station respectively. This code produces the structure shown in **Figure 5.15**.

```
time =  
  
Times with properties:  
  
    d_start: '24-Feb-2015 22:05:41'  
    d_finish: '24-Feb-2015 22:39:41'  
    station: [3x1 double]  
    both: []  
    d_start2: {}  
    d_finish2: {}  
    charge: '24-Feb-2015 22:48:30'  
    tap: '24-Feb-2015 23:15:13'  
    start: '24-Feb-2015 22:47:55'  
    finish: '24-Feb-2015 23:04:44'  
    vessel: 1
```

**Figure 5.15 - Output From Matlab Showing Properties Of A Times Object**

```

%% Desulph
if desulp.data ~= 0
    obj.station = desulp.orig.STATION_NUMBER;
    stations = unique(obj.station);
    for n=1:numel(stations)
        picon.On;
        % help with pitag creation
        stat = {'NORTH','SOUTH'};
        % Create Pi tag
        numtag = strcat('X_HEAT_',stat{stations(n)},'_DESULPH');

        trial.start = datestr(datetime(desulp.orig.CHARGE_TIME_GMT{1}) -
datetime([0,0,0,6,0,0]),'dd-mmm-yyyy HH:MM:SS');
        trial.finish = datestr(datetime(desulp.orig.CHARGE_TIME_GMT{1}) +
datetime([0,0,0,6,0,0]),'dd-mmm-yyyy HH:MM:SS');
        % create string with HN condition
        string = strcat({'STATUS = '},num2str(hn));
        % get data, with minute intervals (no need for too much detail)
        num = PiData(1,string,numtag,trial.start,1,trial.finish);
        num.Data(picon.conn);
        % Close Pi Connection
        picon.Off

    if n==1
        obj.d_start = datestr(num.orig.TIME{1},'dd-mmm-yyyy HH:MM:SS');

```

***Listing 5.12 - Desulph Section Of Times Constructor Method***

The use of the Times object, along with a small piece of code to adjust the Pi Tag depending on which vessel the system is investigating, allows the SQL code generation for data extraction from the Pi database to be automated. An example of the code used to do this in the EB C & EB T system is shown in Listing 5.13.



Once the connection to the database has been created and opened and the SQL code

```
time = Times(pidata.Hn(n),2);  
tag = strcat('MVLAUDIO',letter{vessel},'_PV');  
audio = PiData(1,0,tag,time.start,0.05,time.finish);
```

***Listing 5.13 - Use Of Times Object To Automate Creation Of PiData Object***

generated a method called ‘Data’ located within PiData, is used to send the SQL code to the server via the created data connection. This method is shown below in Listing 5.14.

```
function Data(obj, conn)  
    % Data(conn)  
    % requires a connection, if picon = connpi(), then requires  
    % picon.conn. e.g obj.Data(picon.conn) will get your data  
  
    % creates connection to specific table  
    obj.d = exec(conn, obj.s{3});  
    % extracts the data  
    obj.d = fetch(obj.d);  
    % closes the connection  
    close(obj.d);  
    % writes the data to the .orig structure  
    obj.orig = obj.d.Data;
```

***Listing 5.14 - PiData .Data Method***

### 5.2.3 Application Of The Code

This method works by passing the created database connection to the PiData object as shown below in Listing 5.15. This results in a data structure being created called audio, where all raw data as discussed throughout this chapter is written to the structure within audio called *.orig*. This data is accessible by writing the code ‘*audio.orig*’. A second structure *.sorted* may then be used to contain a sorted or processed version of the original data. This use of structures is important as it allows all versions of the data to be available throughout the system including the raw unchanged data.

```
audio.Data(picon.conn);
```

***Listing 5.15 - PiData Data Extraction***

An additional variable '*.data*' is used to allow, in places throughout the EB C & EB T system, the system to quickly check if there is actually data available within the object for the given time frame requested before trying to process it. If there is no data available then Matlab will by default create a string within *audio.orig* with a value of 'No Data'. The line '`if ~strcmp('No Data',obj.orig)`' is a string comparison, with this condition being met only if there is no data. If this is the case *audio.data* is given a value of 1.

### 5.3 Expert System Output Modules

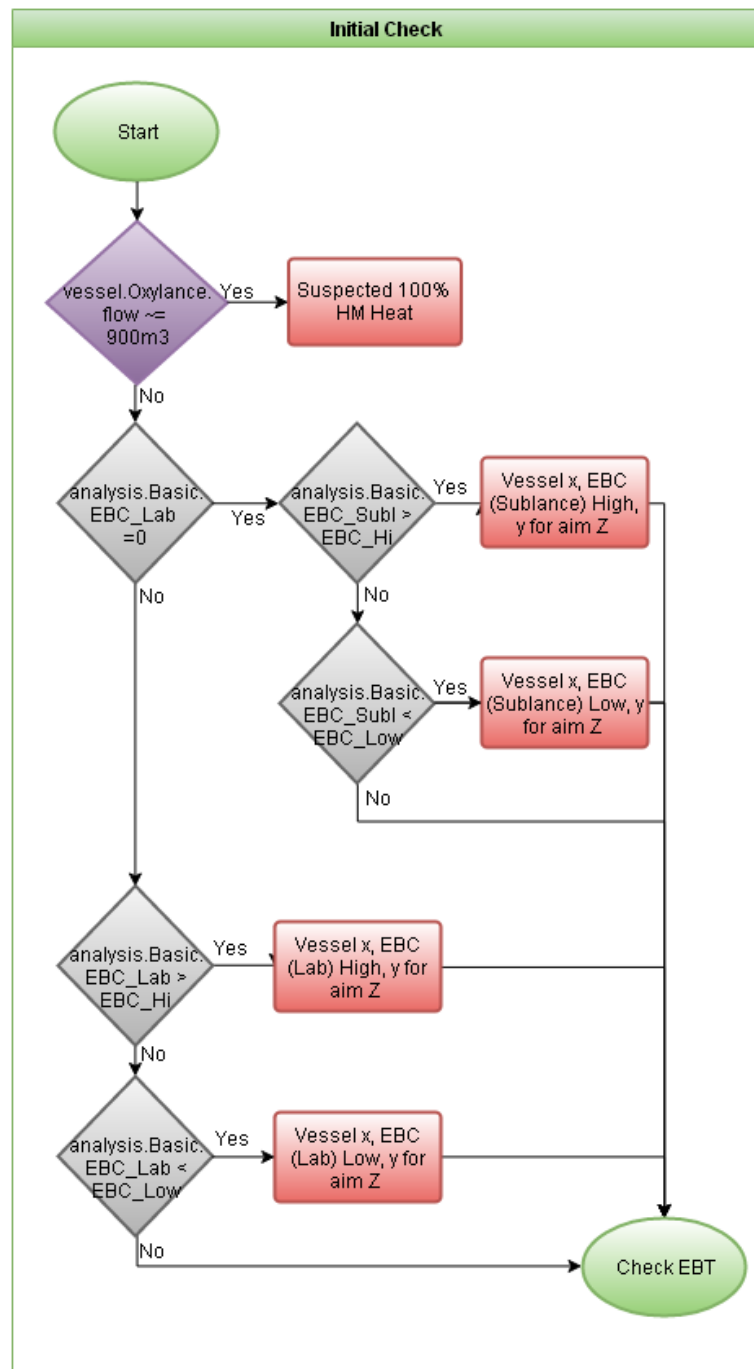
Following on from the methodology used to create outputs within the previous chapter for the desulphurisation diagnostic system, this system has been designed to be modular in nature. What this means for the outputs is that certain diagnostic procedures are only checked if necessary, instead of checking all of the possible outputs sequentially to see which are applicable, and outputting as necessary. The benefits of this are that the system can be easily expanded as deemed necessary and to facilitate runtime on any analysis that needs to take place. This then allows the running of the modules that are relevant to the issues applicable to the heat being analysed. The first step is therefore to check what modules should be run based on the current issues, the first step in a small sequence of outputs for this is shown below in Figure 5.16. The main purpose of this first set of outputs is to check in what state the EB C is at the vessel. The first pair of outputs is identical to the second pair, except the first uses the EB C from the sublance because there is no lab EB C analysis available.

**Table 5.2 - Limit Variable Values**

Variable	Value
EB T Upper Limit	15
EB T Lower Limit	-15
IB T High Limit	30
IB T Low Limit	-30
EB C High Limit	0.1
EB C Low Limit	0.03
IB C High Limit	0.5
IB C Low Limit	0.2

In both cases, if the first output is triggered, the EB C is higher than the upper limit for the EB C value shown in Table 5.2. These are the values within the Limit structure used throughout the system to consider if any of the process parameters are out of specification. A mixture of data mining and expert consultation put this table of values together. Where

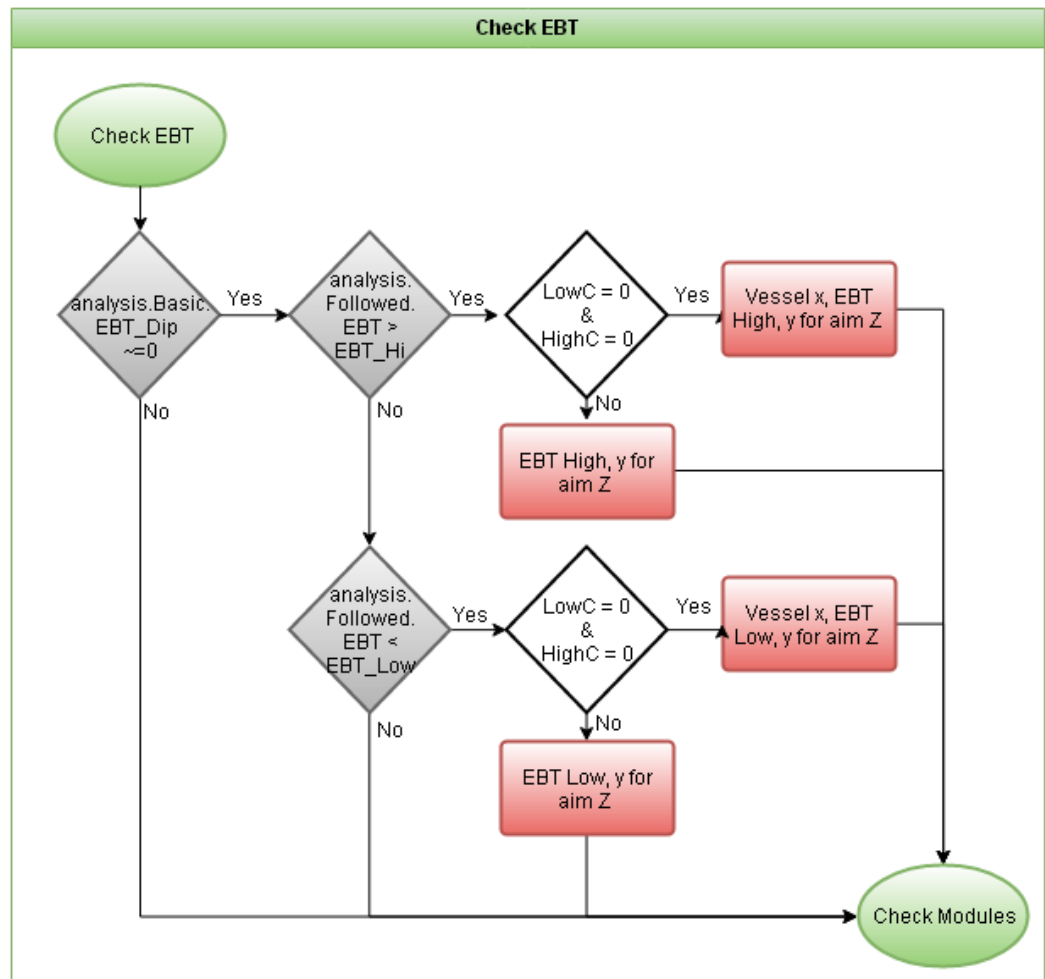
applicable, the analysis behind some of these values will be explained within the diagnostic modules where they are used.



**Figure 5.16 – Flow Diagram Showing The Applied Expert Knowledge Used for the Initial Check Outputs**

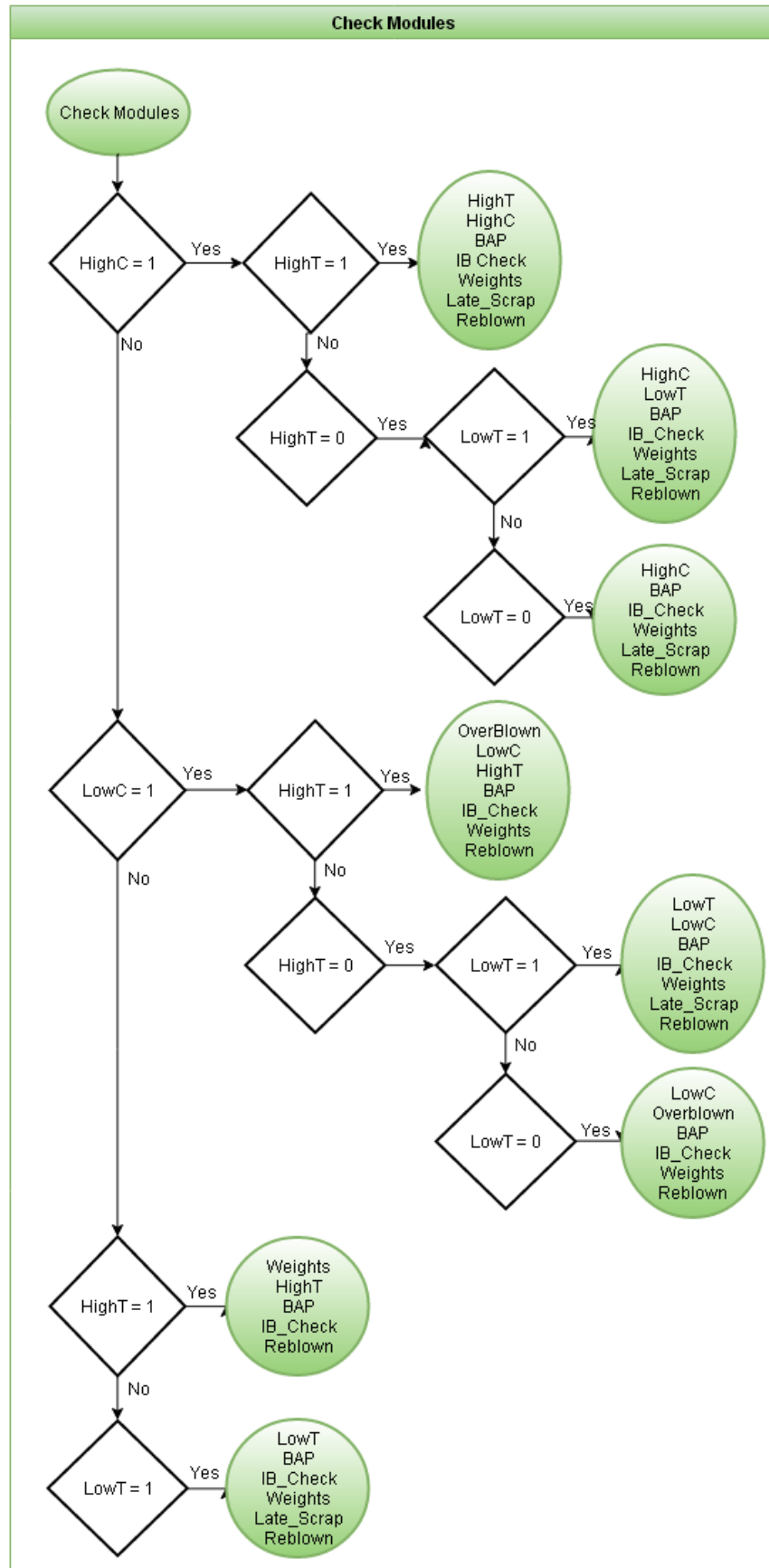
Within Figure 5.16, if the EBC is below the EBC lower limit, along with the output being generated, this sets analysis.LowC equal to 1, and if the EBC is higher than the upper limit, analysis.HighC is set equal to 1. These are used to trigger relevant diagnostic modules later in this section of analysis. The next step within this initial process analysis is to check

the state of EB T at the vessel for the given heat, shown in Figure 5.17. As with the previous check for EB C, the EB T is compared against the upper and lower EB T limits within the limits variable. If the upper limit is exceeded, analysis.HighC is set to 1, and if the lower limit is exceeded analysis.LowT is set to 1. With the outputs, the EB C state is considered to make sure the outputs make sense, if there is a C issue as well, the output is worded as an add on to the C output, otherwise it is worded as a first line output within heat number.



**Figure 5.17 - Flow Diagram Showing The Applied Expert Knowledge Used for the Check EB T**

Once the state of EB C & EB T is checked, the final section of this initial check decides which diagnostic modules need to be checked, as shown in Figure 5.18. Every line within the green ellipses within this figure, is a diagnostic module within the system that is checked due to the given state of the process.

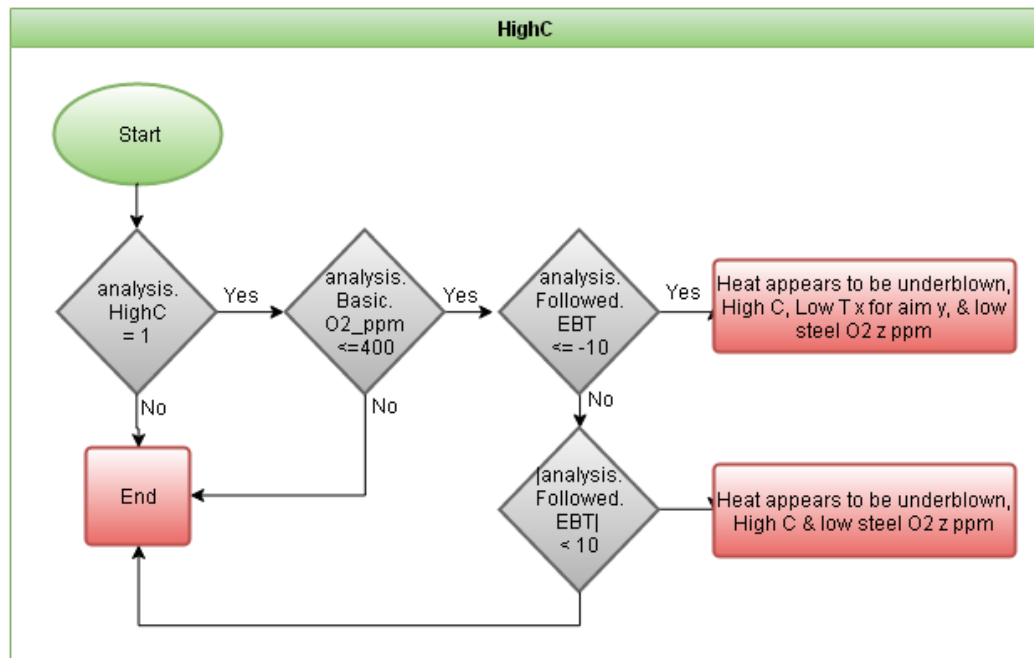


**Figure 5.18 - Flow Diagram Showing The Applied Expert Knowledge Used for the Check Modules**

This section will now present the output modules built within this system, as outlined in Figure 5.18. It will outline the relevant logic and outputs that apply to each section, and explain the reasoning and data processing where necessary behind these. There are currently ten modules built within the EB C & EB T system. These cover analysis ranging from the basic overviews of T and C deviations, to more in depth analysis around post combustion effects within the vessel and the late melting of scrap.

### 5.3.1 High End Blow Carbon

This section of the system is designed to check for simple issues that can be the source of a high EB C value. This section in particular checks for under blowing of the steel which is where insufficient O<sub>2</sub> has been blown into the vessel resulting in a high EB C and a low steel O<sub>2</sub> content.



**Figure 5.19 - Flow Diagram Showing The Applied Expert Knowledge Used for the High C Outputs**

**Table 5.3 - Under Blown, High C & Low EB T**

EB C	≥ 0.1
EB T	≤ -10 below aim
Steel O <sub>2</sub>	≤ 400

There are two scenarios the system monitors for to determine if the steel has been under blown i.e. if an insufficient volume of oxygen has been blown into the vessel. This can be

indicated by a high EB C value above or equal to 0.1% along with either/or a low steel O<sub>2</sub> and a low EB T. The first is indicated in Table 5.3, and shown by the first output in Figure 5.19. The conditions set out in Table 5.4 apply to the second output in this flow diagram.

**Table 5.4 - Under Blown, High EB C & High Steel O<sub>2</sub>**

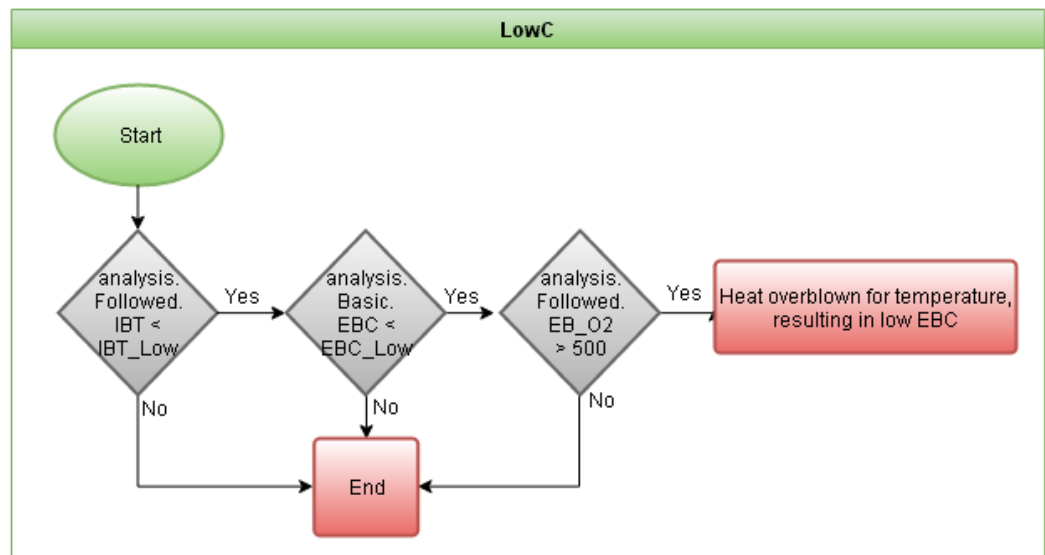
EB C	$\geq 0.1$
EB T	$< 10$
Steel O <sub>2</sub>	$\leq 400$

### 5.3.2 Low End Blow Carbon

Over blowing is where it appears that an excess O<sub>2</sub> has been blown into the vessel. This can be indicated by a low EB C value, along with a high steel O<sub>2</sub>, as shown in Table 1.5.5. The low EB C function only checks to see if the heat has appeared to be overblown. An output for this is shown in Figure 5.20, which applies the conditions set out in the table above. Further diagnosis to isolate the cause of the low EB C is undertaken in other modules within the system.

**Table 1.5.5 Over Blowing, Low IB T, Low EB C & High Steel O<sub>2</sub>**

IB T	Negative 30°C
EB C	$< 0.03\%$
EB O <sub>2</sub>	$> 500\text{ppm}$



**Figure 5.20 - Flow Diagram Showing The Applied Expert Knowledge Used for the Low EB C Outputs**

### 5.3.3 High EB T

The EB T is crucial for secondary steelmaking as there is a target T for each ladle at the casters. If this T is higher or lower than the aim at the end of the BOS processing addition to adjusting the steel chemistry secondary steelmaking also has to undergo additional T adjustments, which can impact steel cleanliness. Therefore meeting the aim EB T at the end of the BOS process is very important. There are a number of areas that this module within the system checks to find the reason behind the high EB T. The effects of post combustion of CO to CO<sub>2</sub> within the vessel itself are monitored, along with the checking of trickle feed coolant weights and any post blow adjustments applied to help cool the ladle steel T ready for secondary steelmaking.

#### 5.3.3.1 Post Combustion Effects

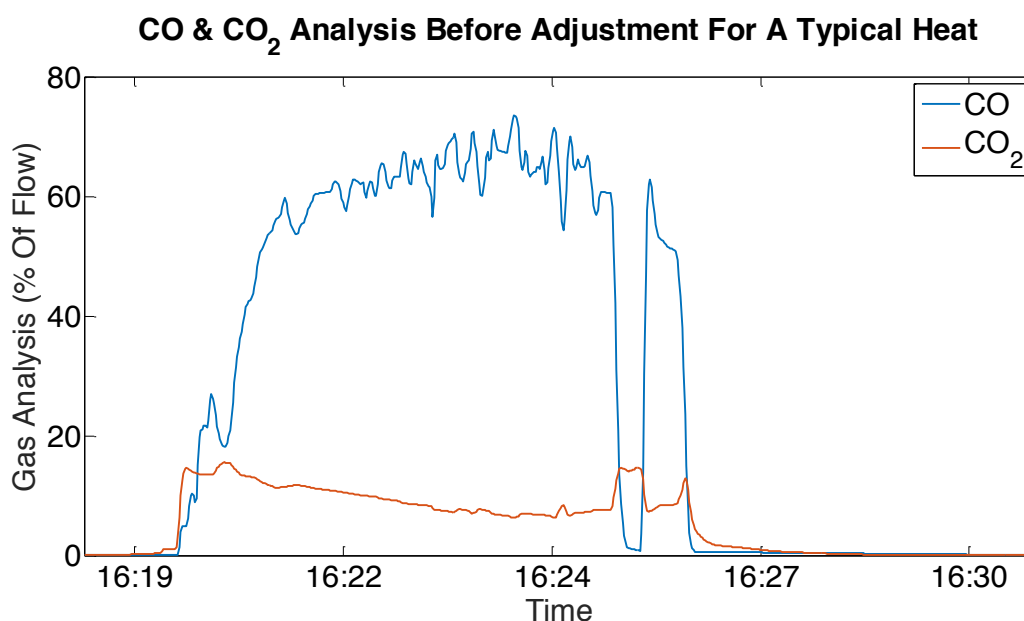
During the BOS process large volumes of CO gas are generated and recovered for use as a fuel elsewhere on site. Approximately 10% of this gas is oxidised in the vessel. Depending on the location and extent of this combustion this can be an additional yet unaccounted for heat source into the vessel. In addition air ingress through the hood of the vessel will cause some of the CO to combust within the off gas system into CO<sub>2</sub>, before the gas reaches the off gas analyser. It is possible to back calculate an estimated level of CO and CO<sub>2</sub> at the vessel by estimating the level of air ingress at the hood based on nitrogen levels at the off gas analyser.

The system splits the off gas analysis for CO<sub>2</sub> into two sections, the first being pre IB dip and the second post IB dip to allow the isolation of this effect on a particular T dip IB or EB. The CO and CO<sub>2</sub> off gas measurements before adjustment are shown in Figure 5.21. The analysis of the CO and CO<sub>2</sub> traces are based on simple statistics of the off gas analysis, using the mean and standard deviation values shown in **Table 5.6**.

**Table 5.6 - Conditions For Pickup Of Post Combustion**

In Blow	Mean	$\geq 8\%$
	Std	$< 2\%$
End Blow	Mean	$\geq 9\%$
	Std	$< 2\%$

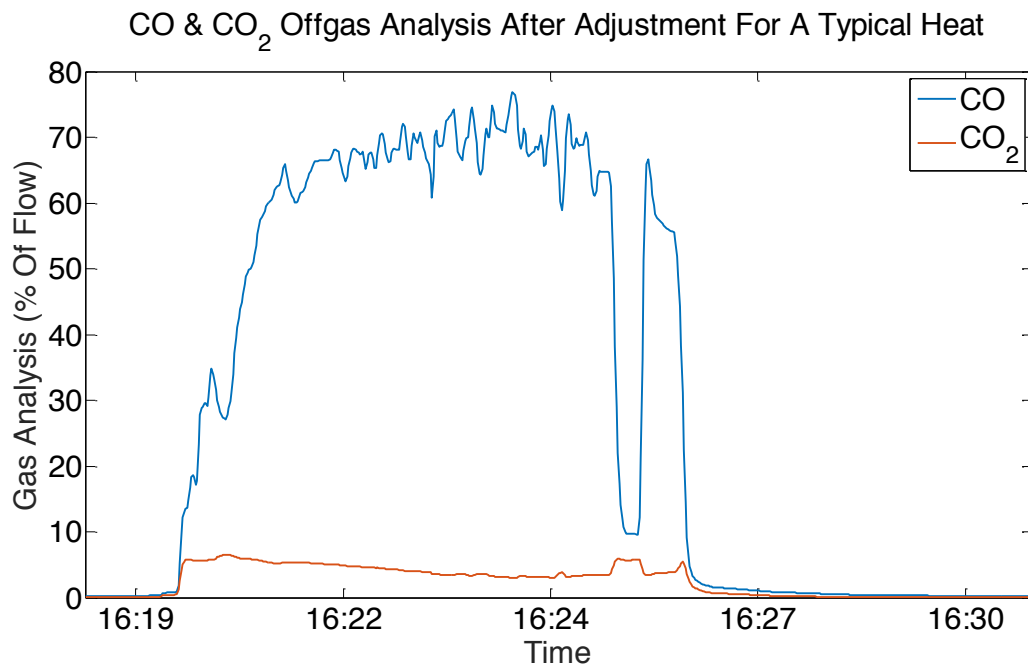




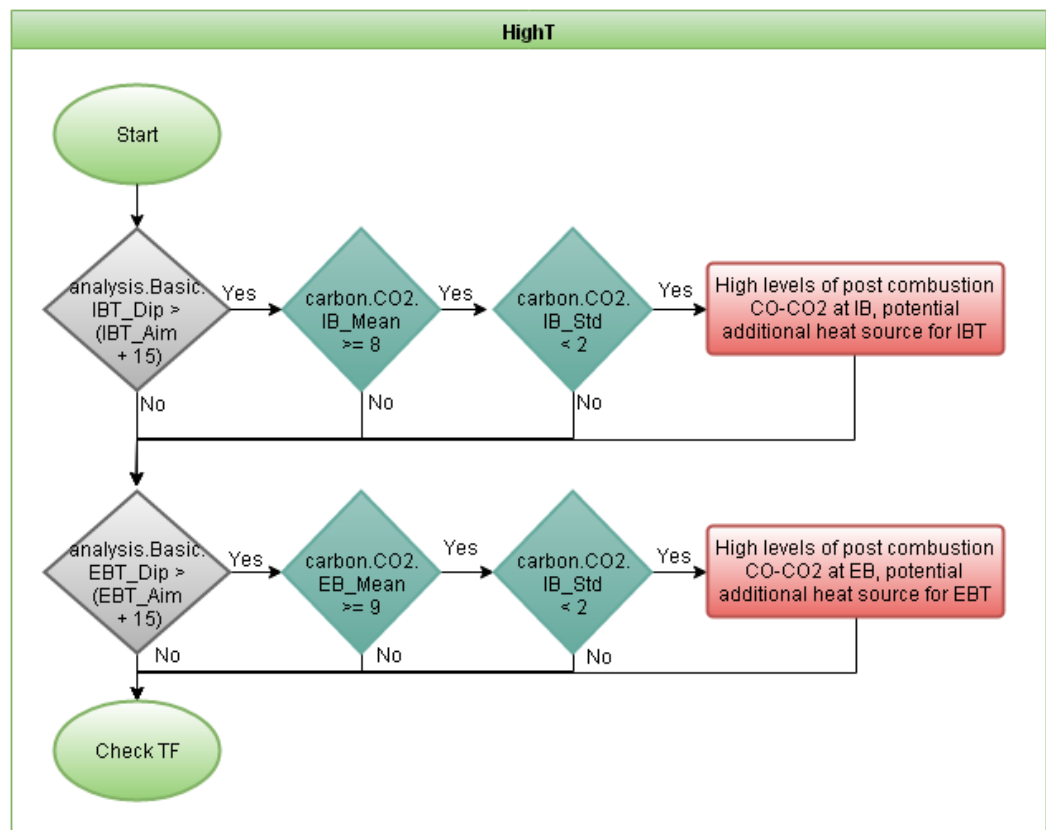
***Figure 5.21 - CO & CO<sub>2</sub> Off Gas Analysis Before Adjustment For A Typical Heat***

The values outlined in Table 5.6 are based on the adjusted values for CO<sub>2</sub>, which are shown in Figure 5.22. This adjustment is made to account for the air ingress through the hood; it reduces the CO<sub>2</sub> value expected at the vessel, as there will be less O<sub>2</sub> available to oxidise the CO gas. It is important to monitor for this, as it will affect the calorific value of the gas that is recovered for use elsewhere on site. This can have a financial impact on the site and the additional energy supplied to vessel by the exothermic oxidation of CO can affect the T of the steel. Depending on the setup of the specific steel plant this combustion of CO within the vessel can be a planned characteristic of the blow. The additional energy allows a higher scrap ratio to be charged into the vessel, due to the exothermic effect and so it is plant dependant. However in Port Talbot there is an aim to recover the CO gas meaning any post combustion within the vessel will be unaccounted for when estimating the EB T.

When the system picks up a high level of CO<sub>2</sub> within the off gas and estimates that this is due to post combustion within the vessel, assuming there is a high EB T, the system will generate an output as shown in Figure 5.23, where the timing is highlighted, informing if this was pre or post IB dip.



**Figure 5.22 - CO & CO<sub>2</sub> Off Gas Analysis After Adjustment For A Typical Heat**

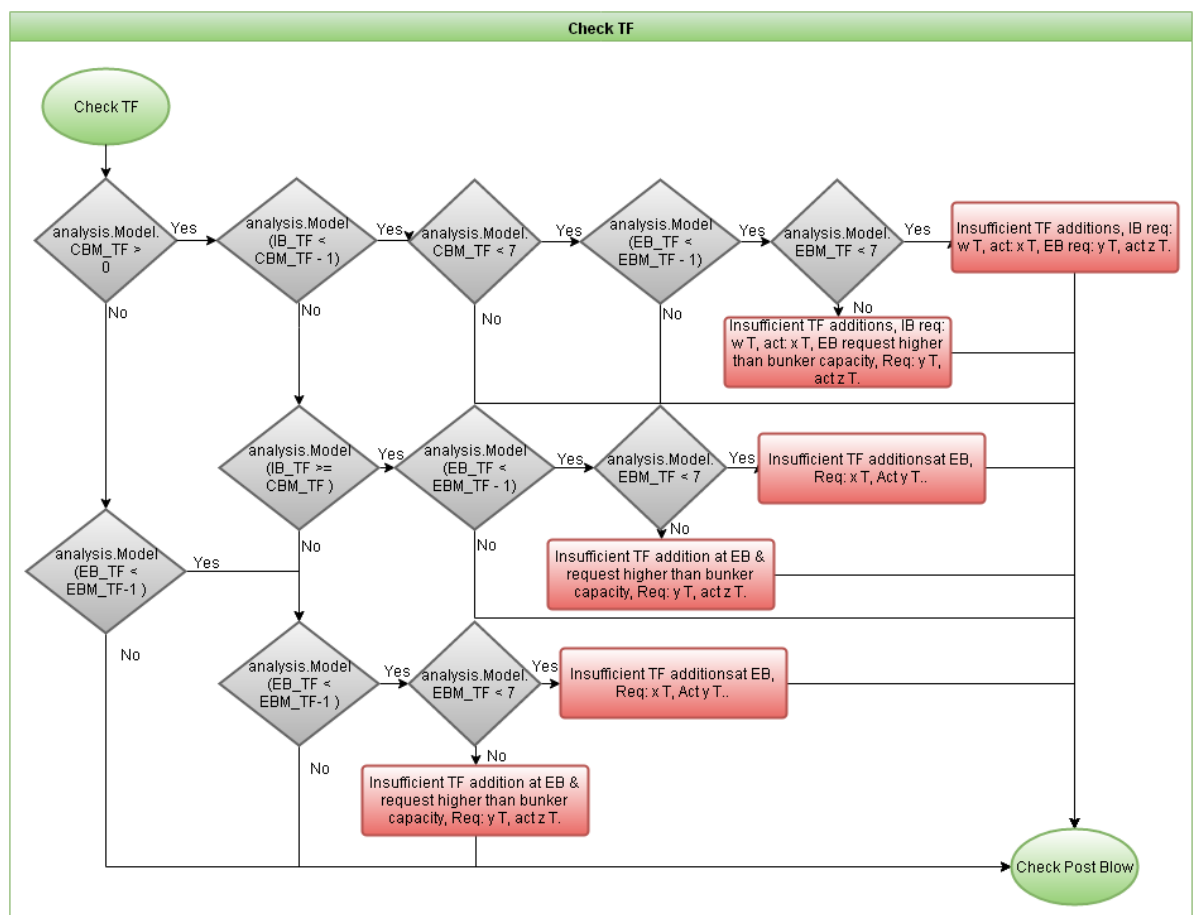


**Figure 5.23 - Flow Diagram Showing The Applied Expert Knowledge Used for the HighT Outputs**

### 5.3.3.2 Trickle Feed Coolant

Trickle feed bunkers are used to add coolant materials such as iron ore or waste oxide briquettes to the vessel during the BOS process. The weights used will be based on estimations from the CBM and EBM, for the pre and post IB dip periods of the blow respectively. The trickle feed bunkers allow the fine tuning of the T within the vessel as these additions can be made without reducing the oxygen lance flow rate.

When a high EB T has been identified by the system, it will check if the trickle feed addition weights have been met. This will be achieved by cross checking the requested and actual weights for these additions, both before and after the dip. This will provide an indication if there was a high IB T, as this could be due to insufficient charging of the trickle feed materials prior to the dip. The first two rows of outputs shown below in Figure 5.24 are for heats where insufficient TF additions pre-IB dip have lead to a high IB T. The later 4 outputs shown in Figure 5.24 are for dealing with insufficient TF additions after the IB dip.



**Figure 5.24 - Flow Diagram Showing The Applied Expert Knowledge Used for the Check TF Outputs**

It is also important to monitor the requested weights from both the CBM and EBM calculations, as the requested weights are not always attainable. The models can request more coolant weight than the equipment allows to be charged, as the bunkers only hold up to 7 tonnes of trickle feed additions at any one time. This is a rare occurrence, as the vessel will not typically be balanced in such a way as to require this amount of additional coolant since this will normally be accounted for with the scrap charge. However when this situation does occur the system highlights the causes accordingly, as shown above.

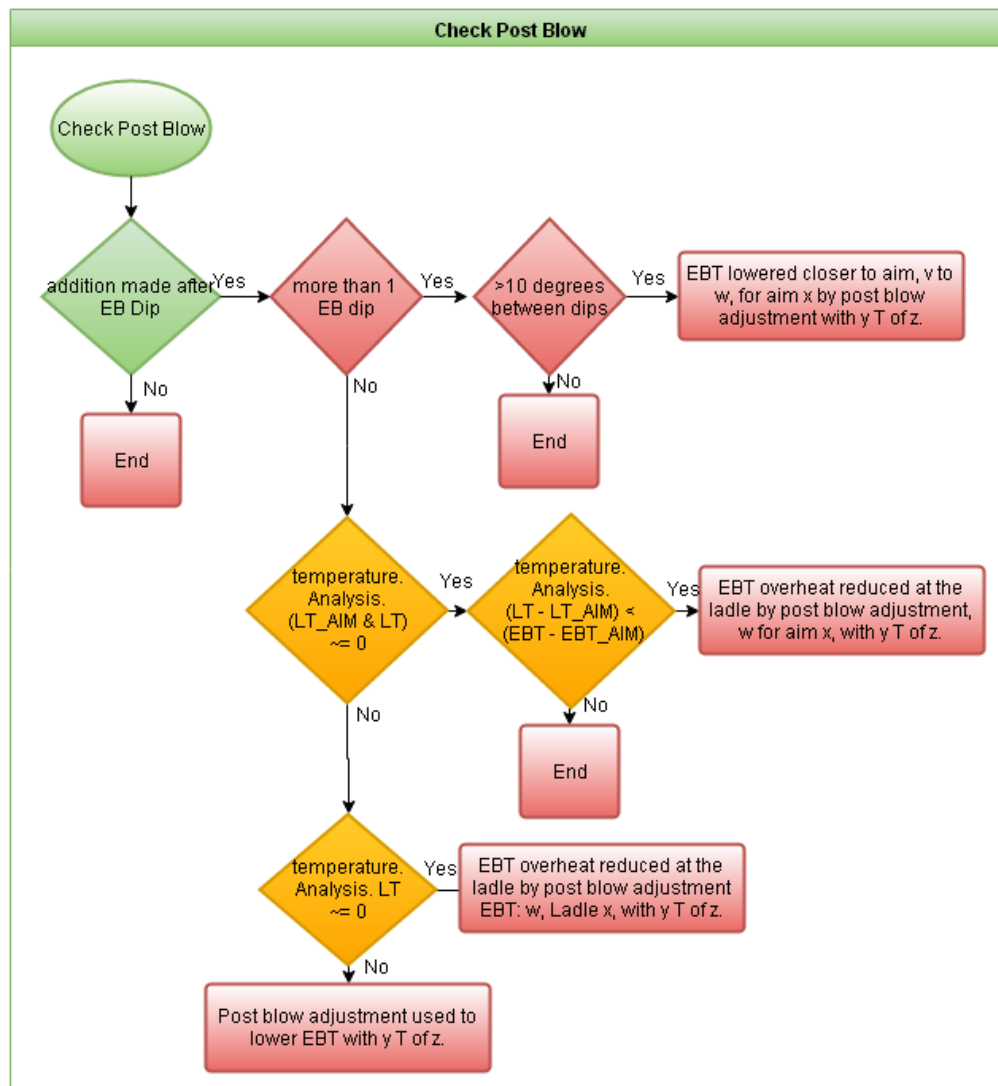
### **5.3.3.3 Post Blow Adjustment**

The final section of the high temperature outputs is a check on post blow adjustments of the process. A post blow adjustment is any addition of coolant to the vessel between the end of blow and the start of tapping. This adjustment is necessary if the EB dip has indicated an excessively high EB T. It will be aimed at reducing the EB T closer to the aim EB T.

The post blow adjustment will typically be done using the trickle feed bunkers. This will be normally be via the addition of WOB's or iron ore, depending on what is currently loaded in the bunkers. The system monitors for a number of different scenarios to ensure the most useful data is output. This means checking the number of EB dips taken and looking into the available aims and Ts at the end of blow and in the ladle after tapping.

The first case is when more than one EB dip has been taken, which is shown by the first row in Figure 5.25. The system can highlight the actual difference in T that any post blow adjustment has made since any additional dips would be taken after the adjustment to ensure the EB T is within specification.

The second case is if only one EB dip has been taken, and a ladle T after tapping is available. The outputs are split depending on whether a ladle aim T exists for the given heat, if this is the case a little bit more information i.e. the ladle aim T is additionally added to the output, otherwise the last output in the figure above is used, simply quoting the weight of coolant added.



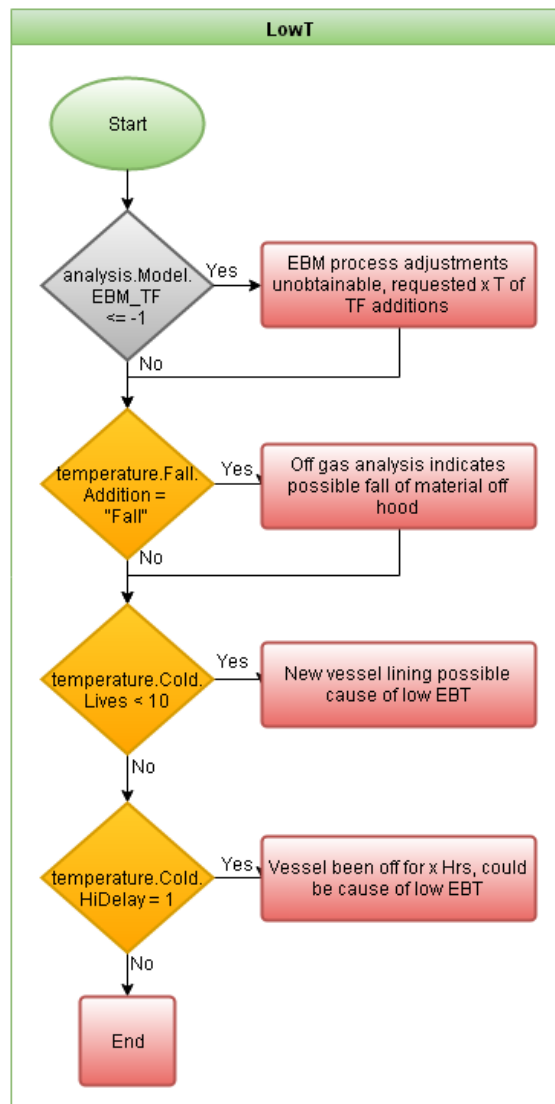
**Figure 5.25 - Flow Diagram Showing The Applied Expert Knowledge Used for the Check Post Blow Outputs**

### 5.3.4 Low End Blow Temperature

If the EB T is below the aim at the end of the BOS process, then, depending on the scale of this error, there can be a requirement for a reblow. This will often be to the detriment of the EB C. As has been mentioned, any deviation in T at the ladle after tapping is an additional parameter that has to be adjusted within secondary steel making.

A low EB T can cause particular issues within Port Talbot steel plant, as the main form of reheating within secondary steelmaking is through the oxidation of aluminium. Depending on the grade being made this can cause issues within secondary steelmaking in terms of steel cleanliness and clogging during casting. This can in turn lead to the down-grading of the steel. All of the outputs relevant to the a low EB T are outlined above in Figure 5.26, with

each of the outputs being relevant to a different situation with the vessel condition, these will be explained individually in the following sections.



**Figure 5.26 - Flow Diagram Showing The Applied Expert Knowledge Used for the LowT Outputs**

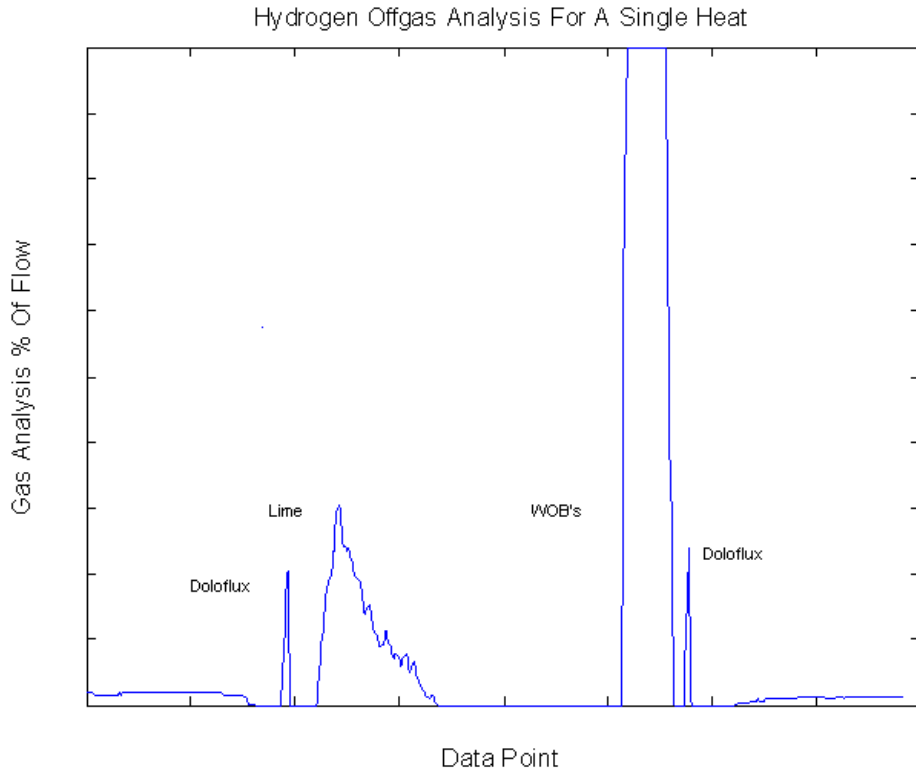
#### 5.3.4.1 EBM TF Additions

After the IB dip is taken, the EBM will use the analysis to calculate required adjustments in the O<sub>2</sub> volume and any coolant weights to allow the EB C and EB T aims to be reached. This model has not been built to recognise unobtainable values, such as negative coolant weights that may arise if the model recognises that the EB T is not going to be reached. The system monitors for this situation and highlights that the EBM requested a negative coolant weight, which is shown by the first row in Figure 5.26.

#### **5.3.4.2 Fall of Material**

The hydrogen analysis within the off gas system can be used as an indicator for a fall of material into the vessel during the blow as this could affect the EB T. This would be typically material built up on the hood falling into the vessel. This particular pattern of H<sub>2</sub> analysis has been applied to the system to monitor such an unexpected event. The hydrogen off gas analysis for a single heat is shown in Figure 5.27, with all the peaks above 1% associated with a charge of material. For this particular heat there was no fall of material; the four peaks are doloflux, lime, waste oxide briquettes and again doloflux respectively. The system cross-references these peaks with the charge times of the materials. When there is no associated charge time for a hydrogen peak the system assumes it is due to a fall of material into the vessel.

There is only an output generated when the EB T is below the pre-set limit, as a fall of material in the vessel will reduce T within the vessel, when this occurs the value of the temperature's .addition.fall is set equal to "fall". This is picked up in row 2 of Figure 5.26, and an output is generated. At this stage the exact effect of this type of event can't be quantified, but as it is being highlighted by the system it can be more easily monitored to improve the level of understanding associated with this type of event.



***Figure 5.27 - Hydrogen Offgas Analysis For A Single Heat, with Labels To Show Typical Effects Of Different materials Added During the Blow***

#### **5.3.4.3 Cold or New Vessel**

The temperature of the vessel lining will have a dramatic effect on the temperature of the steel during the BOS process. A cold vessel lining will act as a heat sink within the process, resulting in a lower than expected EB T. To monitor the vessel lining two different cases were considered, these being the time between the previous tap time and current HM charge time and the number of lives of the vessel.

When discussing a cold vessel lining with process experts, the vessel can be considered cold if the vessel has been empty for more than 6 hours. Based on this the system compares the timings for the previous heat, looking at the tap time in particular compared to the current HM charge time. If this is greater than 6 hours the system sets the HiDelay value within the Model data structure equal to 1, and the 4th row output shown in Figure 5.26 is triggered, highlighting this as a likely cause for the low EB T.

A new vessel lining can have the same effect. Although the new lining will be burnt in it will still to some extent act more as a heat sink during the first few blows. Due to this it



was decided after speaking with experts on the process that if the lining life was below 10 heats and the EB T was low, then this could be considered as a possible cause for the reduced T. The output for this is shown in row 3 of Figure 5.26.

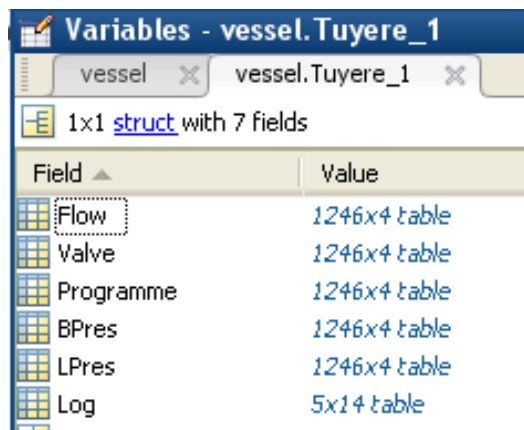
### 5.3.5 Bath Agitation Process

The Bath Agitation Process (BAP) is designed primarily to facilitate homogenisation of the composition and T of the steel within the vessel. This is achieved through the effects of stirring the liquid steel by injecting gases into the bottom of the vessel through tuyeres. The system monitors the BAP when there has been an issue with the EB C, either high or low, as the level of mixing generated by the BAP can affect the efficiency of decarburisation within the vessel and so alter the EB C.

The following sections will firstly outline the data and the programming that has been used to analyse the performance of the BAP, and secondly go through how this analysis then relates to the outputs that the system has been designed to generate when the BAP has been seen to be the source of an EB C deviation.

#### 5.3.5.1 Programming

The data for the BAP all comes from the Pi database. The PiData object as outlined previously, is used to extract all of the data. The measurements extracted from the Pi databases for the tuyeres are shown in Figure 5.28. These indicate the flow rate, valve position, programme flows, back pressure and line pressure. The 'Log' variable is created within the system to contain processed data from the Flow and Programme variables. This data is part of the Vessel data structure that has been outlined previously on page 140.



Field	Value
Flow	1246x4 table
Valve	1246x4 table
Programme	1246x4 table
BPres	1246x4 table
LPres	1246x4 table
Log	5x14 table

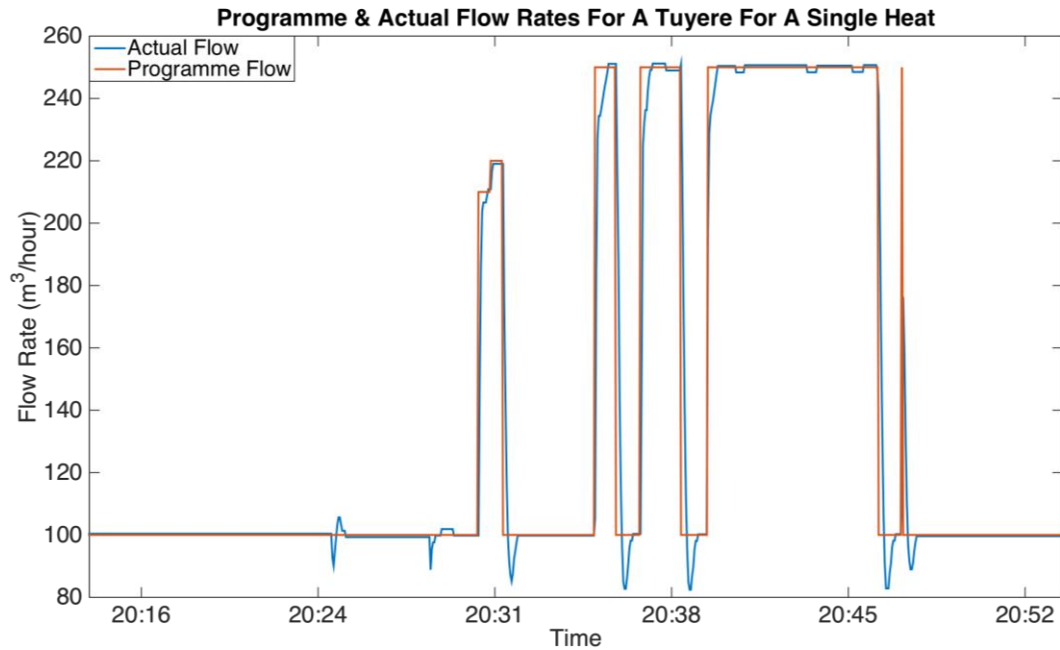
*Figure 5.28 - Tuyere Data*

The first step the system takes is to monitor for peaks in the Tuyere programme flows. The programme flows are the requested flows by the operator, these being a mixture of normal flows and an anti-slop procedure, used to prevent slopping within the vessel. If the Tuyeres are heavily worn, the flows will be set at either 100 or below throughout the heat, to reduce further wear.

***Table 5.7 – Part Of Log Data For Tuyere 1 Flows Shown In Figure 5.28***

<b>Start</b>	<b>Index1</b>	<b>Finish</b>	<b>Index2</b>	<b>Programme</b>				
735924.3	287	735924.3	307	100	210	220	0	0
735924.3	398	735924.3	414	100	300	0	0	0
735924.3	435	735924.3	480	100	300	0	0	0
735924.3	502	735924.3	699	100	300	0	0	0
735924.3	1108	735924.3	1136	100	300	0	0	0

For each individual peak the system records the start and finish time in the Matlab time number format. This is linked with their respective index within the dataset and every different programme step within that peak, as shown in Table 5.7, each line represents a separate peak from Figure 5.29. It was necessary to record each different programme step within each peak, as the anti-slop procedural use of BAP uses two different flows. This helps to identify when this is being used, either separately, or during a normal operating conditions.



***Figure 5.29 - Actual & Requested Tuyere Flows For A Tuyere During A Heat, Showing Reduced Flow For Anti Slop Flows At 20:31***

The next step in the system is to start calculating the mean, median and mode of each of these peaks for both the difference between programme requested flows and actual flows and the actual flows individually. The total requested and actual volumes for each of these peaks is also calculated and recorded. This is necessary as these will be used as inputs into a Fuzzy Inference System to evaluate the programme requested flows. The results will give a ‘Type’ value, which is an evaluation of whether there has been a step change from previous to current heat in requested flows and whether this is due to a change in level of the anti-slop BAP used.

The code in Listing 5.16 is used to populate the Log variable, as shown in Table 5.8, with the required data, for each individual Tuyere in turn. It has been written to allow the same piece of code to be used for each of the 6 tuyeres without needing to rewrite the code 6 times. The ‘vessel.(char(strcat({'Tuyere\_'},num2str(z))))’ section of code produces vessel.Tuyere\_1 when  $z = 1$ , vessel.Tuyere\_2 when  $z = 2$  and so on. This enables the code to be reused for all of the tuyeres rather than ti being rewritten six times.

**Table 5.8 Log Variable Containing Statistical Analysis Of Flow Profiles In Figure 5.28**

dif_me n	dif_med ia	dif_mod e	act_me n	act_med ia	act_mod e	volume_ac t	volume_re q	Type
4.36	-0.97	-0.97	208.64	212.07	219.03	208.64	204.29	2
20.40	-2.63	-0.53	285.11	295.28	299.47	228.09	211.76	4
4.96	-1.88	-0.79	291.92	297.11	299.21	656.82	645.65	4
-5.18	-5.91	-5.35	291.79	293.96	294.65	2874.15	2925.15	4
-3.13	-18.84	-16.82	276.18	281.05	283.18	386.65	391.03	4

**Listing 5.16 - Code To Populate Tuyere Log data**

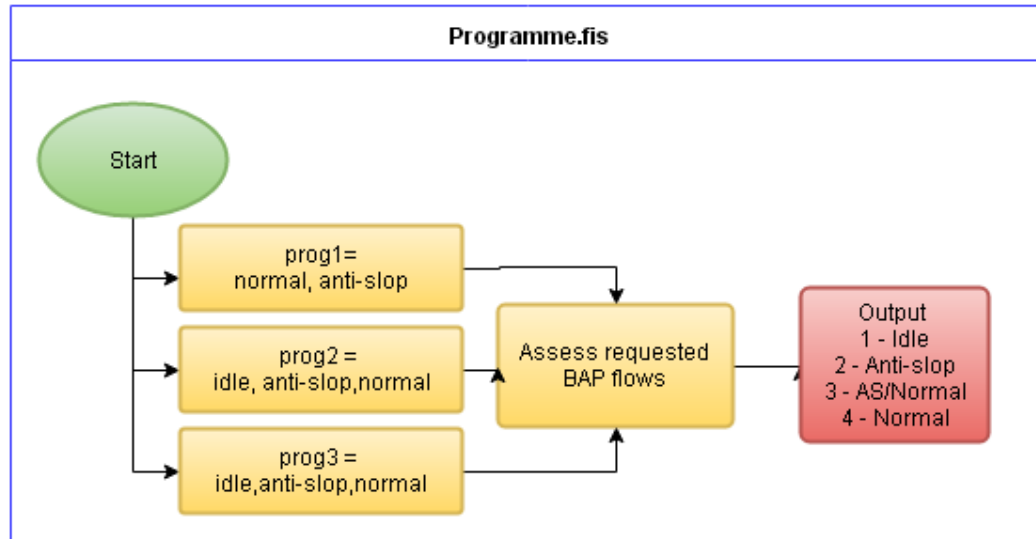
```

Programme = readFIS('Programme.FIS');
for z=1:6
    if vessel.(char(strcat({'Tuyere_'},num2str(z))))Used ~= 0
        for m = 1:numel(vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.start)
            % get idx from .Log
            idx1 = vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.index1(m);
            idx2 = vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.index2(m);
            progr =
unique(vessel.(char(strcat({'Tuyere_'},num2str(z))))Programme.VALUE(idx1:idx2));
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.Programme(m,1:numel(progr))=progr;
            % get dataset from flow.value(idx1:idx2)
            data = vessel.(char(strcat({'Tuyere_'},num2str(z))))Flow.VALUE(idx1:idx2) -
vessel.(char(strcat({'Tuyere_'},num2str(z))))Programme.VALUE(idx1:idx2);
            data2 = vessel.(char(strcat({'Tuyere_'},num2str(z))))Flow.VALUE(idx1:idx2);
            % calculate mean median and mode for the difference
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.dif_mean(m) = mean(data);
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.dif_median(m) = median(data);
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.dif_mode(m) = mode(data);
            % calculate mean median and mode for the actual flows
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.act_mean(m) = mean(data2);
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.act_median(m) = median(data2);
            vessel.(char(strcat({'Tuyere_'},num2str(z))))Log.act_mode(m) = mode(data2);
            % volume

```

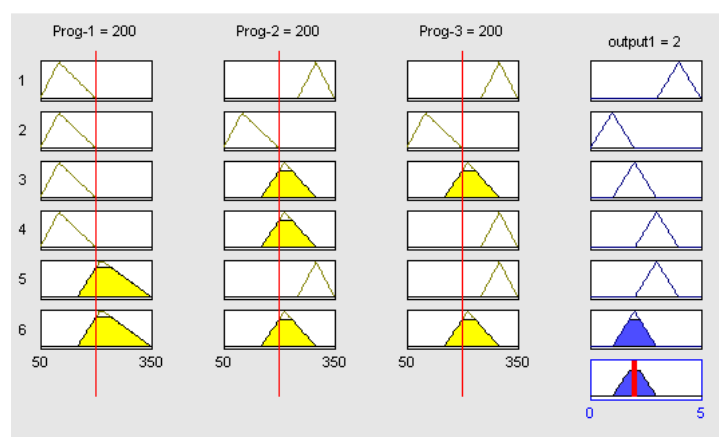
To assist in the analysis of the tuyeres the Fuzzy Logic toolbox within Matlab was used. It was recognized that differences in the data could be linked to the variation in the process and the various scenarios the tuyeres can undergo. The intention was to assist in the analysis of

the tuyere flows to determine if they have had an adverse affect on the process. Two separate Fuzzy Inference Systems (FIS) were created. The first was to analyse the requested tuyere flows to discern if these were either an anti-slop or regular programme flow. The second was created to take the outputs from the programme analysis FIS, for the current and previous heat, to determine if a step change in the process had occurred and if so identify why.



**Figure 5.30 – Flow Diagram Showing Categories Used For Membership Functions Within Programme.fis**

The Programme FIS was designed to separately analyse each tuyere where the flow has gone above 100m<sup>3</sup>/hr, an overview is shown in Figure 5.30. Within each tuyere the programme would also analyse each of the profiles within the Log file separately. This is to allow the system to monitor for each individual tuyere the frequency of each type of flow throughout the heat. This will show up issues with individual tuyeres and identify any high use of anti-slop flows. The rule view of Programme.FIS is shown in Figure 5.31.



**Figure 5.31 - Rule View Of Programme.FIS**

This is an offline test version of the FIS to check the outputs based on predefined inputs. In this case flow rates of 200m<sup>3</sup>/hr as shown. These would indicate an anti-slop profile for this particular section of the tuyere flow rates.

The FIS is accessed using the code shown in Listing 5.16. The first step is to get the log file for the particular tuyere being analysed and then check how many different programme flow values have been recorded. The system needs three values as an input into the FIS. If there have been two programme flow values it has been designed to use the second value additionally as the third. The use of three programme flow rate values is to allow the system to identify instances where a normal flow is either initiated during an anti-slop flow profile or is finished straight into an anti-slop profile. An anti-slop profile is depicted at 20:31 in Figure 5.28, it is where the flow is stepped up to 210, then another step up to 220 m<sup>3</sup>/hour, with the later 3 peaks indicating normal flow patterns at a continuous flow rate.

The first section of code shown in Listing 5.17, evaluates each individual log profile for each tuyere, and records the analysis value from Programme.FIS into a 'type' variable within the Log variable, as shown in Table 5.8 above. The second stage creates an overview of each tuyere, so it sums up the total requested and actual flows for each together with the number of anti-slop and normal flow profiles. This information is configured as an input into the second FIS used.

The final stage of the diagnostic system used the values generated by the first FIS as inputs into the second. The outputs from this analysis will then provide analysis on whether a step change in the process has occurred, and if so why. An overview of the second FIS, Bap\_Flow.fis is shown below in Figure 5.32. The code shown in Listing 5.18 shows how the second FIS is used within the system. It uses six inputs depicting the state of the flow for the current and previous heat to allow a direct comparison.

The FIS has been designed to have three outputs that describe; the state of the programme requested flows, the performance or actual flows and whether a cause has been identified. All of these are output as numeric values, which are then interpreted and associated with the correct output.

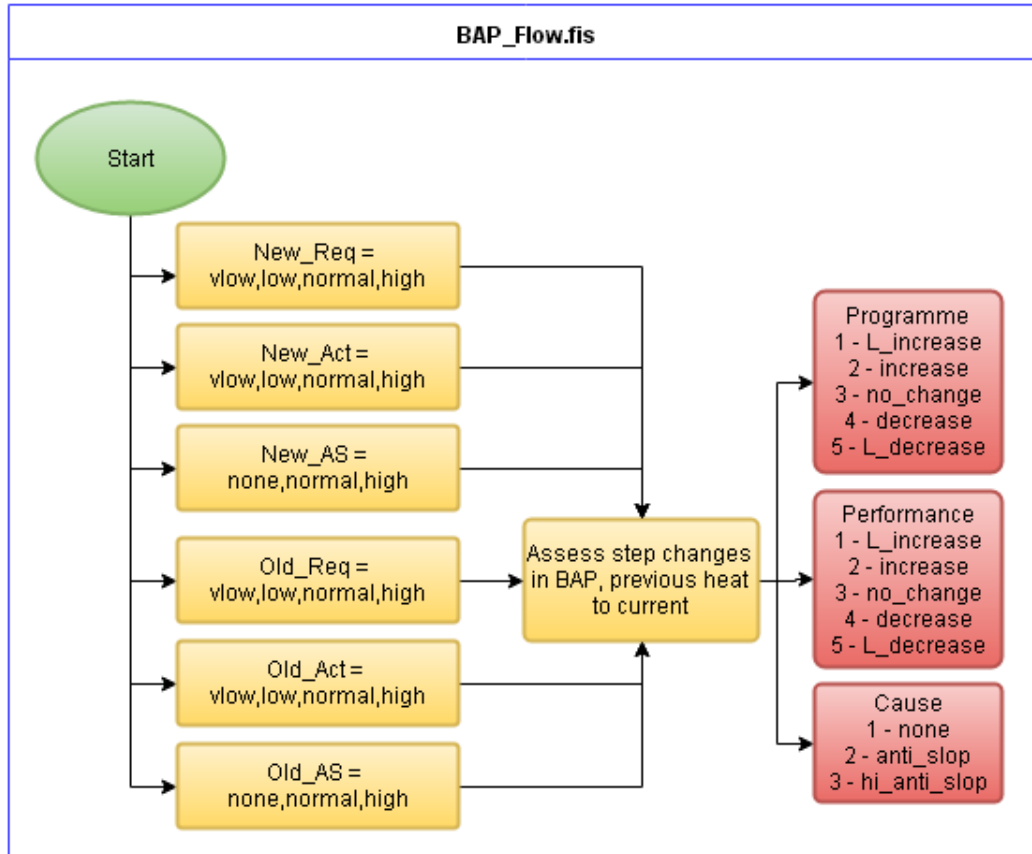
```

% Fuzzy Logic Of Programme Flow Rates
for p = 1:numel(vessel2.(char(strcat({'Tuyere_'},num2str(z)))).Log.Programme(:,1))
    temp = vessel2.(char(strcat({'Tuyere_'},num2str(z)))).Log.Programme(p,:);
    prog1 = temp(1);
    prog2 = temp(2);
    for m = 1:numel(temp)
        if temp(m) ~= 0
            Temp = temp(m);
        end
        if m == numel(temp)
            prog3 = Temp;
        end
    end
    % Evaluating FIS
    vessel2.(char(strcat({'Tuyere_'},num2str(z)))).Log.Type(p) =
    round(evalFIS([prog1,prog2,prog3],Programme));
end
end

% Creating C.BAP
C.BAP2 =
table(cell(6,1),zeros(6,1),zeros(6,1),zeros(6,1),zeros(6,1),'VariableNames',{'Name','Req_Vol','Act_
Vol','Anti_Slop','NOC'});
index = 1;
for z=1:6
    if vessel2.(char(strcat({'Tuyere_'},num2str(z)))).Used == 1
        C.BAP2.Name{index} = strcat({'Tuyere_'},num2str(z));
        C.BAP2.Req_Vol(index) =

```

***Listing 5.17 - Matlab Code To Use Programme.FIS, & Data Processing***



**Figure 5.32 - Flow Diagram Showing Categories Used For Membership Functions  
Within BAP Flow.fis**

```

% Evaluating change in performance
bap = readFIS("BAP_Flow.FIS");
% inputs [new_req,new_vol,new_as,old_req,old_act,old_as] 3 = no change,
% 1-2 = reduction, 4-5 increase in either req or act flow rates
if ~isempty(C.BAP)
    if ~isempty(C.BAP2)
        for z=1:numel(C.BAP.Act_Vol)
            x =
evalFIS([C.BAP.Req_Vol(z)/100,C.BAP.Act_Vol(z)/100,C.BAP.Anti_Slop(z),C.BAP2.Req_Vol(z)/10
0,C.BAP2.Act_Vol(z)/100,C.BAP2.Anti_Slop(z)],bap);
            C.BAP.Programme(z) = round(x(1));

```

**Listing 5.18 - Using BAP\_Flow FIS**



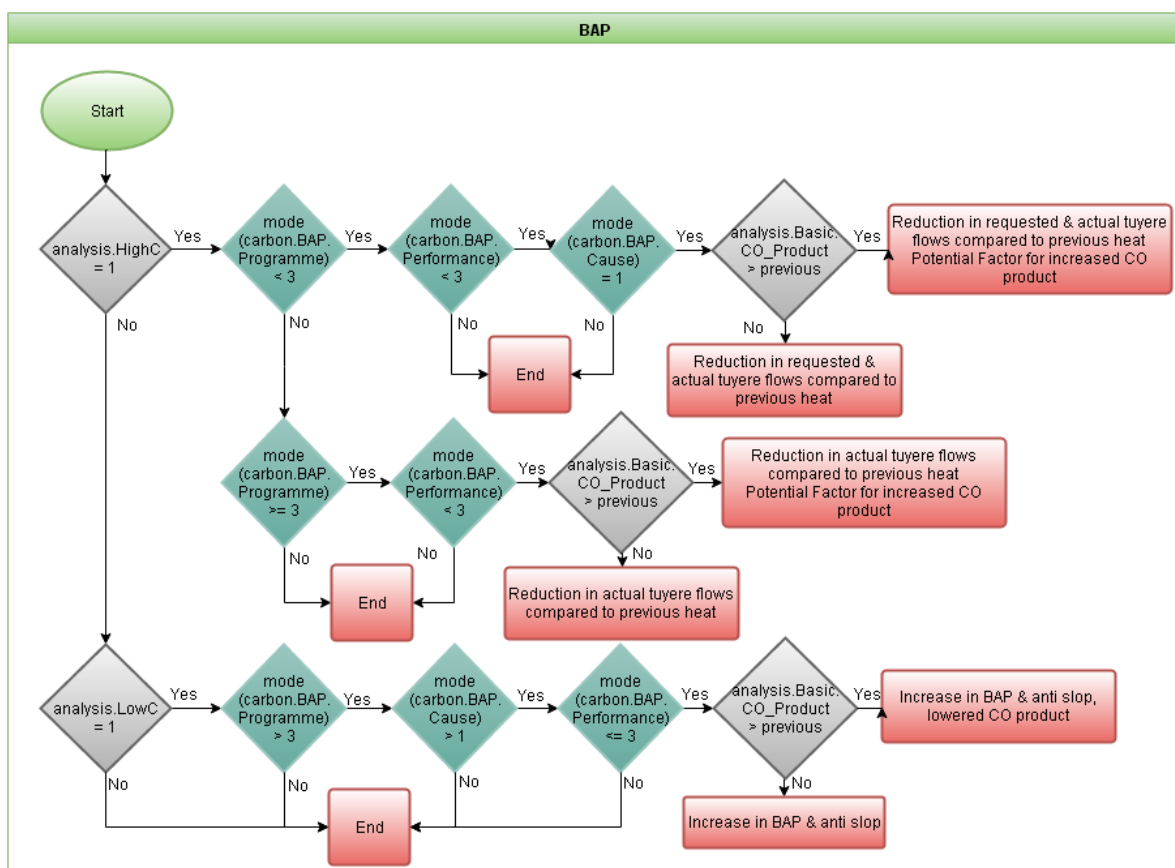
This code generates three outputs for the given heat, the first and second describe the programme and performance flows respectively. These are analysed to see if either of these have had a change in the volumes either requested for the programme flows or delivered for the performance. A value of 3 indicates no change in tuyere flow volume. Values of 1 & 2 indicate heavily reduced and reduced flows respectively. Values of 4 & 5 indicate increased and heavily increased tuyere flow volumes.

The third output identifies the cause. Typically this will be output as a 1, as this would indicate that the use of anti slop flows hasn't been the reason the flows have changed. However if the use of anti slop flows are the cause, a value of 2 is output if this was deemed to have some effect on the tuyere flow volumes. A value of 3 is applied when it is considered that the use of anti slop heavily increased the tuyere flow volumes.

### **5.3.5.2 Outputs**

The system calculates the state of the BAP and using fuzzy logic categorises this into numerical values. This section will outline how these numerical values are interpreted. In doing so it considers the way in which the outputs of the system have been designed and configured to enable the monitoring of changes in BAP performance. As has been established the BAP performance is analysed if there has been an issue with the EB C. These changes can be either high or low, as the BAP affects the stirring within the vessel and level of homogeneity, which will affect the efficiency of the decarburisation of the iron.

An overview of all of the outputs that are generated by the expert system for BAP related issues is shown in Figure 5.33. These outputs, and the logic used to determine them will now be explained.



**Figure 5.33 – Flow Diagram Showing The Application Of Expert Knowledge Used For BAP Outputs**

High EB C can potentially be caused by a reduction in stirring from the BAP, which would be associated with reduced flows. The parameters the system checks for a high EB C focus predominantly on the requested and actual flows compared to the previous heat. These are outlined in the FIS Programme and Performance outputs respectively, as shown in Table 5.9.

**Table 5.9 - Example Of Reduced Requested Tuyere Flows**

EB C	$\geq 0.1\%$
FIS Programme	$< 3$
FIS Performance	$< 3$
FIS Cause	$= 1$

For this particular situation the state of the BAP would indicate a reduction in requested and actual tuyere flows. This would generate an output to highlight this. The system additionally checks the CO product, which is a measure of how efficiently the C has been removed from the steel. An increasing value shows a reduction in efficiency typically

due to a reduced stirring effect. If the current CO product is greater than 3 points larger than the previous heat this is also indicated. These first 2 situations are shown by the first two outputs in Figure 5.33. The same parameters for a heat where the EB C is high, but the requested tuyere flow volumes have stayed the same or increased, are shown in Table 5.10.

**Table 5.10 - Example Of Only Reduced Actual Tuyere Flows**

EB C	$\geq 0.1\%$
FIS Programme	$\geq 3$
FIS Performance	$< 3$
FIS Cause	$= 1$

In this case, the actual tuyere flow volumes have reduced, with no reduction in requested flows. This could be an indicator that one of the tuyeres is either fully or partially blocked. With this level of data it isn't practical to infer the exact cause for the reduction, however highlighting that there has been a reduction to the operators and managers will increase the visibility of the issue if any action needs to be taken. As with the previous output, the system also monitors the CO product and adds the additional line of information if appropriate. This situation is shown by row 2 in Figure 5.33, with the final diamond decision point used to generate different outputs depending on CO product.

As high EB C can be caused from insufficient BAP, it is possible that excessive BAP can cause better than expected C removal. This will result in a lower than expected EB C. This is only the case however if the additional BAP has been requested through excessive use of additional anti slop BAP flows during a heat, with the FIS outputs for this situation shown in Table 5.11.

**Table 5.11 - Example Of Increased Requested & Actual Tuyere Flows**

EB C	$< 0.03\%$
FIS Programme	$> 3$
FIS Performance	$\geq 3$
FIS Cause	$> 1$

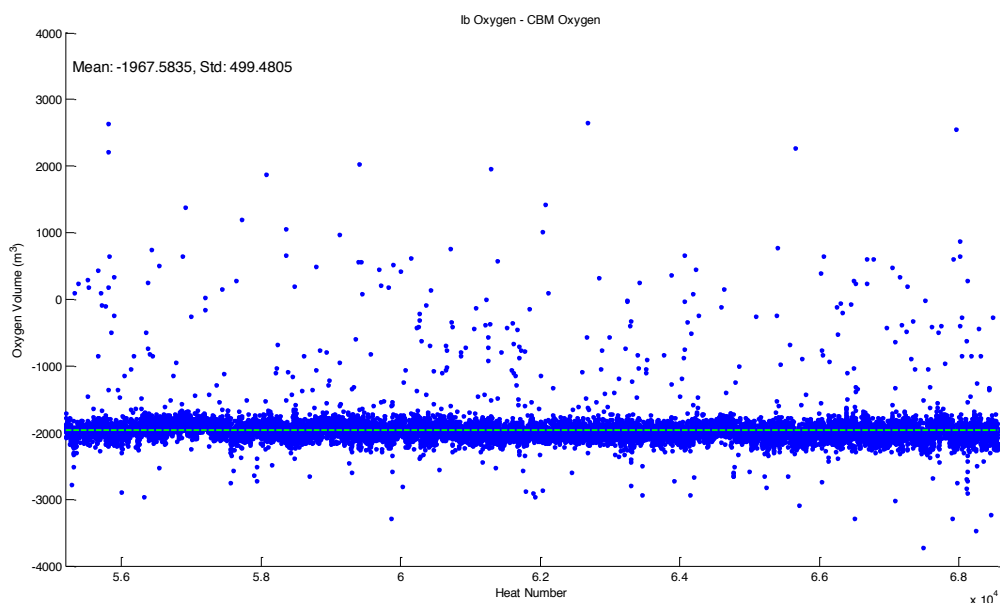
These criteria imply that the requested and actual flows have increased from the previous heat. It is further implied that the flows have been caused by the use of the anti slop profiles, indicated by the FIS cause value being greater than 1. As with all previous outputs for BAP, the CO product is monitored to allow additional detail to be added to the outputs. This situation, along with the impact of CO product is shown by the third and final row in Figure 5.33.

### 5.3.6 In Blow Check

The IB dip is the only point during the BOS process where the steel chemistry, in particular C, is physically measured. The result is used as an input into an EB Model (EBM) that can be either linear regressions or neural network based models. This can then be applied to calculate coolant and O<sub>2</sub> requirements to reach EB chemistry and T. It is important to check if the estimate for C from the IB sublance was accurate by comparing it to the lab analysis of the sample taken. If the sublance estimate of C was incorrect, then the EBM would have been setup incorrectly. This could be the root cause of a missed C and potentially also to a missed T aim.

#### 5.3.6.1 Data Analysis

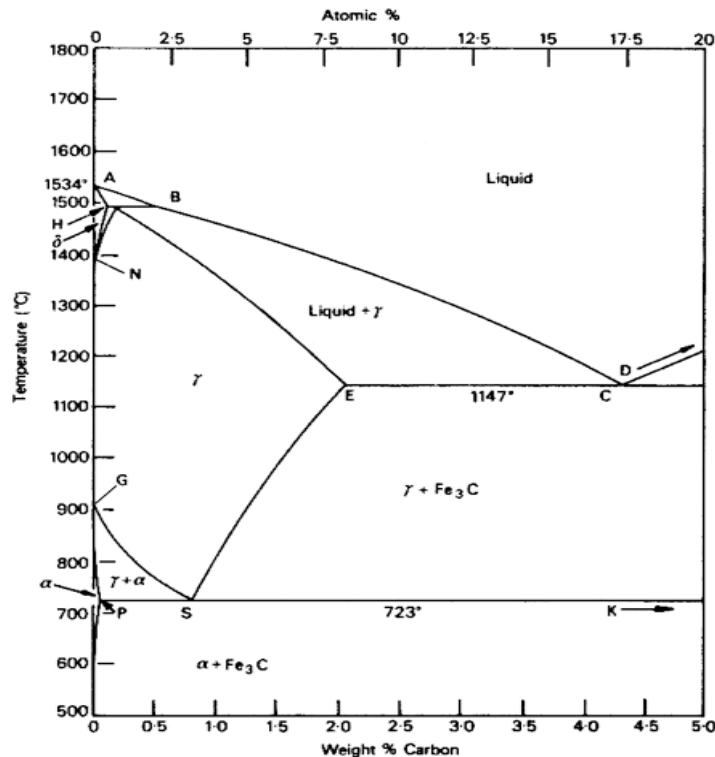
The IB dip measures the C content and T of the steel in the vessel. It is important that these are accurate, as they are used to fine tune the process in order to reach the required aims. Issues with the IB dip can be split into two categories, operator and equipment. Operators can affect the timing of the dip, so initial data analysis was undertaken to learn when this occurs. This was based upon a comparison of the volume of O<sub>2</sub> used with the required O<sub>2</sub> volume. As Figure 5.34 shows this is approximately 2000m<sup>3</sup> short of the CBM estimated required O<sub>2</sub> volume, as shown by the average IB O<sub>2</sub> volume being -2000m<sup>3</sup> short of the CBM O<sub>2</sub> volume required.



***Figure 5.34 - Volume Of Oxygen Used At IB Dip Compared With CBM estimated Required Total Oxygen For 1 Year Of Heats***

The application of the IB Dip is used to measure the steel chemistry in two separate ways. Firstly measurements within the sub lance itself provide a very quick estimate of the chemistry for use in the EBM. Secondly a sample of the steel from the sub lance is analysed within the BOS Plant laboratories to ensure that the IB estimates were correct.

To enable the first measurement the IB sub lance takes a sample of the liquid steel and monitors the cooling period to estimate the C content of the metal within the vessel. This internally generated result is provided quickly as it is based on the liquidus T. The liquidus T, as shown by the steel phase diagram in Figure 5.35, is represented by the line ABD. The information used here is represented in the section between points A and B.



**Figure 5.35 - Steel Phase Diagram (Badheshia, 2012)**

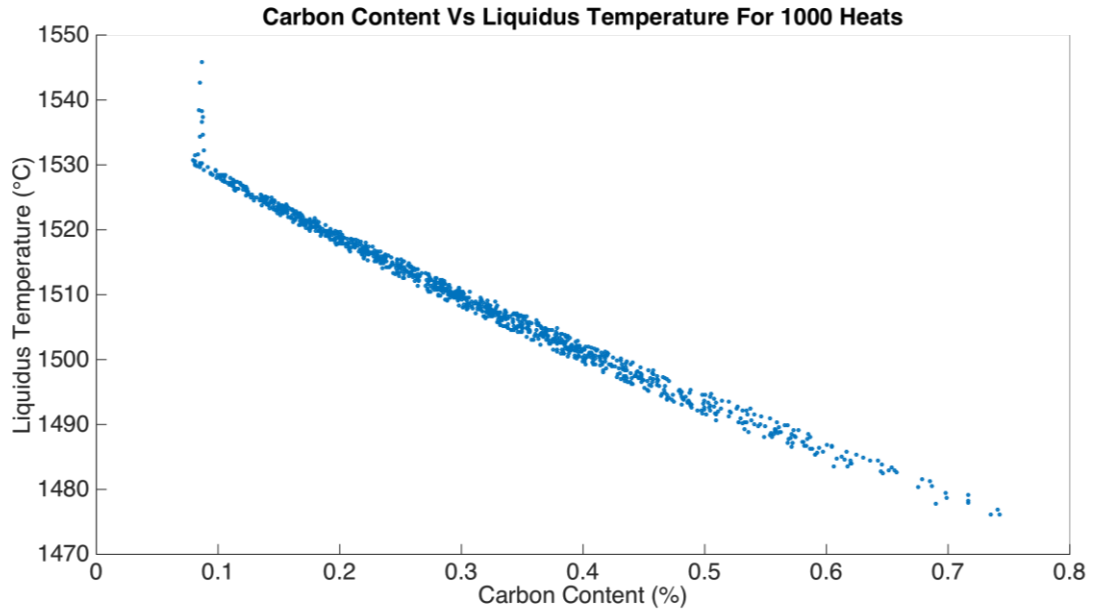
This is due to the steel at the IB dip having a C content of approximately 0.35% at that point in the blow. The liquidus T is measured within the sub lance. By monitoring the T of the sample; the cooling rate can be established. When this cooling rate changes, the liquidus point has been reached and passed; this T is then recorded as the C arrest T. The C content is then estimated by using an equation based on the line A-B in Figure 5.35, to relate liquidus T with C content, the equation used in Port Talbot is shown in Equation 5.1.

**Equation 5.1 - %C Based On Liquidus T**

$$\%C = 0.435 - 0.01259T + 0.0000358T^2$$

$$\text{where } T = T_{\text{Liquidus}} - 1500$$

(6.1)



***Figure 5.36 - C Content Vs Liquidus T For 1000 Heats At Port Talbots BOS Plant, Showing A Clearly Linear Relationship***

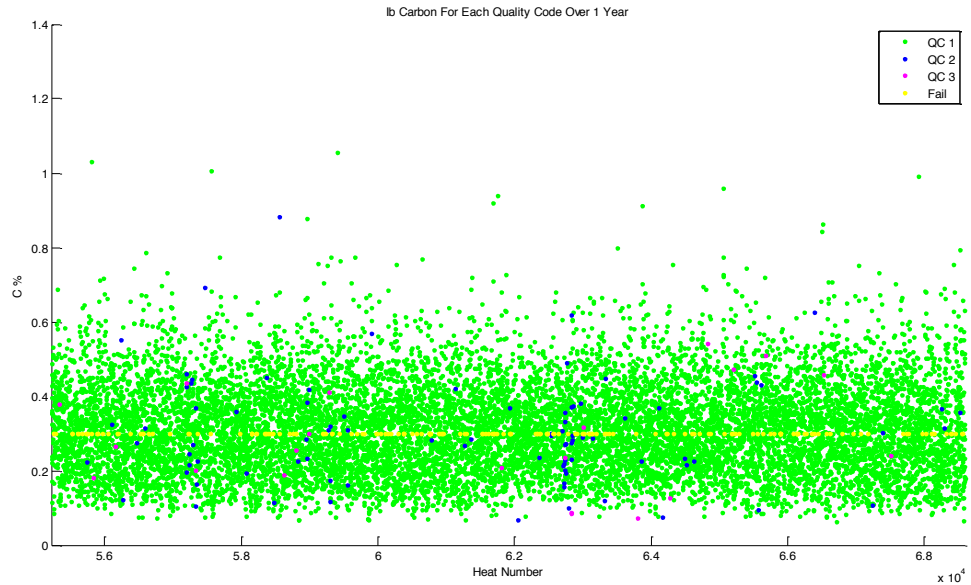
To confirm this method data was collected and the equation applied for a 1000 heats, as shown in Figure 5.36. The line follows the form of that depicted between point A and B in Figure 5.35. The data for the calculated C content of the steel has a spread, which indicates a level of variation. This is because running means are used to adjust the data, as there will be a certain level of variation within the process, which isn't accounted for in the simple equation. This variation is adjusted for by using these running means, which for the 1000 heats plotted, varied between 0.8 and 1.01. This process involves comparing the estimated C content with that directly measured in the labs. It then adjusts the running means so that the difference between the two values is reduced after each heat as necessary. These running means are then used as factors to adjust the sublimance measurements accordingly. If the running mean is above 1, the sublimance measurement will be increased, and below 1 it will be decreased.

The new sublimance is used for each IB dip it is not possible to determine the reliability of each individual "single use" lance. To assist in the monitoring of the overall sublimance reliability however, there is a quality code measurement built into the software provided by the manufacturer. This software is a third party piece of software provided by the sublimance manufacturer.



**Figure 5.37 - Multilab Output For Quality Codes, The Codes Being Based On How Flat The Signal Is**

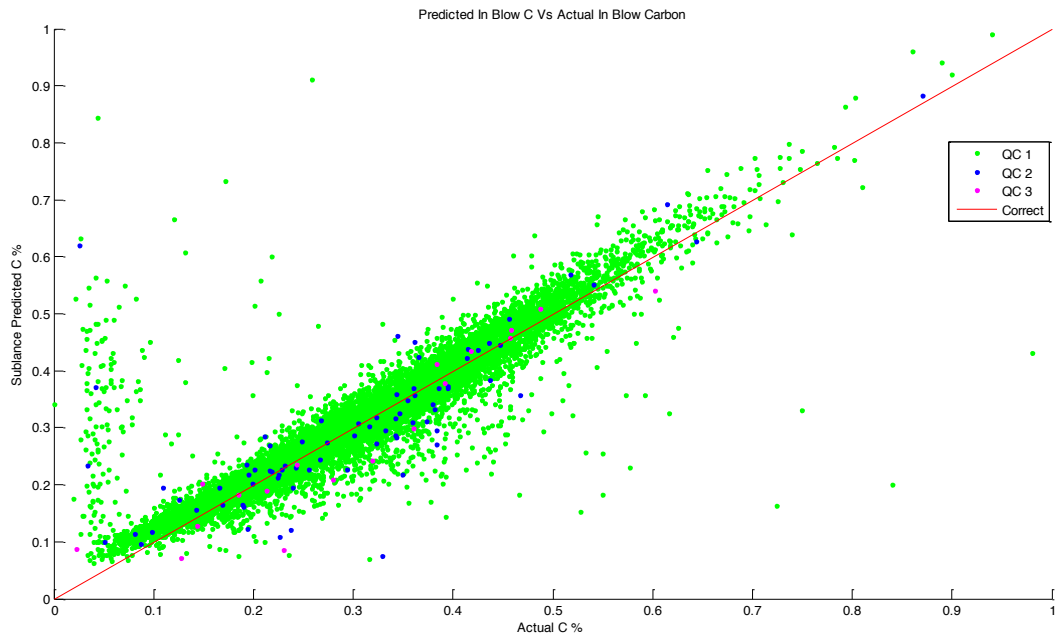
The quality code is based on the level of fluctuation in the measurement signal, shown in *Figure 5.37*. The software looks for a plateau in the signal and assess' the quality of the analysis based on this, with a value of 3 representing a large amount of fluctuation and low reliability and 1 representing a low level of fluctuation and a good reliable measurement. In order to understand if monitoring the quality codes was going to be of benefit to the system, analysis was undertaken to compare the quality code against the measured C which is shown in **Error! Reference source not found.**. The equipment used to undertake this task can have a large effect on the result.



**Figure 5.38 - Quality Code Against C Measurement For 1 Years IB Dips, The Lower QC Value Implies A Steadier Measurement**

As **Error! Reference source not found.** shows the use of the quality code to assess the IB dip is not going to provide much use within this system, as typically the samples are classified as quality code 1 (green in Figure 5.38). It was noticed however that for the analysis that failed a default value of 0.3% C was used and that failed dips could be easily identified as they had a quality code value of 15. A default value of 0.3% C is used, as this is the target C chemistry at the IB point, so an assumption is made that the balancing has been correct if the sample fails. Further analysis was undertaken to determine whether the monitoring of this small percentage of heats with a quality code of 2 or 3 would provide an additional benefit to the system, by showing a lower level in sample accuracy.





**Figure 5.39 - A Graph Of Sublance C Vs Lab Analysed C For IB Dips, The Lower QC Value Implies A Steadier Measurement**

The analysis of the quality codes showed that the level of deviation for code 1 heats was the same as those with a higher value. This was taken to be showing that the level of accuracy for the sublance analysis doesn't vary significantly enough to identify the varying quality codes. As such the use of the code did not offer any additional benefits. Due to this the monitoring of the quality code was not included in the system, other than to indicate a failed dip.

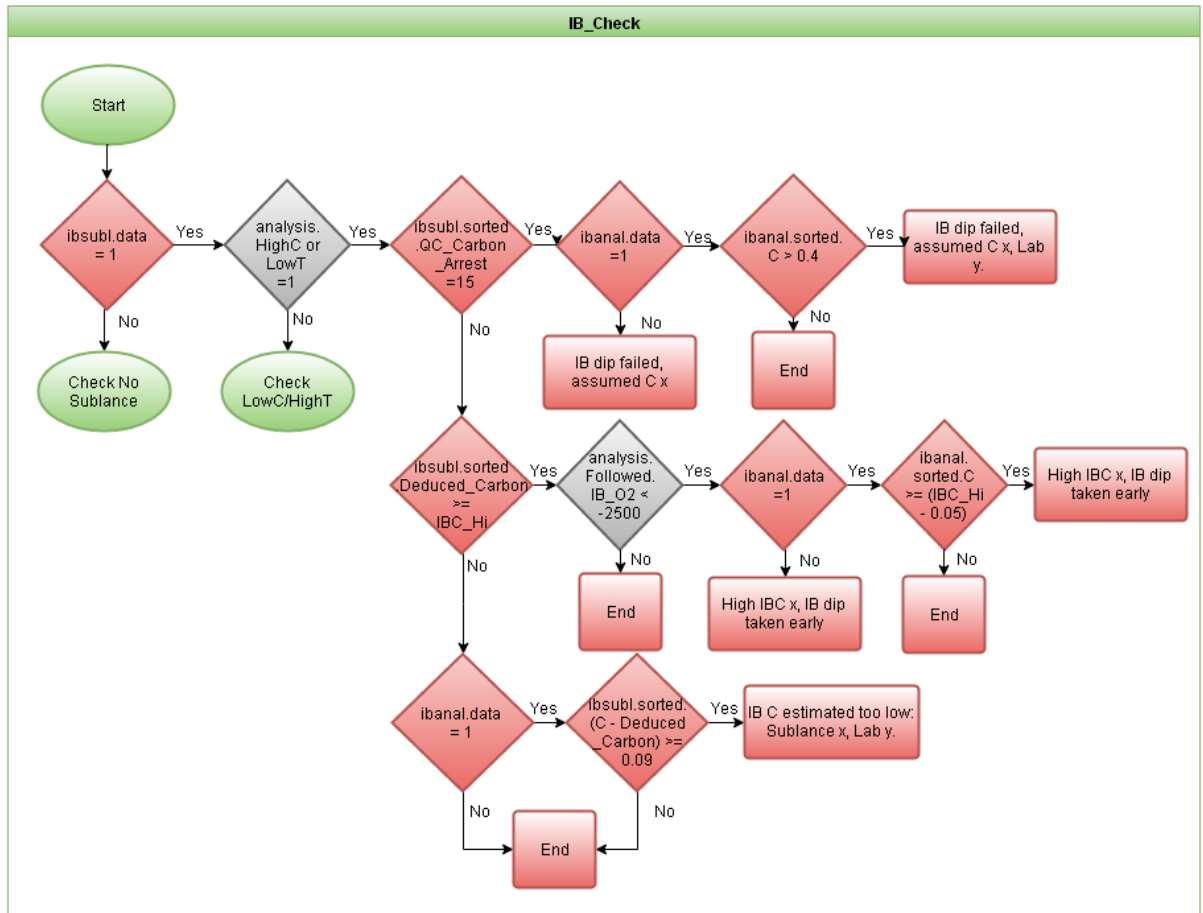
The data analysis of the IB dip showed that a number of different situations could be checked when an unexpected IB analysis occurred. These were predominantly checking if the IB dip was successful, whether the timing of the dip was considered normal, or whether the sublance estimated C was accurate by comparison with lab analysis.

### 5.3.6.2 In Blow Check Outputs

The system checks for a number of cases at IB, the firsts section of outputs are shown in Figure 5.40. The first check determines if the estimate used within the EBM was sufficiently accurate compared to the lab analysis. If this is the case no further diagnosis surrounding the IB dip occurs. However if this isn't the case, the system checks to determine the cause of the discrepancy; for example if the value used was a default value associated with a sublance

failure or a reporting malfunction. A failure can be confirmed by checking for a quality code value of 15 associated with the IB dip, and checking if the IB C equals 0.3%, the default value, as shown by the first row in Figure 5.40.

To further assist in the diagnosis, it was considered beneficial to highlight the used and actual C analysis values. This shows, if applicable, the magnitude of the discrepancy caused by the failed dip.



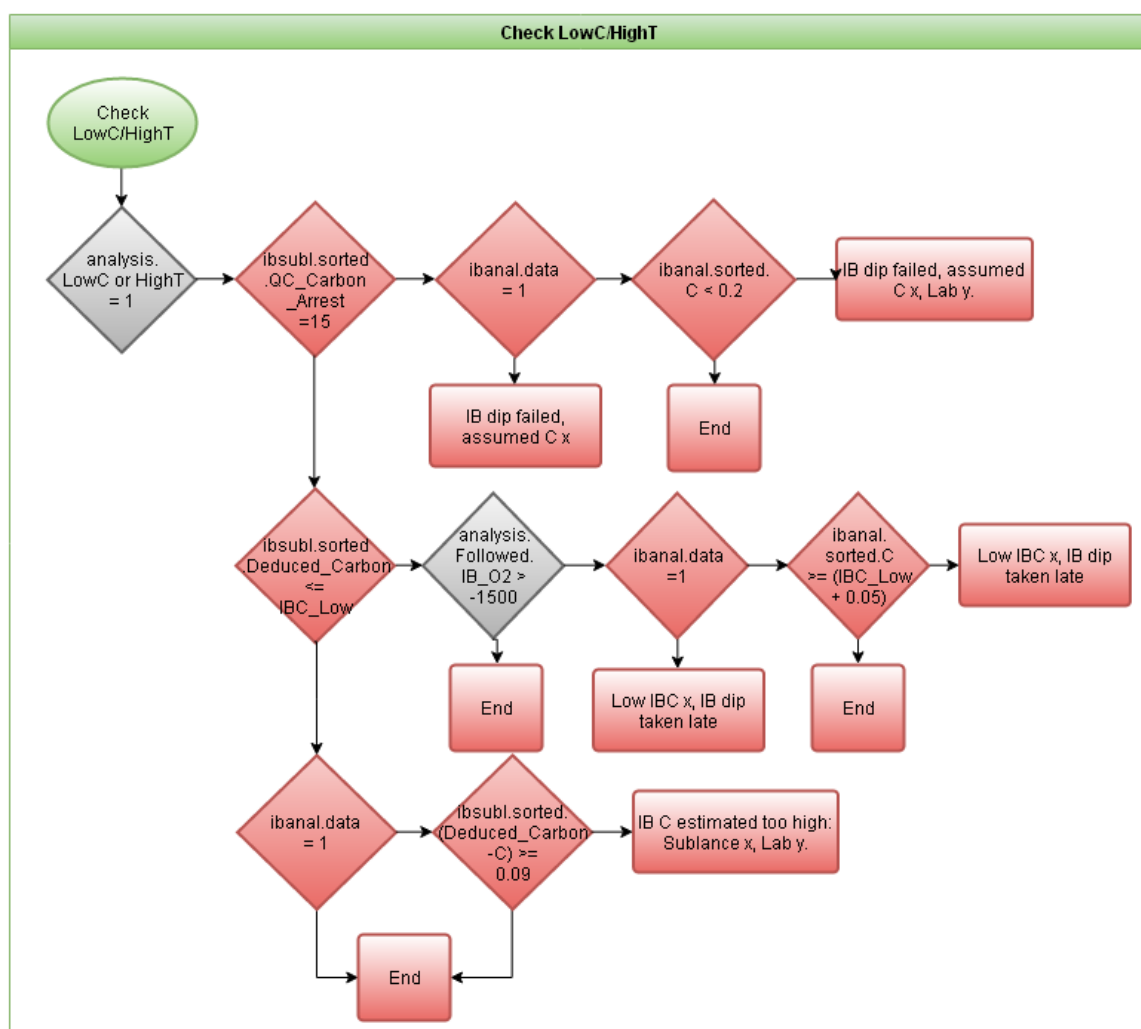
**Figure 5.40 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The IB Check Outputs**

The timing of the IB dip is also monitored as part of the diagnosis. If this is earlier than expected then the C level is likely to be above the aim and T below. The timing of the IB dip was discussed and based upon the quantity of O<sub>2</sub> blown by the IB point. Data analysis shown in Figure 5.34 shows that typically the dip is taken at 2000m<sup>3</sup> short of the initial total O<sub>2</sub> required volume, with a standard deviation of 500m<sup>3</sup>. It was therefore considered that the mean plus or minus 1 standard deviation would represent the threshold for early and late IB dips respectively. Poor IB dip timing can also have a detrimental effect on EB T & EB C

control. In particular if it is late this gives less time for the system to apply the required adjustments to the BOS process to meet the aims. The structure of the output is shown in row 2 of Figure 5.40.

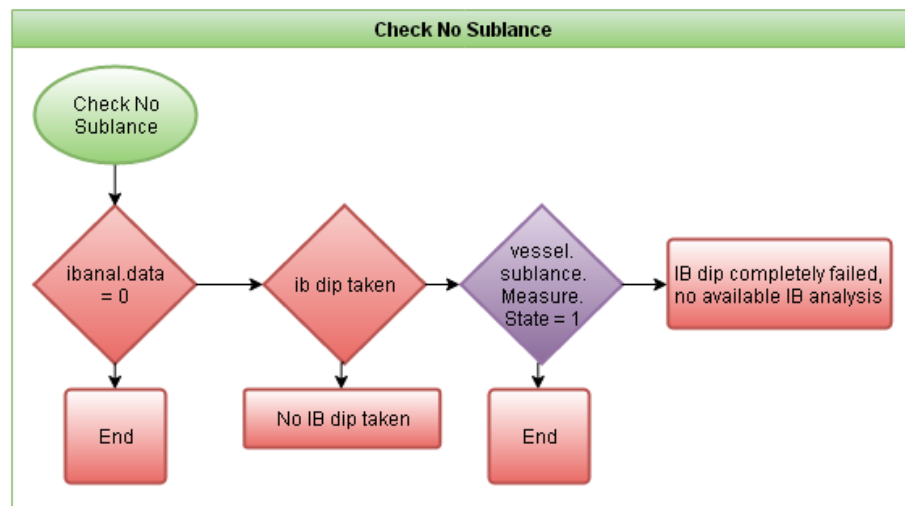
The final row of outputs in Figure 5.40 refer to if there was no IB dip failure or other clear cause for the discrepancy, but the difference between the estimated IB C and the sample was still outside of the pre-set limits, the system generates the output shown above. This is a particularly important output as this could be an indication of faulty substances if the deviation is consistent over a number of heats.

The same logic used above applies to Figure 5.41, except that this applies to heats with either a low C or a high T, so this checks for late dips instead of early dips, and checks if the substance analysis estimated too high.



**Figure 5.41 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Check Low C/ High T**

The final section of the IB check shown below in Figure 5.42 is checking what happened with the IB analysis, as this section only applies to heats that had no IB analysis at all; this section simply checks if the lack analysis was down to no dip being taken, or a complete failure of the IB substance sample.



**Figure 5.42 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Check No Sublance**

### 5.3.7 Weights

The level of accuracy demanded for T control in most modern steel plants requires very careful balancing of all materials added to the vessel, both in terms of mass and energy. This means that an important parameter to monitor within the vessel is weight. This process is made slightly easier as the CBM reruns a few minutes into the process using all of the known charged weights, instead of estimates, to improve the accuracy of the oxygen volume and addition weights required.

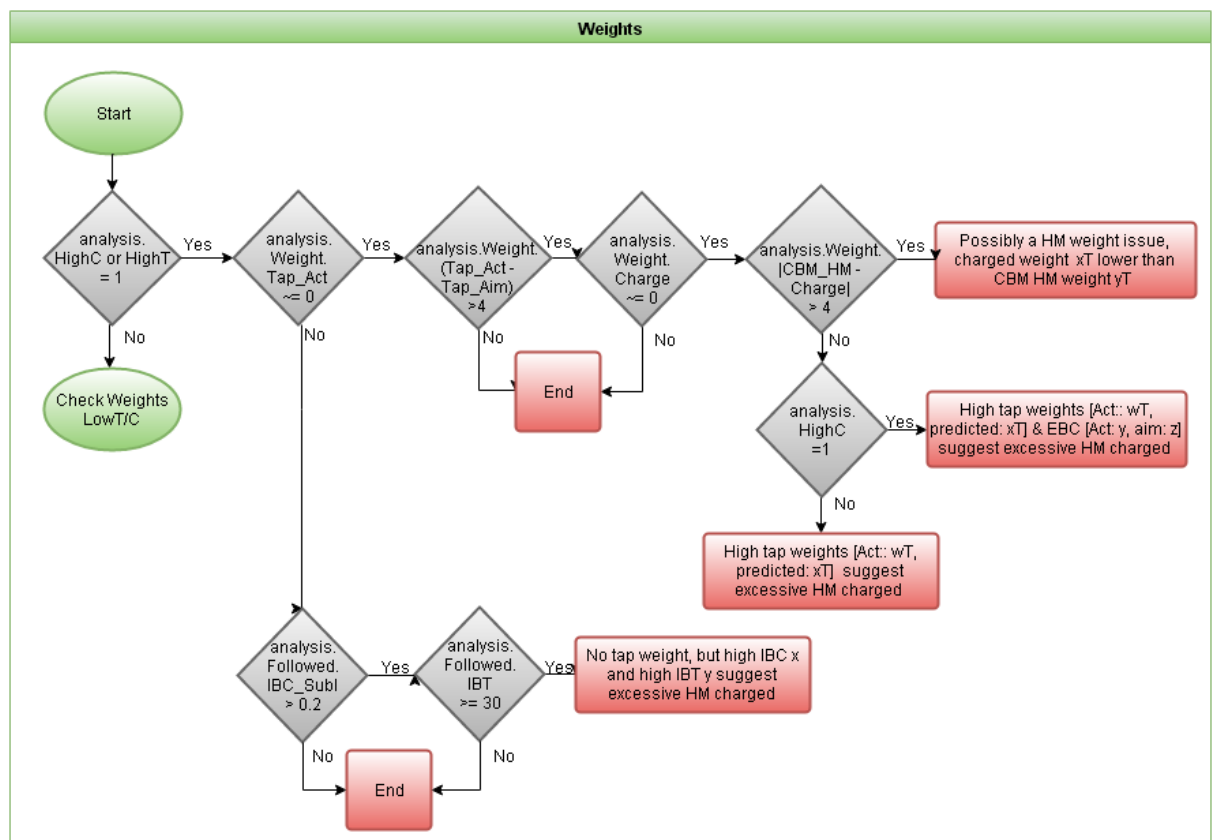
There are a few important stages that the system goes through when monitoring the weight values at the vessel. The first is to check the EB TF additions, as these will have a direct impact on the tap weights. Examining the difference between the demanded and charged weights can be used to adjust the expected tap weight that was calculated by the EBM. This then allows an assumption to be made about other weights being a cause for T and C level discrepancies at the end of blow. If the T is high and the tap weights are also high, this would indicate a possible excess HM charged into the vessel. However if the T is

high and the tap weights are low, this could indicate insufficient scrap charged at the start of the blow.

Due to the need to confirm which of these occurs the analysis of the weights is split into two sections. The first is relevant for heats where either the EB C or the EB T is high and the second for heats where either the EB C or EB T is low.

### 5.3.7.1 High End Blow Carbon and/or Temperature

Initially the system checks the tap weights to account for differences in additions made by the operator against that required, an overview of this is shown in Figure 5.43.



**Figure 5.43 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Weights Outputs**

Consideration of what data is available determines which output is generated by the system. If the charged weight is available and this is more than 4 tonne lower than the CBM expected HM W, then the system generates an output in the format shown in row 1 of Figure 5.43.

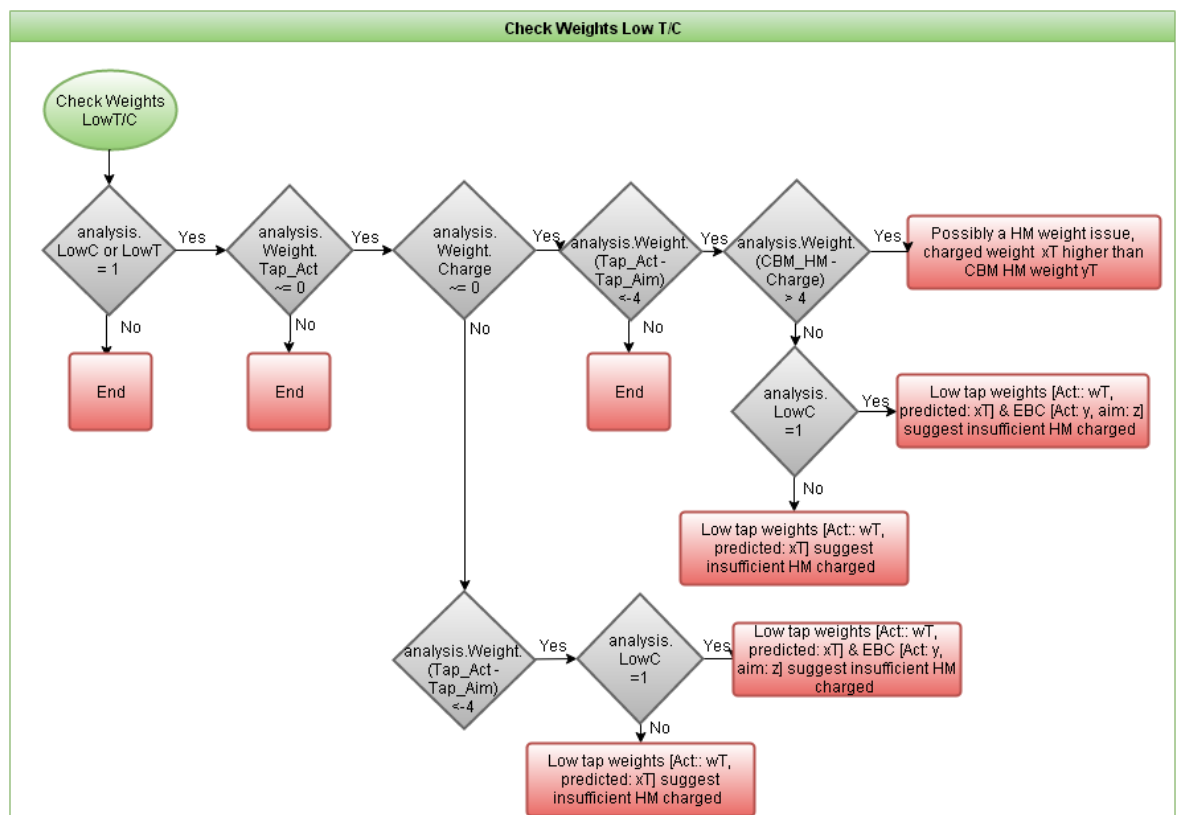
However if the charged HM W is not available, the system then checks if the EB C is high. This output is based on the tap weights and compares the actual value with the expected value calculated by the EBM, shown in row 3 of Figure 5.43. The system assumes

it is a HM weighing issue, as the other main source of mass into the vessel is scrap. The level of accuracy of scrap weighing is significantly better than hot metal weighing.

Finally if there is now HM W available, but the IB C and IB T are high then the system mentions that excessive HM could be a cause for this, as shown by the final row in Figure 5.43.

### 5.3.7.2 Low End Blow Temperature & Or Carbon

The initial checks are the same for a low EB T as they are for a high EB T, except the issues are reversed, instead of looking for high tap weight issues it looks for low tap weight related issues, as shown below in Figure 5.44.

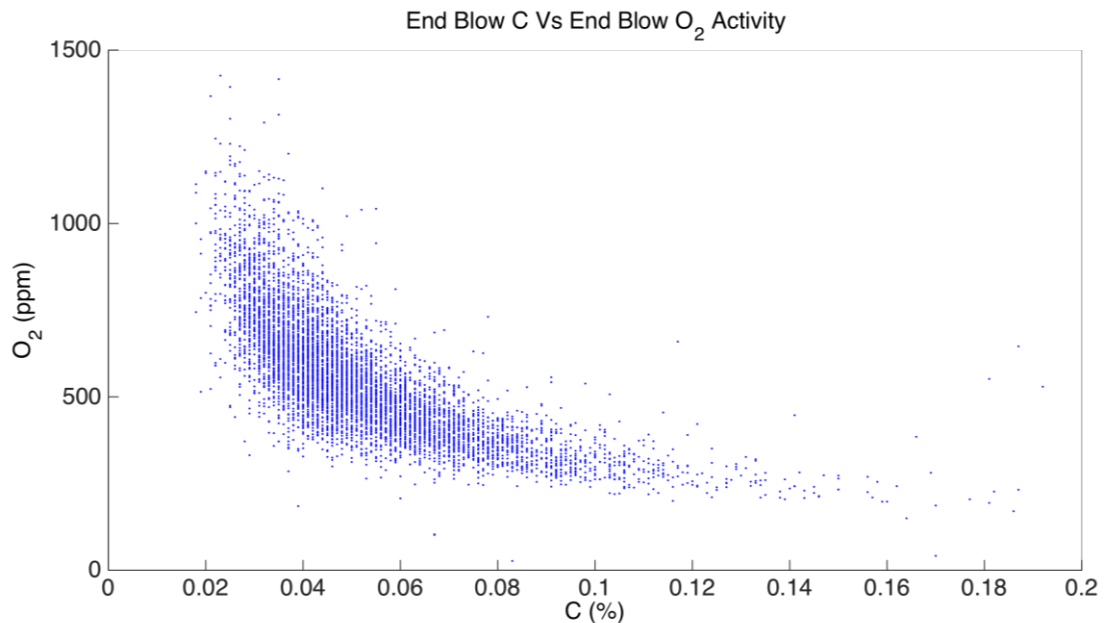


**Figure 5.44 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Check Weights Low T/C**

### 5.3.8 Over Blown & Blowing Flat

The main source of heat into the vessel during the BOS process is the oxidation of C to CO and CO<sub>2</sub> from the iron. This presents an issue if, by the IB dip, either the T is still low or the C level is lower than expected with a normal or low T. The issue is that, increasing the T normally requires the removal of additional C. The process of removing additional C in order to reach the required T aim is known as over blowing. This reflects the decision made in which the C aim is being sacrificed in order to reach the required T. A high steel oxygen

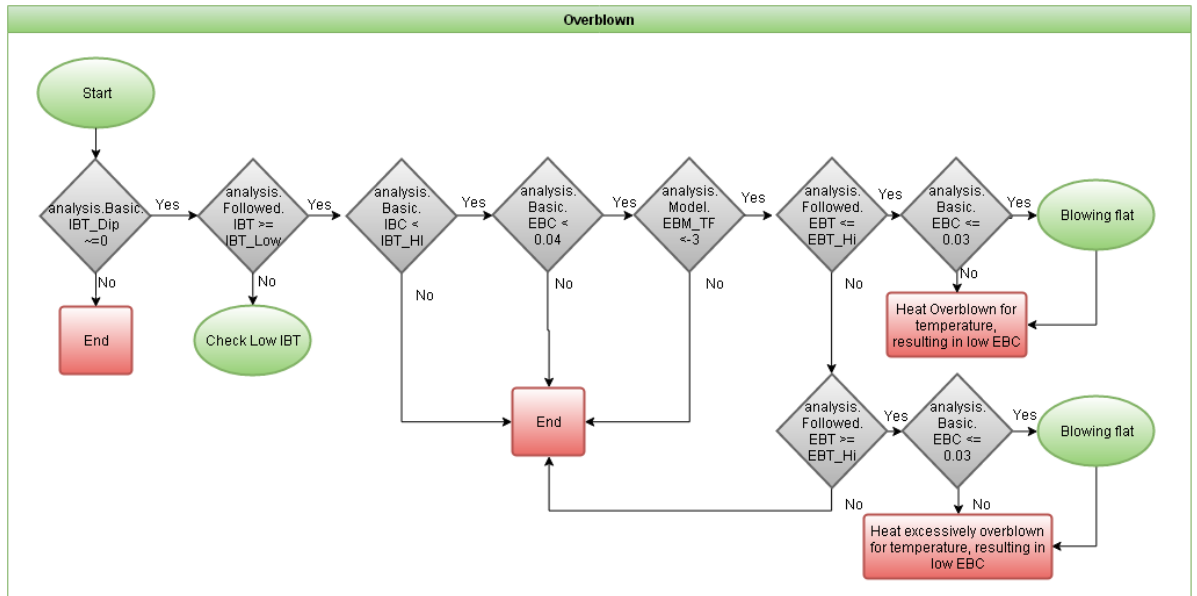
content and very low C content shows this. The relation between oxygen content and EB C content is depicted in Figure 5.45. Oxygen content is shown to rapidly increase as the C content decreases. The system monitors for this type of event by checking the IB C and T, and the EB C and T as well as the EB O<sub>2</sub> content of the steel, as this is a key indicator.



**Figure 5.45 - End Blow Oxygen Content Vs End Blow C Content, Showing A Non Linear Relationship**

If the C levels are found to be either normal or low and the T is low, when the IB dip is taken, it may be that reaching both the intended C and T targets at the end of blow is not possible. Typically if this occurs, the intended EB C value is reduced in order to reach the target EB T. This option is chosen since reheating within secondary steelmaking maybe detrimental to the planned grade being made, as this can only be done chemically by oxidising aluminium. Where the alumina is a non-metallic inclusion, which can cause casting difficulties, and negatively impacts steel cleanliness.

The system has been designed to recognise a number of different situations where a heat has been overblown, a number of these are shown in the first section of outputs in Figure 5.46. The first is shown in Table 5.12, which applies directly to the first row in the figure above, where a heat has been overblown to meet the requirement for T, by sacrificing the EB C aim. Here the IB T is very low with a normal IB C. However the EB C is also very low with a normal T. A key indication of this is also the EBM calculated value for coolant, as the value is negative. The model recognises that the T is going to be lower than the aim based on the current aim C value and coolant levels.



**Figure 5.46 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Overblown Outputs**

**Table 5.12 - Over Blown For T Criteria**

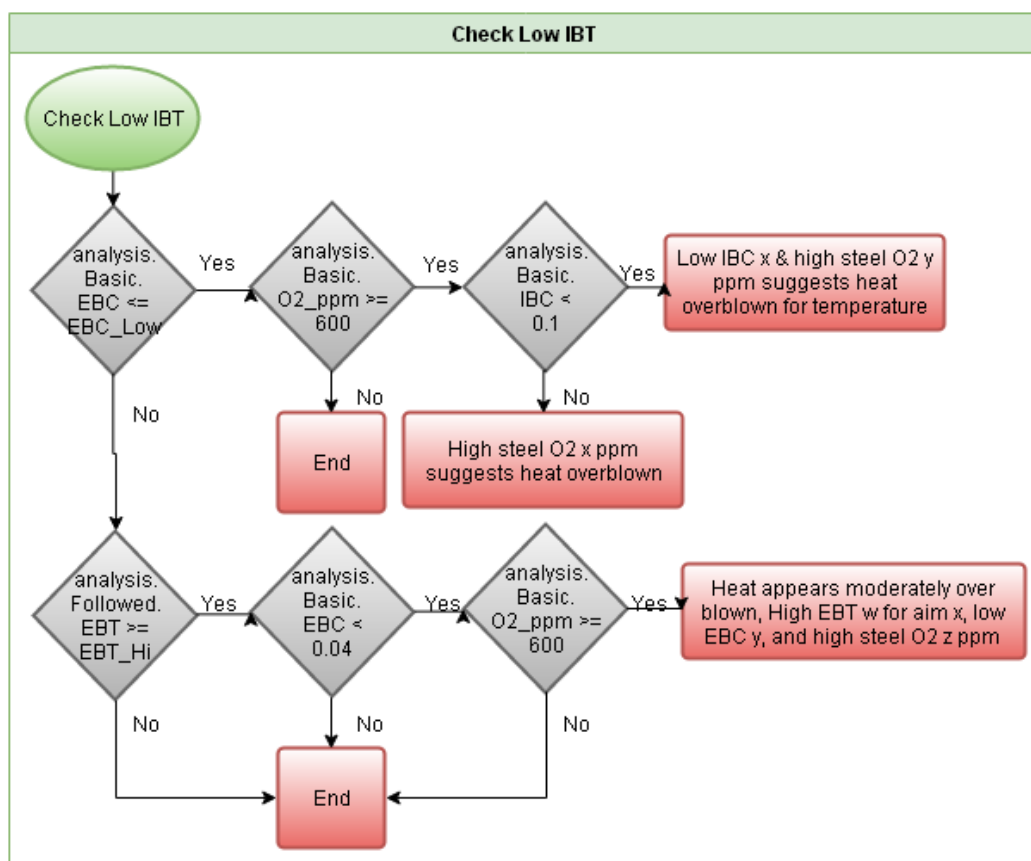
IB T	$\leq -30^{\circ}\text{C}$
IB C	0.2 – 0.5%
EB T	$< \pm 15^{\circ}\text{C}$
EB C	$< 0.04\%$
EBM Coolant	$< -3\text{T}$

The situation outlined in Table 5.13, applies to the row 2 output shown in Figure 5.46, is where the heat has been overblown for T, sacrificing the EB C aim. However this has been done excessively and has resulted in a very high EB T, at least  $15^{\circ}\text{C}$  above the aim. This situation rarely occurs, as normally when a heat is overblown for T due to the C levels, it is difficult to increase the EB T this much. Never the less the monitoring of this scenario is built into the system to ensure this situation can be picked up if and when it occurs.

**Table 5.13 - Excessively Over Blown For T Criteria**

IB T	$\leq -30^{\circ}\text{C}$
IB C	0.2 – 0.5%
EB T	$> 15^{\circ}\text{C}$
EB C	$< 0.04\%$
EBM Coolant	$< -3\text{T}$





**Figure 5.47 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Check Low IB T**

There are instances where a heat has the appearance of being over blown but with a normal IB T. This may arise under conditions such as low EB C and a high steel O<sub>2</sub> activity at the end of blow, which is shown in Table 5.14. These situations, shown above in Figure 5.47, require the additional monitoring of the oxygen activity at the end of blow. This is because a high oxygen activity is an indication that the heat has been blown with a low C level, as the oxygen would typically be taken up by the C to form CO or CO<sub>2</sub>. There are two values for the IB C that are monitored, to define which output should be used in these circumstances, as it is necessary to note if the IB C was additionally low as well as the EB C.

**Table 5.14 - Over Blown Heat With No T Issues Criteria**

IB T	< ± 30°C
IB C	<= 0.1 % or >= 0.1%
EB T	< ± 15°C
EB C	<= 0.03%
Steel O <sub>2</sub> Activity	>= 600 PPM

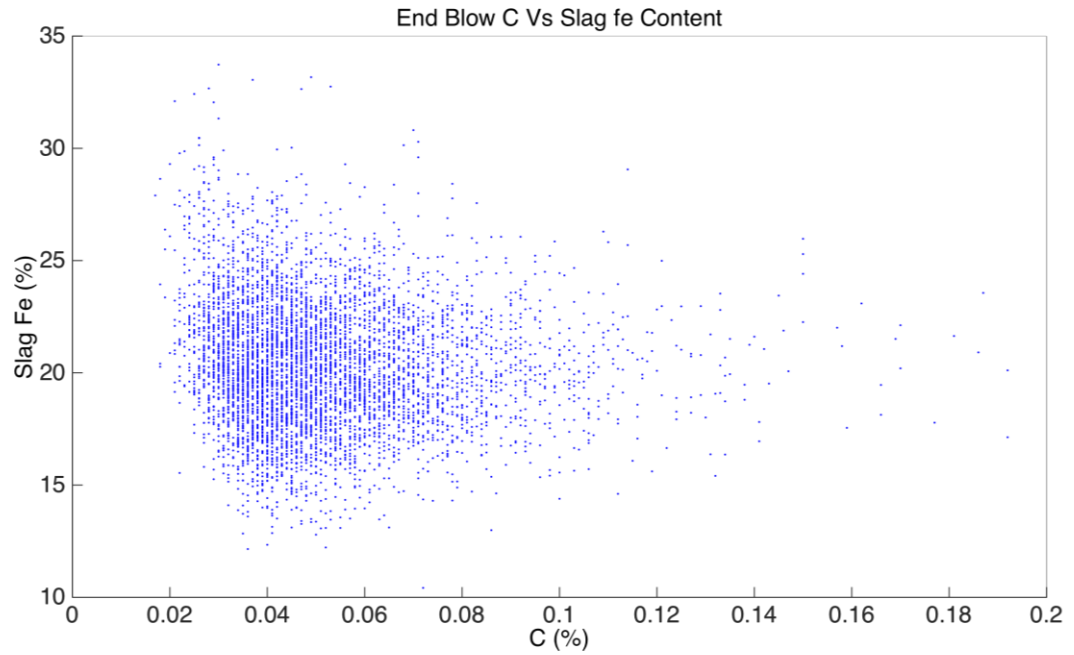
### 5.3.8.1 Blowing Flat

There is an additional situation that follows on from this effect known as blowing flat. This can cause further issues in the process and occurs when there is insufficient C left in the steel to consistently provide a heat source during the blow. When this occurs, instead of oxidising C from the steel, the iron begins to be oxidised into the slag. The result can be a yield loss, as well as a very unpredictable T pick up, as the oxidation of iron is less exothermic than the oxidation of C (Ghosh & Chatterjee, 2014).

The effect of blowing flat is that the C content of the steel drops to or below 0.03% during the BOS process. This causes the oxygen content of the steel to sharply increase, as shown in Figure 5.45. This is typically met with a decrease in C removal from the steel and typically an increase in Fe removal into the slag. The main problem caused by blowing flat is the unpredictable T pickup. This relates to the oxidising of Fe being less exothermic than the oxidation of the C. This effect is depicted by the spread of data in Figure 5.48. It can be seen that the response generated is very unpredictable, often resulting in a lower than expected EB T.

The system has a separate function built to handle this situation, which can be called from within the Over Blowing function if necessary. The majority of criteria are the same for this function to be called, except for the EB C, which needs to be less than or equal to 0.03%, as shown in

Table 5.15.

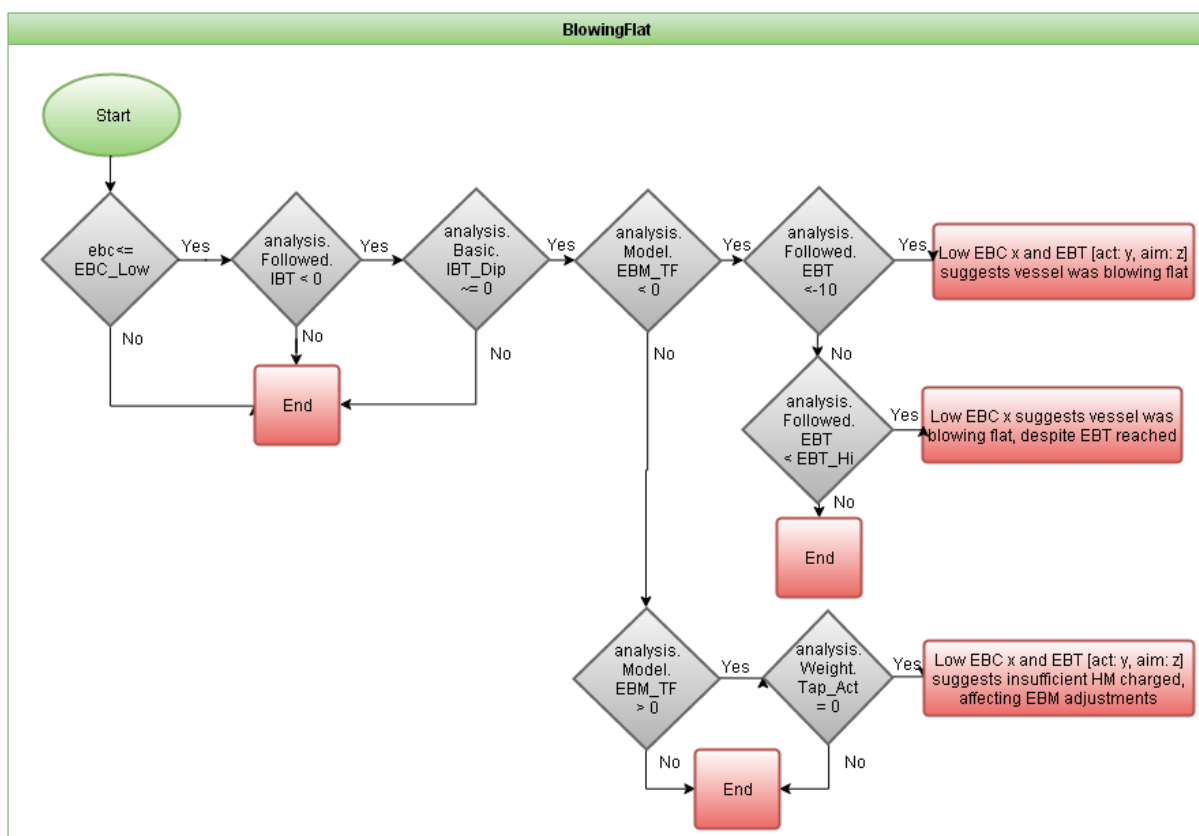


**Figure 5.48 - Slag Fe Content Vs Steel C Content, Clearly Showing The High Variability In The Process Due To The Spread Seen In The “Cloud” Of Data Points**

**Table 5.15 - Blowing Flat Criteria**

IB T	< $\pm 30^{\circ}\text{C}$
IB C	< 0.5%
EB T	< $-10^{\circ}\text{C}$ Or < $+15^{\circ}\text{C}$
EB C	$\leq 0.03\%$
EBM Coolant	< -3T

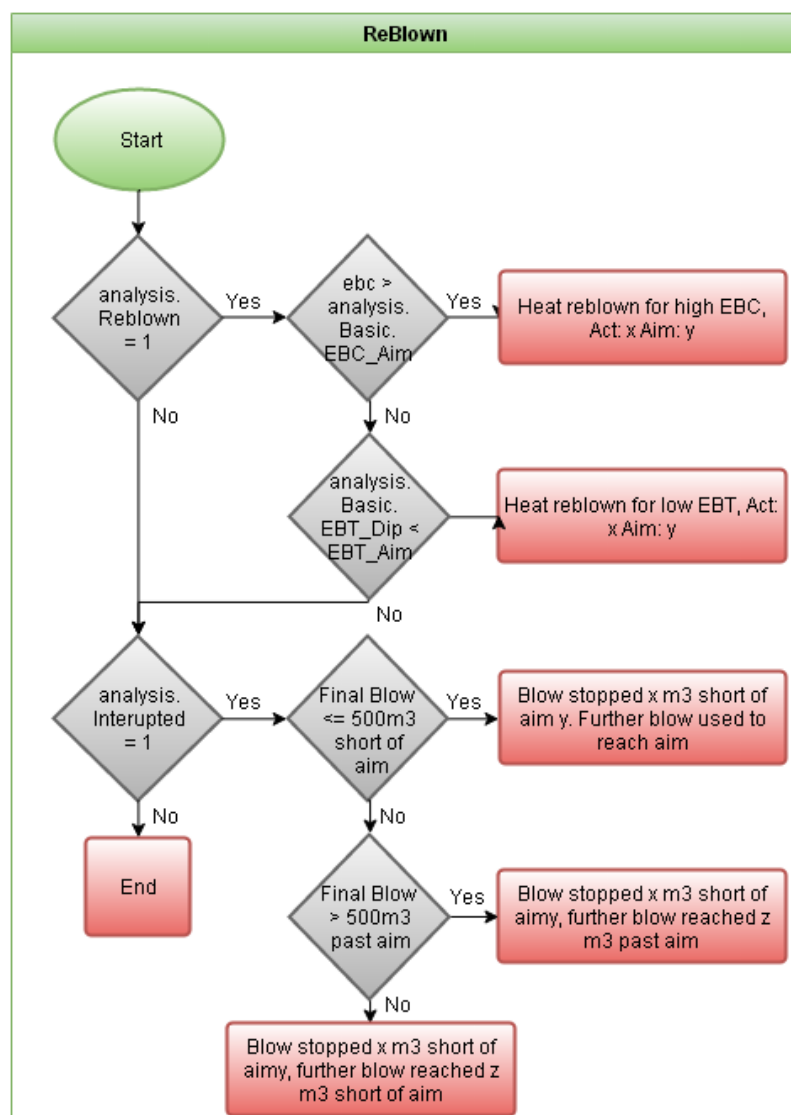
Two values for EB T are used, to allow the outputs for this type of issue to be slightly tailored to allow the addition of the T value if applicable, to further support the issue. All of the outputs generated are shown below in Figure 5.49.



**Figure 5.49 - Flow Diagram Showing The Application Of Expert Knowledge & Logic  
Used For The Blowing Flat Outputs**

### 5.3.9 Multiple Blow Heats

As has been previously noted, it is necessary on occasion when the end point chemistry and or T are out of specification to rework, or reblow the steel within the vessel. Where there has been a heat with multiple blows it is important to characterise the multiple blows, as they could either be an interrupted blow or a reblow. The key difference between the two is that a reblow occurs after a completed blow and is done as an additional treatment. An interrupted blow occurs when part way through the blow an issue arises and the blow is stopped, requiring further blows to complete the initial blow. The flow diagram below in Figure 5.50 shows this difference, with the first 2 rows of outputs corresponding to re-blown heats, and those below for interrupted blows.

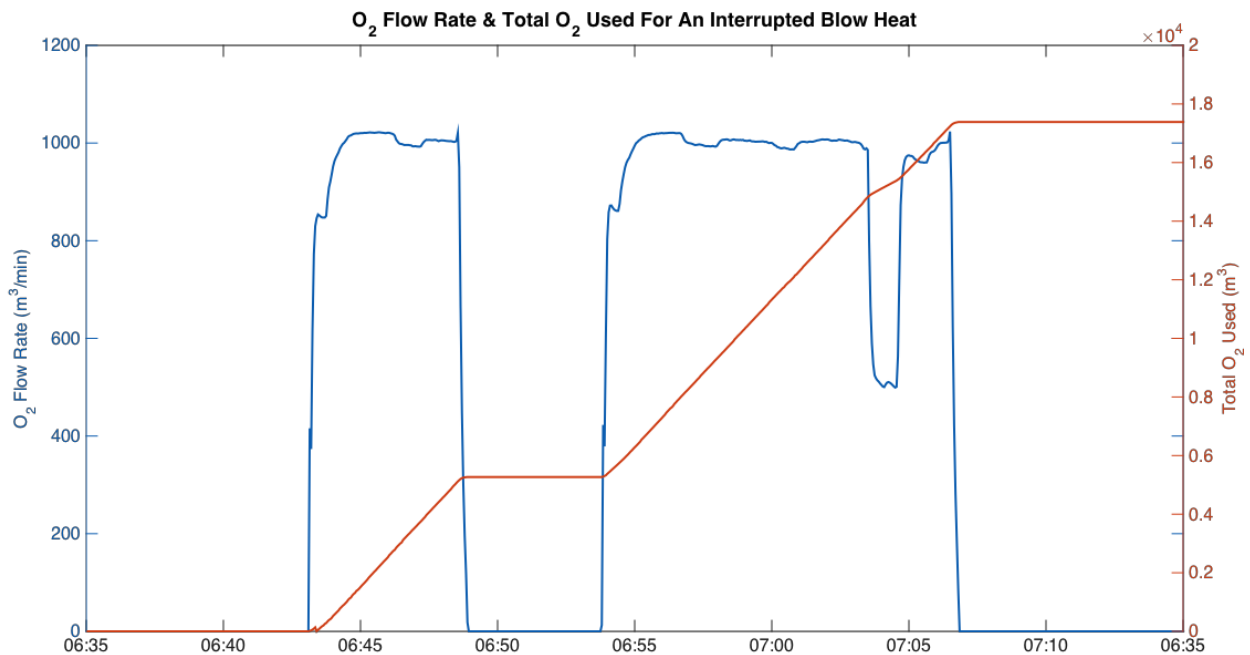


**Figure 5.50 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Re-blown Outputs**

### 5.3.9.1 Interrupted Blow

Within the vessel an interrupted blow could be the result of a lance issue, or an engineering issue with the oxygen flow. This is characterised typically by a short oxygen trace, without an IB dip, as these issues typically arise near the beginning of a treatment. An illustrative example of this type of blow is shown below in Figure 5.51. The first step for a heat with multiple blows is to monitor the O<sub>2</sub> flow rate trace and the cumulative O<sub>2</sub> volume for the heat in question. This will allow the determination of whether there has been an interrupted treatment or if a reblow has occurred. The plateaus in the cumulative volume are recorded within the system. To make this decision it was decided that, if there is a plateau at least

500m<sup>3</sup> short of the CBM estimated O<sub>2</sub> volume, then this is deemed an interrupted treatment, otherwise it will be considered a reblown heat.



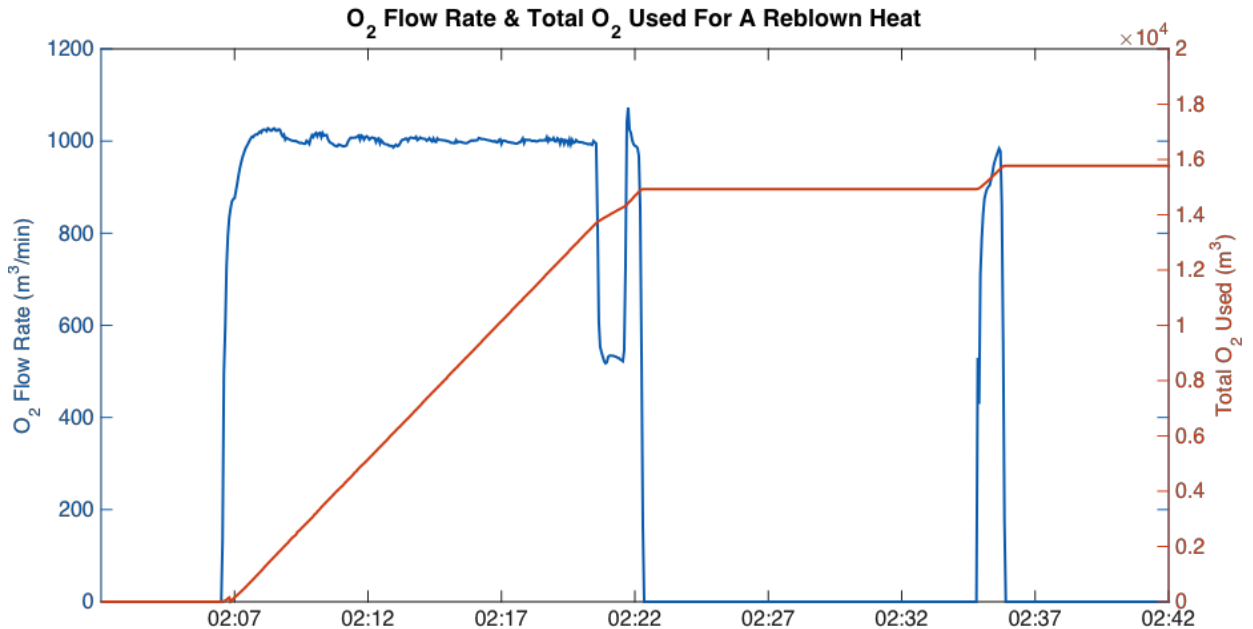
**Figure 5.51 - Oxygen Flow Trace For An Interrupted Blow, The Blow Is The Interrupted Blow**

The outputs for this section of the diagnostic system have been designed to quickly inform the audience of the interrupted blow, and to provide detail on how this affected the total amount of O<sub>2</sub> that was blown into the vessel for the heat. As shown in the lower half of Figure 5.50, there are 3 variations on this output, this first details that the aim O<sub>2</sub> volume was reached, the latter two detail that the aim was either exceeded or was short of the aim by more than 500m<sup>3</sup>.

### 5.3.9.2 Reblown

The reblowing of a heat can point towards inefficiencies in the process if insufficient C has been removed at the end of blow, or poor mass balance if the T is below aim. The actual causes and diagnosis of these have been discussed in depth throughout this chapter, as a reblow only occurs if the EB C and or EB T is significantly out of specification. As can be seen in Figure 5.52 below, the amount of oxygen blown during a reblow is typically quite small compared to that used during the main blow. There are only two variations on the output generated by the system to highlight a reblow, one for a high EB C and the other for

a low EB T, as these are the two situations which require a reblow, as shown by the first two outputs in Figure 5.50.

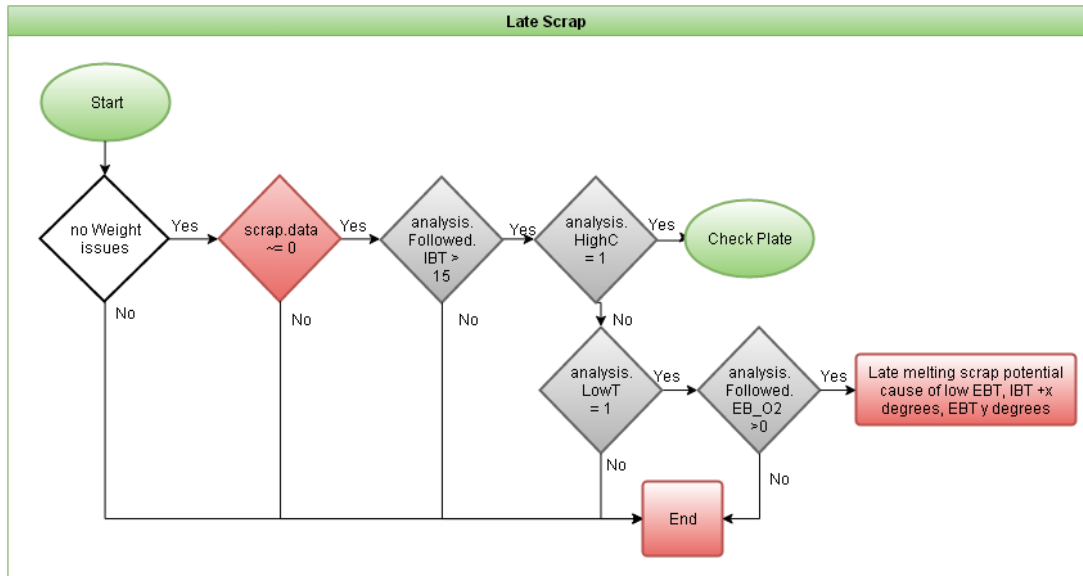


*Figure 5.52 - Oxygen Flow Trace For A Reblown Heat, Delay Seen Will Be Due To Awaiting Lab Analysis*

### 5.3.10 Late Melting Scrap

Within the steel making process scrap is charged into the vessel and HM is then charged on top. Occasionally if large pieces of scrap are used for a heat, by the IB dip these can fail to have fully melted. In this case the process will not have used up all of the heat energy required to be fully melted and will not have contributed to the C level, if high C scrap is used. This can result in unexpected T and C effects on the steel by the IB dip and therefore needs to be monitored.

After discussion with process experts, it was identified that occurrences such as a skull forming around the cold scrap when the hot metal is charged could cause process deviations. In these circumstances it is important to monitor the temperatures at the IB and the EB dips. The parameters for doing so are outlined in Table 5.16. These conditions apply to the output shown in Figure 5.53.

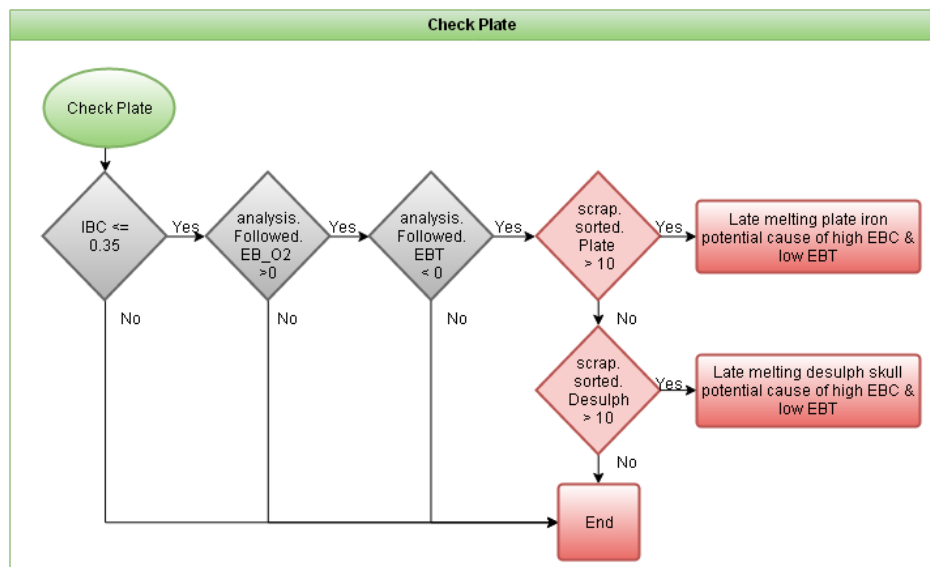


**Figure 5.53 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Late Scrap Outputs**

**Table 5.16 - Late Melt Scrap, Not Due To Large Scrap Criteria**

IB T	> +15°C
EB C	< 0.1%
EB Used O <sub>2</sub> - Aim	> 0
EB T	< -15°C

After further discussion with experts other factors such as the larger types of scrap with a high C content to monitor for this issue in terms of high EB C would be plate iron and large desulph skulls.



**Figure 5.54 - Flow Diagram Showing The Application Of Expert Knowledge & Logic Used For The Check Plate Outputs**



The parameters to monitor for this issue are outlined in Table 5.17. These conditions apply to the outputs shown above in Figure 5.54

***Table 5.17 - Late Melt Scrap Due To Large Scrap Criteria***

IB T	> +15°C
IB C	< 0.35%
EB C	> 0.1%
EB Used O <sub>2</sub> - Aim	> 0
EB T	< 0
Scrap	Plate >10T Or Desulph >10T

## 5.4 Summary

A diagnostic system has been designed and implemented at Tata Steel's Port Talbot works to diagnose, when analysis is available, causes of deviations in EB C and EB T. The system has been designed to be modular to allow the system to be easily expanded in future, and to facilitate in a large scope in allowing the system to diagnose process issues.

As has be shown, the system developed has been done so with a large scope covering common issues as well as those less well understood. The application of Fuzzy Logic within this system has been sparingly used to make sure the applications where it has been used provide significant benefit either in terms of analysis or by simplifying the necessary code to do the analysis.

## 6 Hard & Soft Blowing

As has been described in previous chapters, liquid iron is converted to liquid steel by blowing oxygen at high speeds into the bath of iron to remove carbon, in the form of CO and CO<sub>2</sub>. A photograph of a nozzle used to undertake this process is shown in Figure 6.1. The distance between the tip of the nozzle that the oxygen is blown through and the top of the molten iron bath is incredibly important within this process. This is because the distance affects the level of penetration of the oxygen jet into the steel, which will impact on the oxidation state of both the iron but also the slag. The reason the level of penetration is important is because it governs the location of the oxidation reactions within the vessel.

Hard and soft blowing is used to describe the state of blowing within the BOS vessel, with hard implying that the oxygen lance is too close to the steel and impacting the melt too hard, and soft implying the lance is too far away from the steel and not impacting the bath sufficiently.



*Figure 6.1 - BOS Oxygen Lance 6 Port Nozzle*

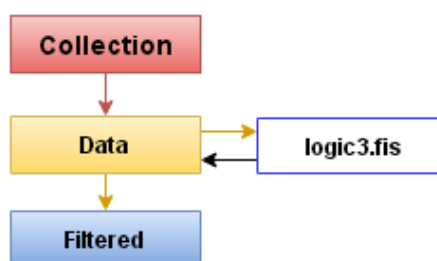
If the lance is positioned too high, then the level of penetration will be low and the majority of the free oxygen will be used for reactions within the slag. This isn't an entirely negative affect, as it will facilitate the removal of phosphorus from the steel, which is difficult to remove in secondary steelmaking. This will however have an impact on yield performance within the vessel, as there will be less oxygen for carbon removal, typically resulting in higher EB C, but also there will be more Fe oxidised into the slag, which will reduce tapped steel weight at the end of blow.

Alternatively, if the lance is positioned too low then the inverse occurs, decarburisation is very efficient, and slag Fe content is very low. In terms of yield this is

beneficial, however this will result in high EB P, which as mentioned is difficult to remove in secondary steelmaking. So the height of the lance is a fine balance between efficient decarburisation and low slag Fe content whilst maintaining sufficient phosphorus refining capacity.

## 6.1 System Overview

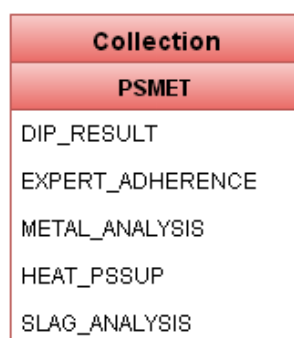
An overview of the expert system structure will now be given, going through the different data structures used, and the FIS models used. The Hard & Soft blowing system developed, is the simplest of the four systems outlined within this thesis, as shown by the overview in Figure 6.2 below. A more detailed outline of the subsequent sections will be outlined in the following sections.



*Figure 6.2 - System Overview*

### 6.1.1 Data Collection Overview

An overview of the plant data used within the system is shown below in Figure 6.3, which shows that only one database is used for data extraction for this system, and only 4 tables within this database. This is a stark contrast to the EB C & EB T system outlined previously, where 3 different databases, and an extensive array of tables were used. Experience gained developing the previous 3 systems, meant that there was sufficient confidence in this approach to allow the development of a simple system with few data inputs required.

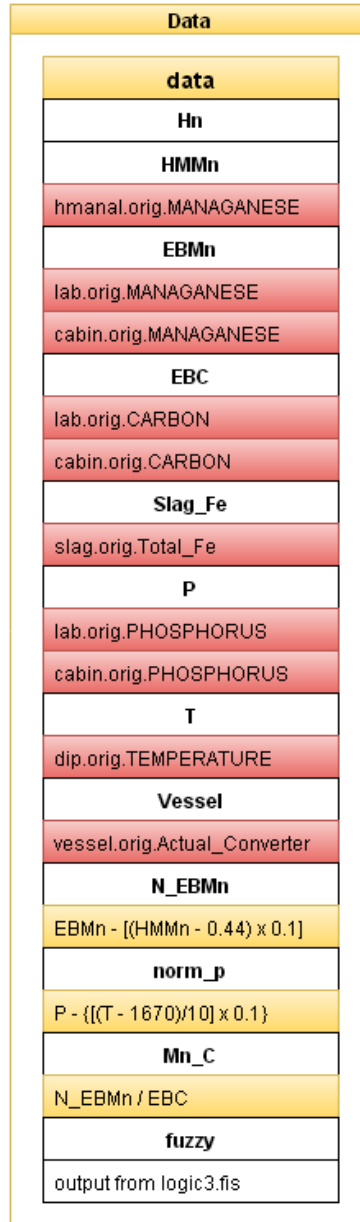


*Figure 6.3 - Data Collection Overview*

All of the data tables within the PSMET database have been used within previous systems. DIP RESULT contains temperature measurements, METAL ANALYSIS contains steel chemistry results, and SLAG ANALYSIS contains slag chemistry results. HEAT PSSUP is used for timings of the process, and expert adherence contains outputs from this and all other systems developed.

### **6.1.2 Data Structure Overview**

The overview of the data structure is shown here in Figure 6.4, along with a full explanation of where data has come from. Any information in red is showing the relevant raw data source where the data has come from. The hmanal, lab and cabin names indicate data from the Metal\_Analysis table, with these representing data for HM, main lab analysis of the EB sample, and cabin lab analysis of the EB sample respectively. Where the cabin and lab datasets are indicated, either will be used, dependant on where the analysis took place, as it will not be done at both locations. The slag and dip datasets indicate that the data for those columns has come directly from the Slag\_Analysis and Dip\_Result tables respectively. The three columns shown in yellow, correspond to data that is calculated using the data stored within the Data structure, and will be explained in more detail in this section.



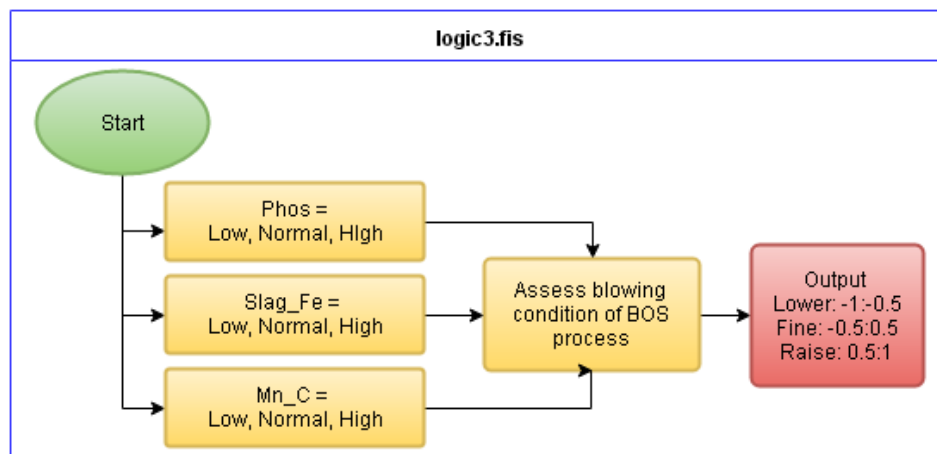
**Figure 6.4 – Diagram Showing The Data Sources & Logic Used Within The Data Data-Structure**

### 6.1.3 Fuzzy Inference System Used

A system has been developed to assist in achieving this fine balance, by assessing the lance position in terms of vessel performance. The main focus initially was on slag Fe content, with data mining used to see if it was feasible to predict the content from other process parameters, to assist in inferring a hard or soft blowing state within the vessel. Unfortunately the level of variation within the process and the quality of the available data meant that the highest level of prediction achieved was an  $R^2$  value of 20%, which is insufficiently accurate for any use. However, this data analysis along with process experts highlighted three main

parameters, these being the slag Fe, the EB Mn/C ratio and the EB P as they were all shown to have some relation to lance position.

The data analysis approach was an unsuccessful approach for hard and soft blowing, so the application of expert knowledge through fuzzy logic was attempted, based on previous successes. This approach used the parameters highlighted in the data analysis and by experts of the process. An outline of the FIS used to apply these 3 parameters is shown below in Figure 6.5.



**Figure 6.5 - Flow Diagram Showing Categories Used For Membership Functions Within logic3.fis**

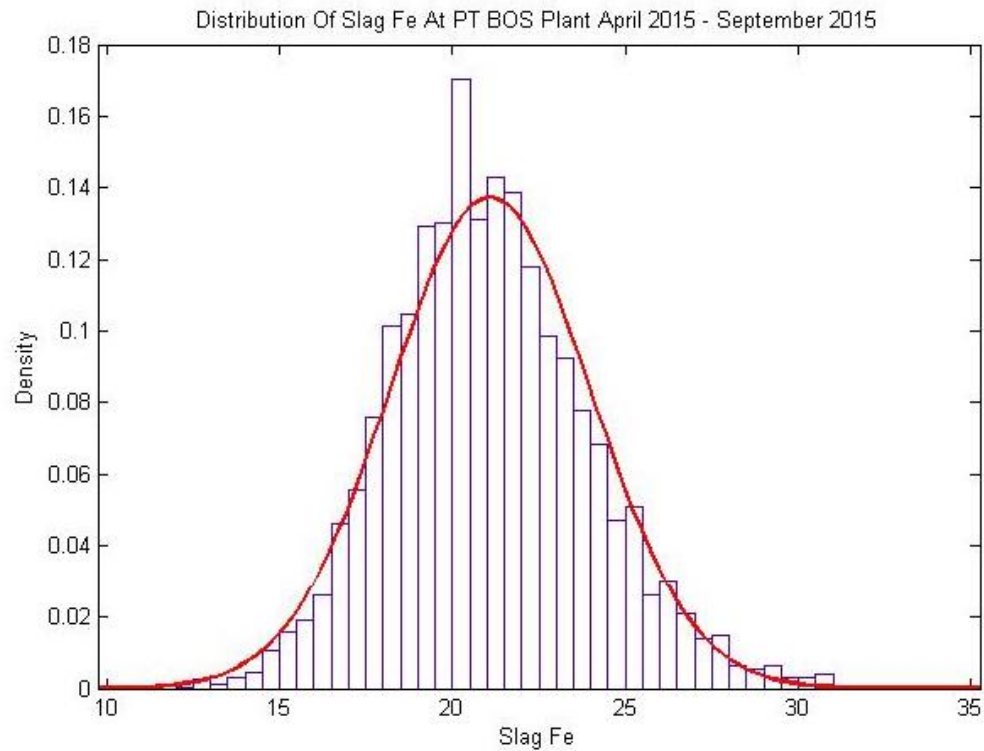
### 6.1.3.1 Slag Fe

The slag Fe is a good indicator of whether the vessel is blowing hard or soft, as has been touched upon it gives an indication to where the oxidative reactions are taking place within the vessel, and so this is a key parameter of the monitor. Table 6.1 below shows the limits used to define low, normal and high slag Fe values within the monitor.

**Table 6.1 - Slag Fe Membership Function Boundaries**

<i>Slag Fe</i>	<b>Lower Limit</b>	<b>Upper Limit</b>
<b>Low</b>		15
<b>Normal</b>	16	21
<b>High</b>	24	

These limits have been based upon the data shown in Figure 6.6, as well as consultation with experts and operational targets for the process. A target of an average slag Fe of 18.5% has been set for the implementation of this system, and so the normal region represents this accordingly.



**Figure 6.6 - Distribution Of Slag Fe In Port Talbot BOS Plant, Showing Typical Values Around 21%**

The data shown in Figure 6.6 has a mean value of 21.09%, and a standard deviation of 2.9. The industrial target of a reduction to 18.5% for slag Fe represents a noticeable shift to the left on the graph, and will be a significant improvement on performance.

The above graph shows all of the slag Fe samples within the time frame, however within the system, the slag Fe values will require filtering. Heats that are either under or over blown, so these will be heats where the EB C  $\leq$  0.03%C or EB C  $\geq$  0.075 respectively, will be removed as it has a direct impact on the slag Fe.

Under blown heats can have unrepresentatively low slag Fe analysis, as insufficient oxygen has been blown into the vessel, and alternatively the over blown heats can have high slag Fe due to excessive oxygen being blown, which does not reflect the lance position.

### 6.1.3.2 EB Mn/C Ratio

The ratio of EB Mn and EB C has been shown to have some indication of the hard and soft blowing state of the vessel. The EB Mn is normalised based on the incoming HM Mn using the formula shown in Equation 6.1, derived by the technical department at Port Talbot steel plant from previous research:

#### *Equation 6.1 - Normalising EB Mn*

$$\text{Normalised EB Mn} = \text{EB Mn} - [(\text{HM Mn} - 0.44) \times 0.1]$$

Then the Mn C ratio is simply calculated by Equation 6.2:

#### *Equation 6.2 - Mn:C Ratio*

$$\text{EB Mn/C ratio} = \text{Normalised EB Mn} / \text{EB C}$$

**Table 6.2 - Mn/C Ratio Membership Function Boundaries**

Mn/C Ratio	Lower Limit	Upper Limit
Low		1.5
Normal	1.9	3.1
High	3.5	

As will be shown later on, this ratio is used to assess the state of the process along with the slag Fe and EB P levels, however the EB Mn/C ratio is only used as an additional indicator and is over ridden by the other two parameters if deemed necessary, as they have a direct impact on yield and grade specifications respectively.

### 6.1.3.3 EB P

The EB P has also been used as an indicator for hard or soft blowing, as it can infer the state of the slag within the vessel. As with the EB Mn, the EB P is normalised, however this is done against EB temperature, once again using a formula calculated within Port Talbots steel plants technical department based on previous work done shown in Equation 6.3:

#### *Equation 6.3 - Normalised EB P*

$$\text{Normalised EB P} = \text{EBP} - [(\text{EB T} - 1670)/10 \times 0.001]$$

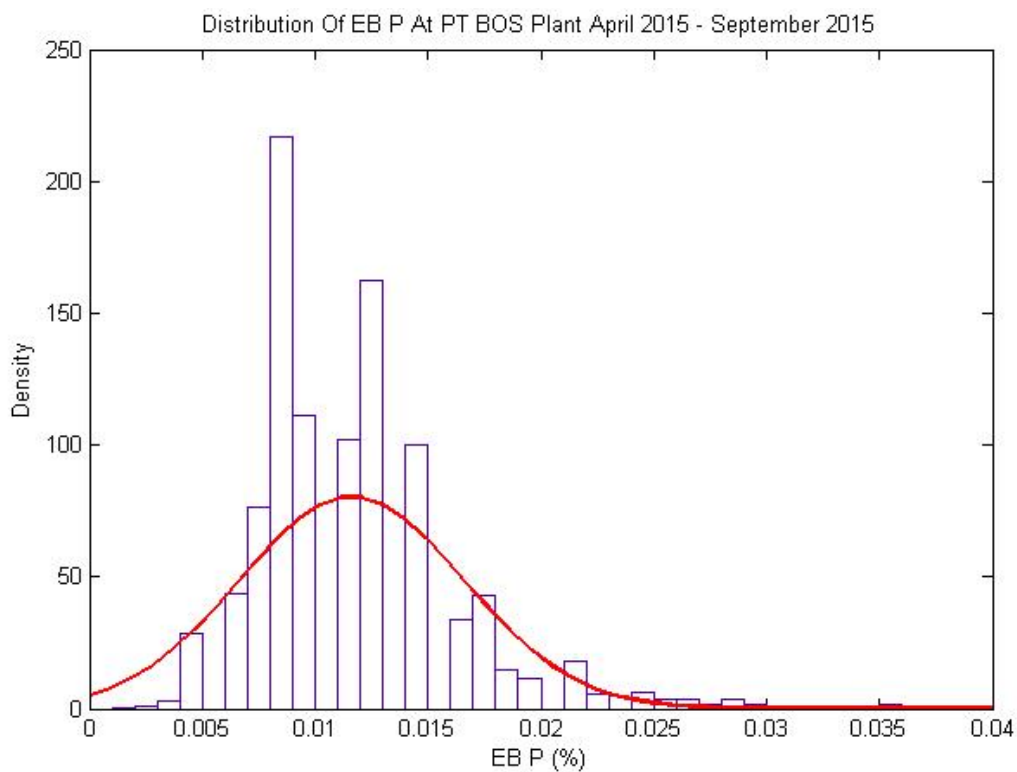


What this means is that a heat with an EB T of 1700°C with an EBP of 0.02 will have the same normalised EBP as a heat with EB T of 1670°C with an EBP of 0.017.

**Table 6.3 - EB P Membership Function Boundaries**

Normalised EB P	Lower Limit	Upper Limit
Low		0.008
Normal	0.0095	0.018
High	0.0195	

The EB P is a key driver in the optimisation of lance height within the vessel, as it is a difficult element to remove from steel after the BOS process. Therefore if the EB P is high, there is a risk that this could lead to a downgrade in the steel being made at the caster, which can be a large cost to the steel plant dependent on the original grade. Due to this the EB P takes precedent over the slag Fe and EB Mn/C ratio for lance control. The first part is to get the EB P under control, and then to optimise the lance height to reduce slag Fe levels after this.



**Figure 6.7 - Distribution Of EB P In Port Talbot BOS Plant**

### 6.1.4 Rule Set

Once the key process parameters were decided upon, outlined above, the next step is to work out what interactions should dictate a change in lance height, and in what way. This is where the work on designing the FIS is very important, as it will decide based on the incoming parameters what the correct course of action should be.

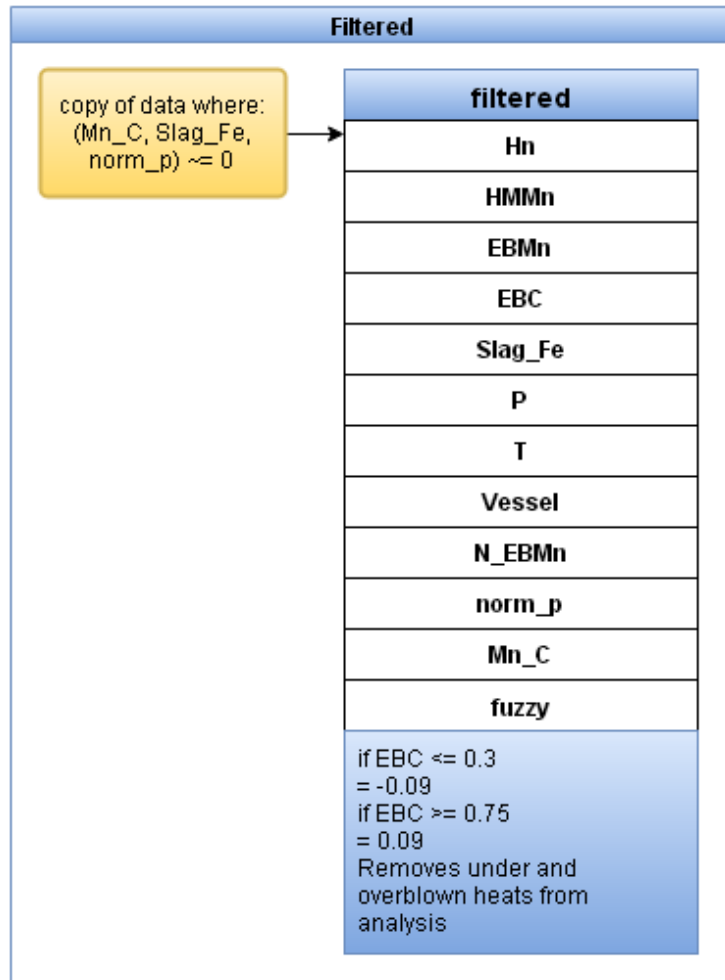
We decided on the boundaries for low, normal and high, which have been outlined above in detail, then simply went through all 27 scenarios and decided what course of action would be appropriate. So for example, in the fourth column (highlighted in yellow), if the EB P and Mn/C ratio is normal, but the slag Fe is high, the appropriate action would be to lower the lance. A small selection of these scenarios are shown in Table 6.4 to give insight into the approach. All scenarios are shown in Appendix F.

**Table 6.4 - Selection Of Hard & Soft Blowing Fuzzy Logic Rules**

Hard / Soft Blowing								
P	O	H	H	O	H	H	O	O
Fe	O	O	H	H	H	O	H	O
Mn/C	O	O	O	O	H	H	H	H
	-	Up	Up (P)	Down	Up (P)	Up	-	-
	H	High						
	O	Ordinary						
	L	Low						

### 6.1.5 Filtered Data Structure

This section of the system is used to contain filtered data, which is then used as part of the outputs from the system to be used on plant. Details of the implementation of this system will be explained in the next chapter. As shown below in Figure 6.8, this section is essentially a filtered section of the Data structure shown in Figure 6.4. The system ensures that all heats that have analysed by the FIS have non zero values, if the analysis is going to be output. As described previously, it is at this point that heats that are considered either under or over blown are removed as well, based on EB C values, as outlined in blue below in Figure 6.8.



**Figure 6.8 - Flow Diagram Showing The Data Sources & Logic Used Within The Filtered Data Structure**

## 6.2 Hard And Soft Blowing System Outputs

The nature of this system, in trying to advise the operators in a change of lance gap resulted in a simpler approach than previously used, in that no linguistic outputs are generated. The only output from this system is the FIS outputs from the FIS column within the filtered data structure. The exact implementation of this is described in the next chapter.

## 6.3 Summary

A system has been designed for use at Tata Steel's Port Talbot Steel plant for use in controlling lance height based on process conditions. The system that has been developed relies heavily on the use of Fuzzy Logic to infer the state of the process, and scales the outputs to infer if any adjustment to lance height is necessary. Based on data analysis, the system has been designed to rely on a small set of process data that provides the most insight into the effect the lance height is having on the process, and advise if the vessel is blowing hard or soft.

## **7 Implementation**

The intention of engineering the expert diagnostic systems was very much that is was to be implemented and used by TATA. This section outlines the implementation process used for all of the systems described in the previous chapters, covering database and web page design and outlines where possible the direct financial impact of the systems. A common approach has been used across all four of the systems developed as part of this work. In this way outputs are written to a database, which can then be read by and displayed upon an intranet web page. This approach will first be detailed, before a more specific explanation of each particular system is given.

### **7.1 Database Design**

Port Talbot steel works operate a number of information systems, which utilise web-based displays for data analysis and process management. It was thus decided that all of the expert systems would be deployed to web pages. The simplest and most efficient way to do this was to create a database that the systems could write all of the messages relevant to each heat to, which could then be extracted and displayed up on the web page. As this is the main method of deployment for all of the systems supporting different aspects of the BOS process, the database also needed to be future proof.

The initial design of the database is shown in Figure 7.1. It contains eight separate columns. The first column identifies the “Heat Number Set” which is used within the method by which data is stored in the steel works. It is there for when the heat number reaches 99999, at which point heat number set will increase by 1, and the heat number will be reset to start from 00001. The web page script uses line number; to order the outputs in the same way the system has outputted them. The process type is there to discern between the different expert systems writing to the same database; the scrap adherence system is set to 1, desulphurisation system to 2, EB C & EB T to 3 and hard and soft blowing to 4.

1	2	3	4	5	6	7	8
HEAT_NUMBER_SET	HEAT_NUMBER	LINE_NUMBER	PROCESS_TYPE	OUTPUT_TYPE	ADVICE	TIME_STAMP	TIME_STAMP_GMT
2	59525	1	1	2	No Scrap Weight Data Available	'2013-05-30 10:...	'2013-05-30 10:54:3...
2	59527	1	1	1	'Adherence Good	'2013-05-30 12:...	'2013-05-30 12:58:0...
2	59527	2	1	11	'Adherence Good	'2013-05-30 12:...	'2013-05-30 12:58:0...
2	59527	3	1	17	'A Steel Skull At 50% Due To Al2O3 Problems	'2013-05-30 12:...	'2013-05-30 12:58:0...
2	59527	4	1	14	'Alumina QA, Reduce C Skull To 50%	'2013-05-30 12:...	'2013-05-30 12:58:0...
2	59527	5	1	14	'Sulphur QA, Reduce A Desulph To 50%	'2013-05-30 12:...	'2013-05-30 12:58:0...
2	59528	1	1	1	'Adherence Good	'2013-05-30 13:...	'2013-05-30 13:21:3...
2	59528	2	1	11	'Adherence Good	'2013-05-30 13:...	'2013-05-30 13:21:3...
2	59528	3	1	17	'A Steel Skull At 50% Due To Al2O3 Problems	'2013-05-30 13:...	'2013-05-30 13:21:3...
2	59528	4	1	14	'Alumina QA, Reduce C Skull To 50%	'2013-05-30 13:...	'2013-05-30 13:21:3...
2	59528	5	1	14	'Sulphur QA, Reduce A Desulph To 50%	'2013-05-30 13:...	'2013-05-30 13:21:3...
2	59529	1	1	1	'Adherence Good	'2013-05-30 14:...	'2013-05-30 14:01:3...
2	59529	2	1	11	'Adherence Good	'2013-05-30 14:...	'2013-05-30 14:01:3...
2	59529	3	1	17	'A Steel Skull At 50% Due To Al2O3 Problems	'2013-05-30 14:...	'2013-05-30 14:01:3...
2	59529	4	1	14	'Alumina QA, Reduce C Skull To 50%	'2013-05-30 14:...	'2013-05-30 14:01:3...

**Figure 7.1 - Expert System Database Design**

To allow the searching of the database by other people who need to find specific process issues, and their corresponding frequency, process type corresponds to certain types of output within each process. An example of the varying process types is shown in Table 7.1, which corresponds to a selection of the scrap adherence system outputs.

**Table 7.1- Scrap System Output Types**

Harsco	1	Good Adherence (Overall)
Harsco	2	Poor Adherence (Overall)
Harsco	3	No Weight Data Available
Harsco	4	Weight Data Manually Input
Harsco	5	Scrap Partially Left out
Harsco	6	Scrap Completely Left out
Harsco	7	Recycle
QA	11	Good Adherence (Overall)
QA	12	Poor Adherence (Overall)
QA	13	Manual Scrap Mix Change
QA	14	Due To Direct Charge
		No New Alumina Samples Last 5
QA	15	Heats
QA	16	Non QA Scrap Left out
QA	17	Alumina QA - Reduce To ...
QA	18	Alumina QA - Keep At ...

The Advice column is where all of the outputs from each of the systems are written; for the scrap adherence, desulphurisation and EB C & EB T systems this will be where the linguistic

outputs are written. For the hard and soft blowing system, this is where the values from the FIS are written.

Finally the last two columns are for time stamps of when the relevant system run for the given output generated. This is done as a database requirement, with one of the time stamp columns adjusting to reflect British Summer Time (BST) adjustments, and the other with no BST adjustment.

## 7.2 Scrap Adherence System

In order for this to be easily visible and widely used, it was important to use a current web page and add on the outputs from the system as an extra feature of the page. It was decided that the scheduling page would be adjusted as the CBM coordinators use it. The webpage adjusted to display the system outputs as well is shown below in Figure 7.2 below.

SCHEDULE - Last update 14:22 <span>REFRESH</span>									
Heat	Scrap Box Req Time	Scrap Box Act Time	Start Blow Req Time	Grade	Scrap Type Required	Scrap Type Loaded	Weight	Loading/Loaded	Complete HM Ladle Wt
61829	07:26	06:32	07:46	3190	Normal	Normal	57.0		295
61830	08:17	07:34	08:37	3190	Normal	Clean	59.5		295
61831	09:01	08:20	09:21	3190	Normal	Normal	58.5		301
61832	09:40	08:50	10:00	3298	Normal	Normal	64.5		293
61833	10:23	09:46	10:43	3841	Clean	Clean	71.0		285
61834	11:05	10:42	11:25	3190	Normal	Clean	54.5		300
61835	11:42	11:22	12:02	3842	Clean	Clean	55.0		300
61836	12:19	12:01	12:39	3842	Clean	Clean	58.0		296
61837	12:56	12:37	13:16	3190	Normal	Normal	58.0		300
61838	13:48	13:06	14:08	3190	Normal	Clean	57.0		297
61839	14:40	13:38	15:00	3190	Normal	Clean	61.5		295
61840	15:17	14:12	15:37	3842	Clean	Clean	55.5	North : 55.5 of 56.1	300
61841	16:09	:	16:29	4085	Ultra Clean			South : 9.5 of 61.0	295
61842	16:46	:	17:06	3842	Clean				Pour Not Complete

EXPERT SYSTEM			
Advice for HARSCO		Advice for QA	
1	Adherence Good 30/07/2013 14:43:58	11	Adherence Good 30/07/2013 14:43:58
		23	Detinned Can Bales At 0% Due To Other 30/07/2013 14:43:58
		17	Alumina QA - Reduce C Skull To 50% 30/07/2013 14:43:58

The following Scrap Modifiers are being applied to all Scrap Boxes			
L:Scrap - Detinned Bales	0	%	Other

Dirty	Normal	Normal Hi Cu+Cr	Clean	Ultra Clean	Bales Only
-------	--------	-----------------	-------	-------------	------------

Figure 7.2 - Scrap Adherence Intranet Web Page

### **7.3 Desulphurisation Expert System**

The implementation of the desulphurisation system was based on the previous work done for the scrap adherence system. As the implementation through a database, to a web page worked well. The same database table, Expert Adherence, was used by the desulphurisation system to write all outputs to; ready to be read by a webpage that has been setup on the intranet. A view of the web page used is shown the Appendix G, as can be seen, due to the nature of the system running every 24hours, it is beneficial for the database to be searched to allow a review of previous days reports, as the top drop down menu allows.

The system has been designed to run at 7:30am every morning, to allow a full report on the desulphurisation process for the past 24hours to be available for management at the morning meeting at 8. This approach has helped to progress the implementation of the system on plant, it has been developed from a test web page with limited access limited to technical personnel and process managers for review, to being added to the available reports live on the site intranet, accessible by all.

### **7.4 End Blow Carbon And Temperature**

As with the previous 2 systems mentioned, all outputs generated by this system are written to the Expert\_Adherence table, and then read by a web page setup on the intranet, shown in Figure 7.3. This particular system, in contrast to the desulphurisation system has been designed to run after every heat, if analysis is available, to provide real time assistance to the operators. The web page developed for this application has been designed to show results for a day at a time, with times being adjusted based on shifts, so a day starts from 7am instead of midnight to correspond to shift rotations.

**Vessel Expert System Results**

Select date:  Submit

**Expert Results**

Treatment Advice
15621, Vessel 1, EBC (Lab) Low, 0.03 For Aim 0.04
High Steel O2 982.6ppm Suggests Heat Overblown
Low Tap Weights [Act:309.3, Predicted:316.3T] & EBC [Act:0.03, Aim:0.04] Suggest Insufficient HM Charged
15629, Vessel 2, EBC (Lab) Low, 0.028 For Aim 0.04
High Steel O2 863.9ppm Suggests Heat Overblown
15631, Vessel 2, EBT Low, 1627 For Aim 1650
15637, Vessel 1, EBC (SubLance) Low, 0.02671 For Aim 0.04
High Steel O2 1116ppm Suggests Heat Overblown
15641, Vessel 1, EBC (Lab) Low, 0.029 For Aim 0.04
High Steel O2 1196ppm Suggests Heat Overblown

***Figure 7.3 - EB C & EB T Intranet Webpage***

This system has been deployed to the intranet visible to all operators and steel plant personnel, after an initial 3 month trial period where it was only accessible to the technical department. This was done to ensure all of the outputs were correct

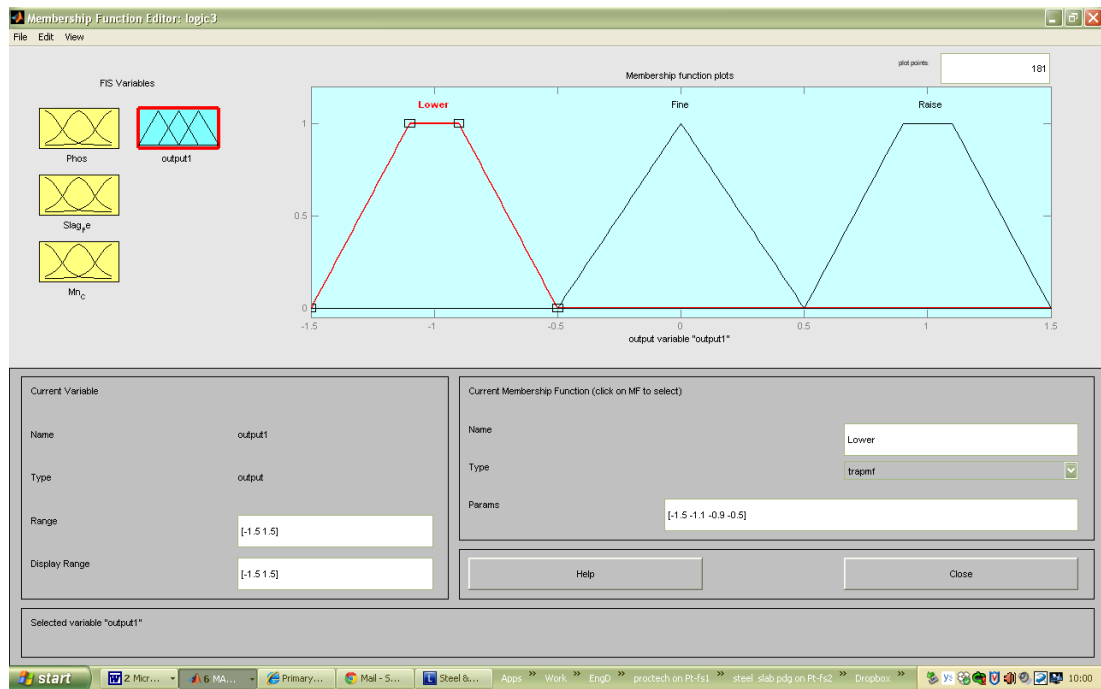
## **7.5 Hard & Soft Blowing**

As mentioned previously, the outputs of the Hard and Soft blowing system are just numbers, which evaluate the lance height being used within each of the vessels. The implementation of this system differs from the previous 3 systems because of this.

### **7.5.1 Implementation**

The FIS for the hard and soft blowing system has 3 inputs, and one output that have 3 membership functions. These being to raise, lower and to maintain lance gap respectively.





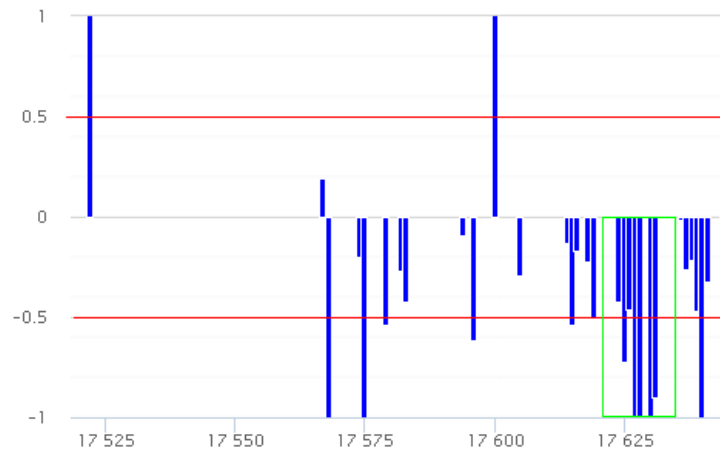
**Figure 7.4 - FIS Output Membership Functions**

The output of the FIS is a score for each individual heat, on the level of hard and soft blowing. As is shown by the membership functions in Figure 7.4, a value above 0.5 indicates the lance needs to be raised, a value below  $-0.5$  indicates the lance needs to be lowered, and anywhere between these limits suggests a need to maintain current lance gap.

The limits were specifically designed like this to allow an SPC type graph to be displayed to the operators, on the state of the lance gap to advise on changes. The level at which the line is above or below these limits depends on the membership values previously mentioned, and implies the level of adjustment required. It was decided based on consultation with process experts and operators that action should not be taken on a single heat, but should be monitored for several heats for a trend. This removes the risk of acting on an inaccurate lab analysis, as this will be easily visible if taken as part of a trend. If the bar is consistently between  $-0.5$  and  $-1$ , as shown by the green box, then an appropriate action would be to lower the lance.

An important part of this system has been the consultation with the operators, firstly on the rule base used within the FIS, and secondly on the display that the information is generated on. After a month of trialling the system on shifts, it was noticed that because action was being taken on a trend of 3 heats, and the slag analysis can often take an hour for

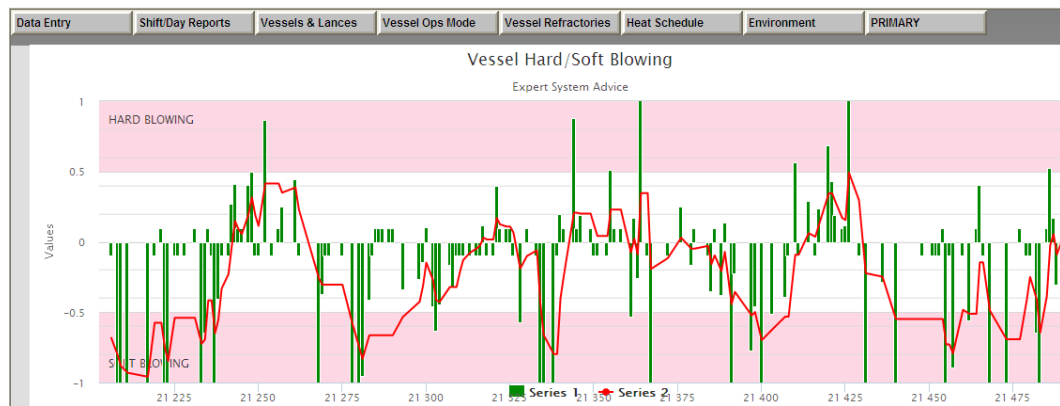
results to come through, that any changes were quite delayed. An initial trend of results from the system for a single vessel over a couple of days is shown below in Figure 7.5.



***Figure 7.5 - Hard & Soft Blowing Display, Green Area Highlighting Region  
Where System Would Suggest Lowering the Lance***

In response to this the trending of the individual results was examined using a running mean, to try and identify when the process is drifting in terms of hard and soft blowing. This could be a consequence of the ports on the nozzle or the refractory lining of the vessel wearing, which would impact how hard the vessel is blowing.

This led to the solutions being sought using the Statistics toolbox within Matlab. In this case use was made of the Exponentially Weighted Moving Average (EWMA) to analyse the values. The individual scores from the FIS were then filtered to remove heats that were under or over blown. This modified data was then input into the EWMA function in Matlab to generate a moving average. The resulting typical trend, with additional EWMA added is shown below in Figure 7.6.



**Figure 7.6 - Hard & Soft Blowing Scores With EWMA Values**

The main benefit we found with using the EWMA over the operators looking for a trend in the data, was that the drifts were picked up sooner, and adjustments were made 1-2 heats sooner, which improved vessel performance over all.

The deployment of the system has followed the same method as the previous systems, with all outputs being written to a table called Expert\_Adherence. However for this system the outputs have been written into the PSSUP and PSMET databases. This has been done to facilitate the addition of a popup for the operators on the blowing screen. This indicates when a change needs to be made based off the EWMA, when this goes below  $-0.5$  or above  $0.5$  it recommends the hard and soft blowing screen is checked, and an appropriate change is made. The blowing screen with this in use is shown below in Figure 7.7, with the output shown within the red ellipse.

It was decided against giving direct advice in which direction to adjust the lance and by how much. This was deemed appropriate to leave in the hands of the operators, as other issues can affect slag Fe and EB P, which are not due to lance gap control. Along with the individual scores for each heat from the FIS, the moving average values for each heat are written to the Expert\_Adherence table on PSSUP and PSMET, where they are displayed on the intranet page as shown in Figure 7.67.

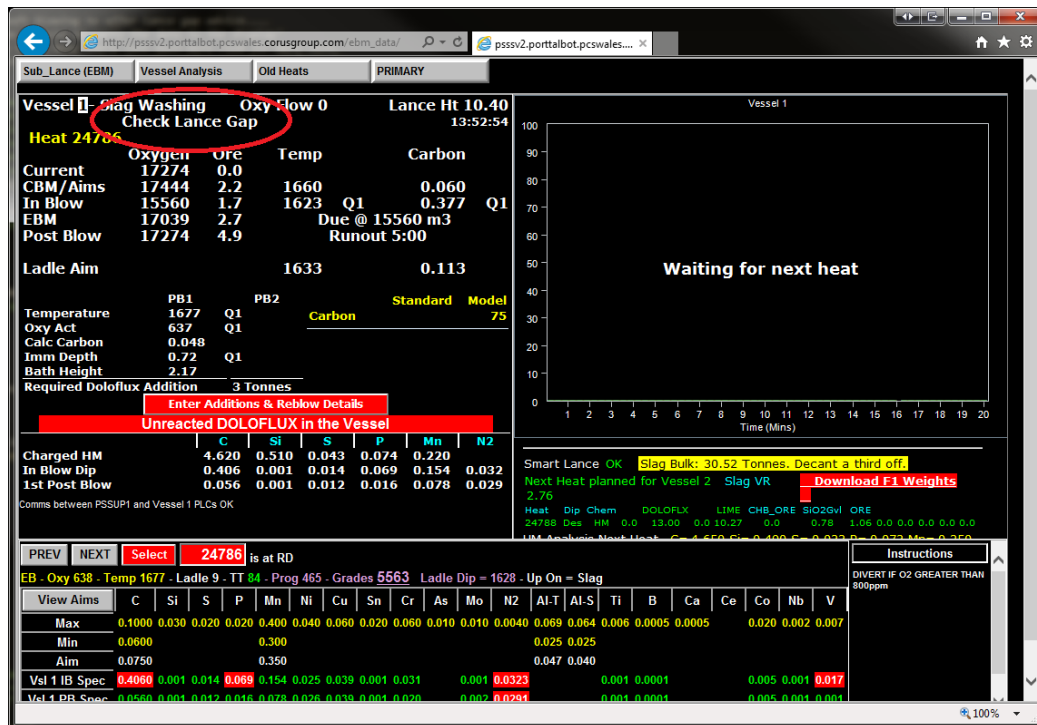
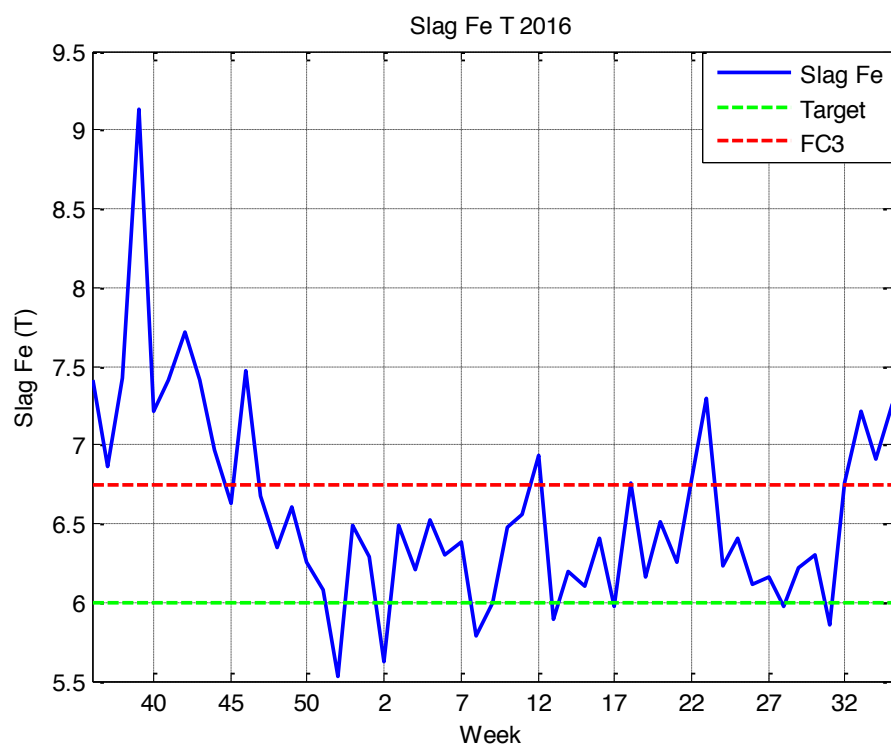


Figure 7.7 - Blowing Screen With Lance Gap Output Shown Within The Red Ellipse

## 7.5.2 Impact of system

A programme has been taking place at Port Talbot steel works to reduce the cost of liquid steel, through various technical projects and initiatives. The hard and soft blowing system has been used as a project within this to drive down the slag Fe's at the vessel, by assisting the operators in lance height control. The progress made in this project is shown in Figure 7.8. This assistance in lance height control facilitates the reduction in Slag Fe's whilst maintaining good phosphorus refinement.

The target of the project is to reduce average slag Fe in tonnes from 6.75t (FY '15-'16) to 6t, which over a 12-month period will provide an estimated saving of £560,000 directly to the steel plant in improved converter yield. So far in 2016 a reduction of approximately 0.35t to 6.4t has been achieved through the introduction and use of the hard and soft blowing system. In terms of business impact, this has so far provided a financial benefit to the company of approximately £20k per month, with further reductions planned.



***Figure 7.8 - Impact Of Hard & Soft Blowing System On BOS Plant Slag Fe's***

To ensure that the savings for this project were accurately recorded within Tata, a baseline figure was calculated using the previous year's figures. This baseline was then compared to the actual performance to assess to what extent the slag FE losses had been improved. The following steps outline the method used to estimate the financial savings, although illustrated using generic figures..

**Table 7.2 - Data Showing Example Ratio Of Slag Weight Produced For Each Tonne Of Liquid Steel**

	kg/tls		1T Steel	320T Steel
Slag Weight	100		0.1T	32T

As Table 7.2 shows, assuming that a steel plant produces 100kg of slag for every 1tonne of liquid steel they produce, this would equate to 32 tonnes of slag for every heat from a 320 tonne converter. To estimate the improvement in Fe, when going from 20% to 15% it is possible to produce an actual value in Fe tonnes saved, which can be directly given a cost.

**Table 7.3 - Data Showing How Slag Fe % Relates To Fe T Saved For A 32T Slag Bulk**

Fe%	20%	15%
Fe T	6.4	4.8

Table 7.3 shows that assuming a 32 tonne slag bulk, when considering Fe, improving from 20% Fe in slag to 15% would save 1.6 tonnes Fe per heat. This initially doesn't appear to be very significant given the scale of the process. However, a large integrated steel works like Port Talbot can produce over 5M tonnes of liquid steel per annum, and, as Table 7.4 shows this equates to 15,625 heats a year for a 320 tonne converter. On this basis a saving of 25,000 tonnes of Fe would result.

**Table 7.4 - Data Showing How Fe Savings Per Heat Scale At An Integrated Steel Plant Per Annum**

Tonnes	Heats	Fe T
5M T	15,625	25,000

The financial saving for this project was assessed using slag weights in kg/tls corresponding to Port Talbot, and the saved Fe T figure for a year was multiplied by the value used at PT for a tonne of liquid steel.

## **8 Conclusion & Research Contributions**

This thesis has outlined four expert systems that have been developed for the application within Tata Steel Port Talbot BOS Plant, covering a range of processes. Each of the systems has been outlined in detail, covering the data sources used, along with the relevant processing steps and expert knowledge used where appropriate to outline the system outputs, and the scope of issues that each is capable of diagnosing. The implementation of each of the systems has been described, explaining how the final link between development and industrial implementation has been created to realise actual benefits for Tata.

### **8.1 Scrap Adherence Expert System**

A diagnostic system has been designed and implemented at Tata Steel's Port Talbot works to facilitate BOS operators on scrap mix selection, when sulphur and alumina issues occur within the process. The system monitors the slag alumina levels, and the steel sulphur levels and provides advice based upon plant Quality Assurance (QA) procedures to isolate and rectify scrap-based sources of increased levels in both compounds.

There have been a number of successes from the system development and some key learning points, which helped direct development for subsequent expert systems outlined in this thesis. These can be said to represent the contributions made by the author during this Engineering Doctorate programme.

The approach used was the first to use Fuzzy Inference Systems (FIS) within Port Talbot. This proved very successful, as it facilitated in the creation of a system to follow the QA procedures for both sulphur and alumina issues consistently. A large body of knowledge was gained from the development of this first system with regards to the application of FIS, as this system used it extensively. In subsequent systems it was deployed less frequently, and was focussed on areas where it was deemed to provide a significant benefit in the better interpretation of results, or simplified the programming required to analyse the processes. However this insight was only possible through the initial work done on this system.

The implementation of the work done on the scrap adherence system demonstrated the successful use of the database to web page approach. This was then used across all systems as it provided a simple but effective solution to link from system outputs, so making the advice openly visible to all plant personnel, particular operators.

As a key part of the implementation it was found that the target audience was an area that the development of this system actually struggled with. The target audience for this system were the plant operators and so the outputs and the web page used were tailored specifically to this application. However, the development of the system, solely relied upon input from process experts within the Technical department at the BOS plant, with very little interaction with the operators. This interaction only occurred when the web page was created and the system was introduced to the operators as a tool to assist them. This proved very unsuccessful, with adoption of the system by the operators not occurring. It was also apparent that because the managers were not particularly involved during the development from an early stage, there was little buy in the management either. A lot was learnt from this however, as in all subsequent expert system development the operators and managers were consulted during the initial stages to try and get a bigger buy in, and adoption for process diagnostics.

The system, although proving unsuccessful on final implementation, provided a lot of learning points and development methods, which benefited subsequent expert system development in other process areas. The use of Fuzzy Logic proved successful, with this being applied to 2 of the later 3 expert systems developed. The database to web page method used to implement the expert system has been continued for all expert systems outlined in this thesis. Finally the interaction with groups with which the project interfaced during the subsequent expert system development, grew significantly because of the experience of this system, which helped with the implementation and more importantly adoption of future expert systems.

## **8.2 Desulphurisation Expert System**

A diagnostic system has been designed and implemented at Tata Steel's Port Talbot works to generate a report every morning, on the state and operation of the desulphurisation plant, which considers the past 24 hours of production. The system monitors the model setup by operators, allowing better control of material use for the desulphurisation treatments. The performance of the process is monitored, highlighting interrupted treatments and re-treatments. The system supports the diagnosing of possible causes for these. Particular attention is paid throughout to highlight deviations in material use and the effects this has on end point chemistry. This system has allowed a detailed overview of the process to be easily available to all personnel on plant, allowing the state of the process to be better understood, and the control of the process and material usage to improve.



There have been a number of successes with the development and implementation of the desulphurisation system. The approach taken, the programming techniques used, and the target audience have all proven to be applicable and successful for this type of system.

The approach taken was to keep the system as transparent and as understandable as possible. This meant ruling out all black box modelling, or other data mining/prediction methods, as often the understanding of where the relationships come from is relatively vague. Instead the system has been built on process understanding, and applying the logic of expert personnel, for the varying situations the system encounters in monitoring the desulphurisation process. This has meant discussing and defining set boundaries or control limits for a wide range of parameters throughout the system, to allow the various issues to be easily classified into a decision tree type system.

Given that the system is aimed at providing diagnosis of issues, unlike many expert systems where end point prediction is instead the focus, the design of the outputs being text based has also proved very successful. The design of the outputs has been heavily developed, through discussion with the primary technical department at Port Talbot steel works. This has been done to ensure that all relevant information is contained within the outputs, whilst assuring that they are as clear and as concise as possible, to improve the adoption of the system by the managers.

The final implementation of the system to a web page on the intranet has also proven successful, with a tab being added to search by date. The benefit of this approach is that the system advice is easily accessible to a very wide audience and allows a single version of the system to be run. The single system runs and writes all of the outputs to a database designed for this system that is then read by the webpage and updated accordingly.

The programming techniques used have developed alongside the system, with more use of Object Oriented Programming being implemented as the project developed. The main benefit of this approach is the re-usability of code, reducing the need to copy and paste code into different areas of the program. This involved the use of structures within Matlab variables to better organise the data, and make the required data processing far easier to follow and understand from an outside perspective.

The code was built to be robust, so there are an appropriate number of conditional checks throughout. These aim to identify and catch statements to prevent issues, as this is designed to run daily with no input from anyone. This was assisted by the use of nested

functions, as it causes far less issues with passing the required data, as it allows access to the whole workspace.

The target audience for this type of system is very important, as it is essential that the information provided is relevant to those using it. It is also vital that the audience is open to use the system. The desulphurisation system from the start of the project has been aimed directly at the managerial level within Port Talbot Steelworks. This approach was taken, as aiming a system directly at the operators where an important part of the system's capability is indicating when the operators are not following the model, simply would not get adopted. This is because that level of information is of use to those managing the process, and not those controlling it.

The system has been designed to highlight all issues, both those caused by the equipment, but also those caused by the operator adjustments. It is very difficult to aim a system at operators where their adjustments and effects on the process are being highlighted in order to ensure that they receive constructive recommendations. Due to this the system was aimed at the managers initially, as they have an interest in fully understanding all issues going on with the process. The additional benefit is also that the visibility of the system is drastically improved.

This system has provided a lot of success to the project, and so can be further built upon. The on-going development cycle is being undertaken with the next system developed being the end blow carbon and temperature deviation in the BOS process. Specifically the further development of the Object Oriented Programming, to further improve the efficiency and the robustness of the code is being written and developed.

### **8.3 End Blow Carbon & Temperature Expert System**

A diagnostic system has been designed and implemented at Tata Steel's Port Talbot works to diagnose, when analysis is available, causes of deviations in EB C and EB T. The system has been designed to be modular to allow the system to be easily expanded in future, and to facilitate in a large scope in allowing the system to diagnose process issues. This system has had a number of successes in terms of the range of data being used, the complexity of the issues being monitored and development of programming methods used during the development.

The approach used was based upon the successes of the desulphurisation expert system, this time using data from PSMET and PSSUP databases and expanded to include the Pi database.

The initial development in handling and using data from the Pi database was all done during the development of this expert system. This was then retrofitted into the desulphurisation system to improve its capacity to make use of Pi database for improved diagnostics.

The work done in developing the objects to handle all the database connections, as well as other useful tools such as the Times object, simplified the programming of the expert system significantly. This resulted in a reduced amount of code being required, and additionally made the code more robust which from a development perspective is a great success.

The modular approach taken with this system was also a great success, as it meant during the development extra modules could be added. This was because all of the relevant data sources were already added to the system at the start to make the addition of more modules far easier. The main benefit to this is the scope was significantly increased throughout the development, and covered a wide range of issues from those fully understood such as over blowing, to those less well understood, such as the falling of material off the hood during the BOS process.

The application of Fuzzy Logic was more sparingly used within this system, being applied where it facilitated in the ease of analysis and required programming. The use was successful, as it allowed the easy interpretation of BAP flows within the process, and an evaluation of the affects it had on the process, both positive and negative.

The target audience for this system was tailored again to the operators. However, due to the insight gained from developing the previous two systems, the managers and operators were more involved right the way through the development. This facilitated in the implementation stage of the process, and the adoption and use of this system as a tool for diagnosis during the process. Due to the nature of the system, there's no direct benefit to the number of issues that occur within the BOS process that correspond to EB C & EB T control, however the number of affected heats inevitably reduces in fixing the issues.

The aim of the project as a whole was to create a process diagnostic for the BOS process, and although it was decided early on that a single system would be unmanageable due to the size and complexity of the process, in terms of the BOS process, this system is the most comprehensive system developed as part of this project on the BOS process. The system developed can successfully diagnose between a large array of issues, which affect the EB C and EB T in particular.

#### **8.4 Hard & Soft Blowing Expert System**

A system has been developed and implemented at Tata Steel's Port Talbot works to advise on lance height control within the BOS process. The development of the system was made possible because of the insight and experience gained from the development of the previous three expert systems.

The application of Fuzzy Logic within the system, as a sole method of evaluating the process, was only possible because of the experience gained from the development of the previous systems. Process experts and operators at Port Talbot knew of the technique because of these previous developments and so they were willing to accept the sole use of it as part of this work.

This system has been the best application of Fuzzy Logic in the work done throughout this thesis, with the outputs being tailored through a lot of consultation with process experts and operators. The outputs do not simply imply a raising or lowering of the process, but also advise as to the level by which the adjustment is required, with the output moving between -1 and 1, depending on the severity of the issue.

This aspect of the system made the implementation and particularly the adoption of the system very easy. The operators appreciated that it additionally gave insight into the level of adjustment required. The work done in deploying the application of the exponentially weighted running mean made good use of this feature as well. As if it picked up a small number of severe issues then it reacted quicker due to the weighting, and enabled and helped the operators to implement a change sooner.

Due to the Cost of Liquid Steel (CLS) programme taking place at Port Talbot Steel works currently, the financial benefits which normally are difficult to calculate, have been made a lot clearer to see. To date, the system has helped a CLS project on improving lance performance deliver savings of approximately £20,000 per month since the system was fully implemented in week 47 of 2015.

## 8.5 Research Contributions

This research has designed and deployed four expert diagnostic systems, covering a range of steel making processes. This has made a number of contributions to the Steel Industry and to Tata Steel Port Talbot Steel Plant in particular:

- The successful implementation of these systems has contributed to creating a wider acceptance of the utilisation of expert systems within steel making production and technical functions. The EngD project initially started with the majority of Tata Steel production and technical personnel involved having little or no faith in a successful outcome. This was because a number of expert systems projects had been attempted within the R&D functions of Tata Steel UK, with little successful implementation. This research has changed this perception.
- The research has created detailed process maps of the plant being controlled as a direct consequence of the engineering of the expert systems for each of the involved areas. Through the application of appropriate techniques on a number of different steel making processes, this research has clearly demonstrated that expert systems can provide benefits to steel making production. This has been demonstrated by the successful implementation of these systems into the plant and through their use by production and technical functions within the steel plant.
- The steelmaking process is operated continuously and generally process experts cannot be expected to provide twenty-four hour support. These systems can provide enhanced support and contribute to effective management at all times. Although the systems are by no means a replacement for these experts, they are a very good alternative to assist with production issues when the experts are unavailable. This is by far the biggest contribution of this project to the steel plant, as it makes the invaluable knowledge that the process experts have, significantly more accessible to production 24/7, better reflecting production requirements.
- The systems act as an aid to operator understanding and knowledge development as when they are used an explanation is always given with each instruction as part of the output. As shown throughout the thesis, extensive flow diagrams have been used to break down the process and all of its respective issues into useful sections to allow the system to discern, with relative clarity, as to the exact cause of any process issue

or deviation. These flow diagrams map out the process in a high level of detail, and represent the first time the process has been broken down into this level of detail, including appropriate data sources within the plant databases for the necessary variables. This is a good contribution to the technical functions within the steel plant. It has particular relevance where the workforce is quickly aging as it can facilitate knowledge transfer to new starters.

- The final contribution from this project is in the method that was used to design and develop the expert systems. The methodology utilised to produce each system has evolved to provide a very successful data and expert knowledge driven method to design and deploy expert systems. This was enabled by tailoring the expert system structure around the process, instead of trying to fit the process into a pre-existing piece of third party software. The typical approach used has been to use a pre-existing expert system shell and fit the process within this. In contrast, from the outset of the project the approach used has been to gather as much data as possible to understand firstly what is available to assess the state of the process, and secondly to assist in process understanding. From this point the system was then built around the process, for which the benefits are clear when comparing the end blow carbon and temperature system to the hard and soft blowing system. They are derived from the same method, but have a completely different design, tailored specifically to the requirements of the process.

This project has demonstrated the use of expert systems to be a successful approach, which has additionally resulted in several tools developed for use within the system for data extraction and processing being available for use within the steelworks as part of additional developments undertaken since the project has finished.

In addition to the contributions mentioned, 2 conference papers have been presented to date as part of the project (Jamie; Short et al., 2014; Jamie Short, Barnes, Evans, & Prickett, 2015).

## **8.6 Lessons Learned**

The work carried out as part of this thesis highlighted several key lessons that were learned, which facilitated in the success of the project. The first was understanding the audience for which the system was going to be used by. The analytics approach used, in this case Fuzzy logic, was chosen because it was seen to fit the operator's expectations, and

avoided techniques they already had negative preconceptions about. This is important, as developing any system that cannot get operator buy-in will mean that it becomes increasingly difficult to get the system adopted and successfully implemented within the live industrial environment. This issue surrounding operator buy-in has been touched upon within the Scrap Adherence Expert System development within this thesis, where implementation became very difficult.

The second lesson is to carefully consider the software used to develop the system. This was only fully appreciated on handing over the software to be maintained solely by Tata. During the hand over period it became apparent that Matlab for the EngD was the most appropriate software for system development. However, within Tata there were very few people who had experience with Matlab, predominantly due to the commercial licence costs required. The one area not considered when choosing the software to develop the expert systems in, was how easy would it be to maintain within the industrial environment.

Thirdly as part of this work expert systems have been developed for 4 different processes related to the BOS process. The important lesson here is that for each of these processes, the system has been tailored to the process itself. The approaches used have stayed the same, but the system design and exact implementation have been tailored to the process itself, ensuring there have been no compromises. It's quite usual to find a design and an approach that works, then copy and paste it over to a different process where it can be adapted and made to work. However, it was avoiding this approach that allowed the hard and soft blowing system to be developed, and very successfully implemented. The approach of fuzzy logic was carried over from the other systems, but the implementation was considerably different.

Finally, the most important aspect of getting an expert system developed and implemented was basing myself within the industrial environment full time for the whole of the EngD, and surrounding myself with some very knowledgeable and willing process experts. This allowed for access to the process data and allowed the building of good relationships with process managers and operators alike. This accelerated the development of process understanding considerably. It was the smaller details gleaned from the process experts that allowed the wide range of process issues to be covered within the EBC & EBT system. This also provided sufficient insight to develop the hard and soft blowing system. The relationships established with the process managers and operators, facilitated by the implementation of the systems, built up a level of trust, which is required when dealing with a process on the scale seen within the steel plant.

## **8.7 Summary**

The aim of the project was to develop an expert diagnostic system for the BOS process at Port Talbot's Steel plant. It became apparent very quickly that a single system to do this would be too complex in nature, and that solving the problem would be more manageable as several smaller modules on aspects of the BOS process.

This thesis has outlined the development and implementation of four systems that cover a wide range of aspects of the BOS process, ranging from the desulphurisation of the liquid iron before being charged into the vessel, the scrap mix used during the BOS process, deviations in EB C & EB T control as well as lance height control. Between these four systems, the BOS process has been extensively covered, with a large number of process issues being encompassed within the overall scope of the systems developed.

The method of using linguistic outputs for the first three systems and that developed to output numerical values for the hard and soft blowing system, were both appropriate and successful for their respective applications. The development of several programming tools through Object Oriented Programming (OOP) during the project, which have been integrated within a number of the systems, have additionally benefited the steel works. Several of these have been used for developments within Tata's technical department, on other aspects of steel making, assisting with on-going data analysis developments. This alongside the financial benefits outlined for the Hard and Soft blowing system have shown the research and development done as part of this work for Tata Steel on the BOS process has been of benefit to the process.

## **8.8 Further Work**

The development of diagnostic systems, as outlined within this thesis, can be seen as a step in the process of automation. This is particularly apparent with the Hard & Soft blowing system as this has been designed to advise operators on lance height control. However it still relies upon operator interaction with the system outputs, to make the adjustment of the lance height. The first area of further work would be to further develop the Hard & Soft blowing, improving upon accuracy and progressing it along the development route to a fully automated control system.



The methodology used to assess the lance height has been shown to be effective, and with successful implementation as an advisory tool it has provided improvements in process control. This original requirement of the system was to help standardise the operator's reactions to lance height control. This could be further improved by removing the operator's from the control loop, and having the system directly control the lance height.

This thesis developed expert diagnostic systems based around the BOS process, and were shown to have success in several areas. A key area offering a significant opportunity for further work is within secondary steel making, across all the units. Within secondary steel making the liquid steel produced by the BOS process is alloyed to create the chemistry required for a specific grade. This area was not developed within this thesis for two main reasons, insufficient time and poor data quality. An obvious development would be an expert system to automate alloying additions at the various units used, as a high level of accuracy is required for some of the grades produced in these units, and so removing a level of human error from this control would inevitably improve on accuracy levels. As mentioned however, this would be difficult within Port Talbot as the quality of the available data is very poor when compared with primary steel making processes such as the BOS and desulphurisation processes. However, further work into improved PLC systems within these units, tied in with expert system development around alloying additions and control, would be of significant benefit to the steel plant both in terms of alloy recovery levels, and reduced miscasts.

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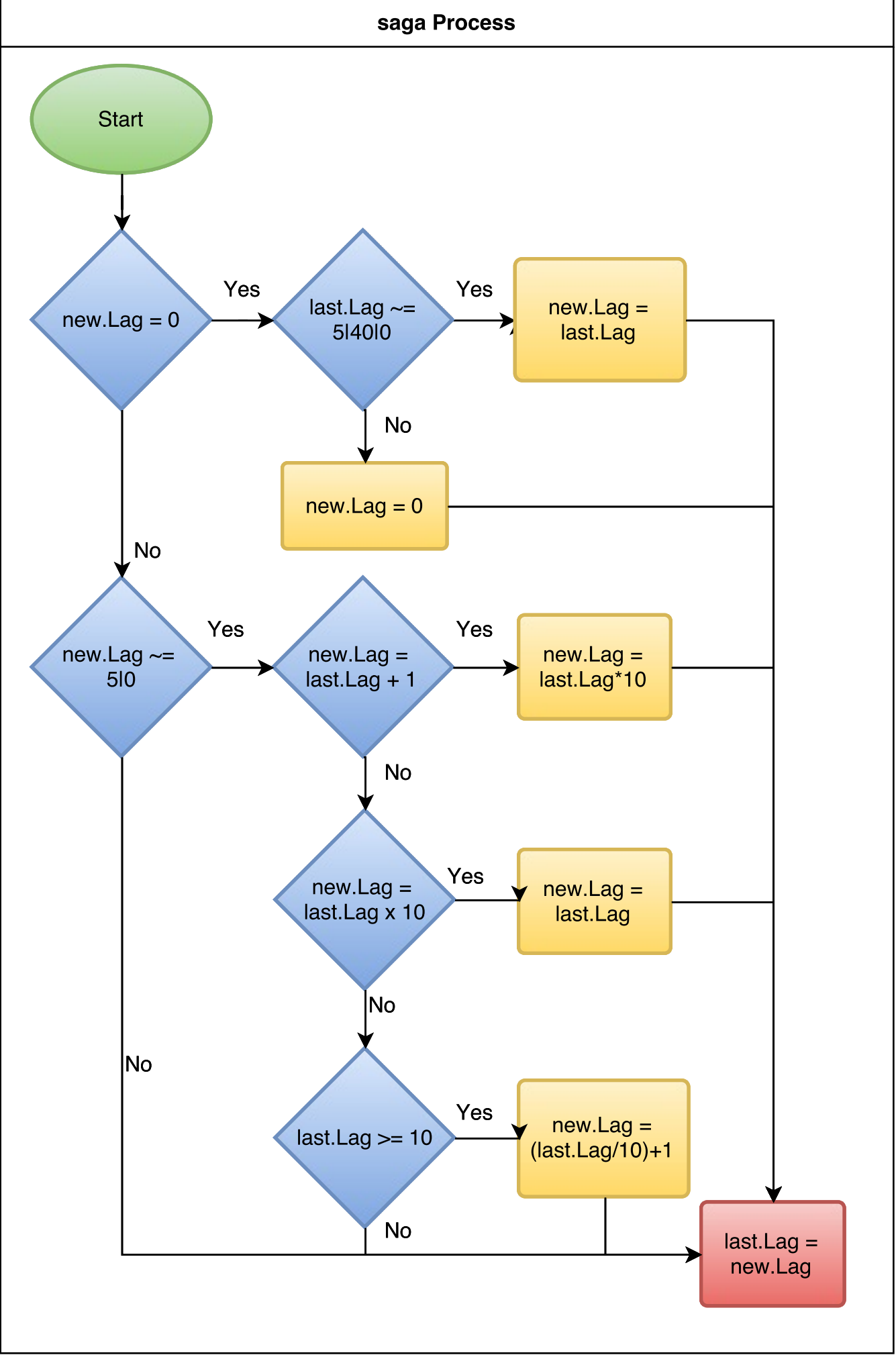
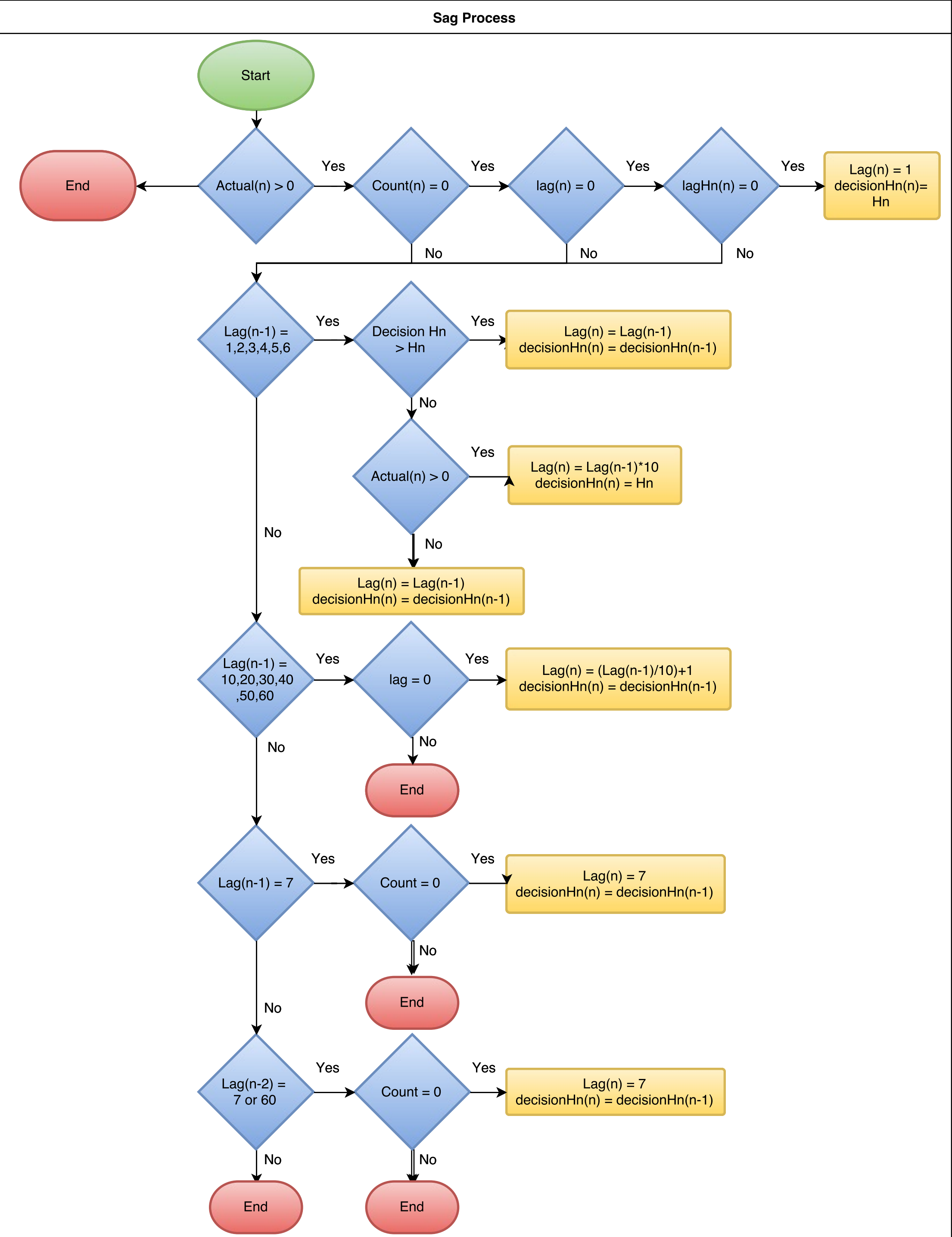
## **10 Appendix A - Alumina QA Decision Tree**

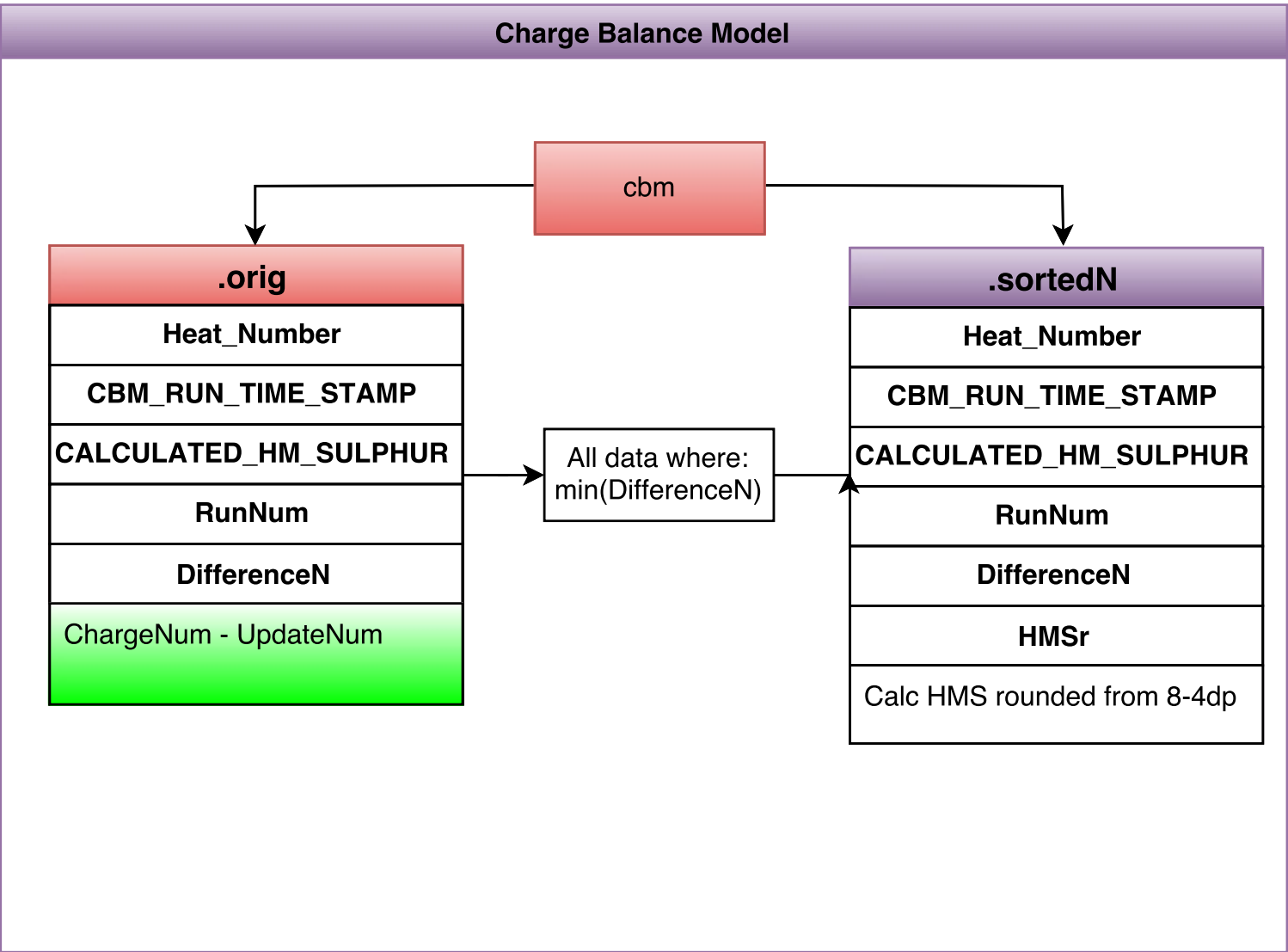
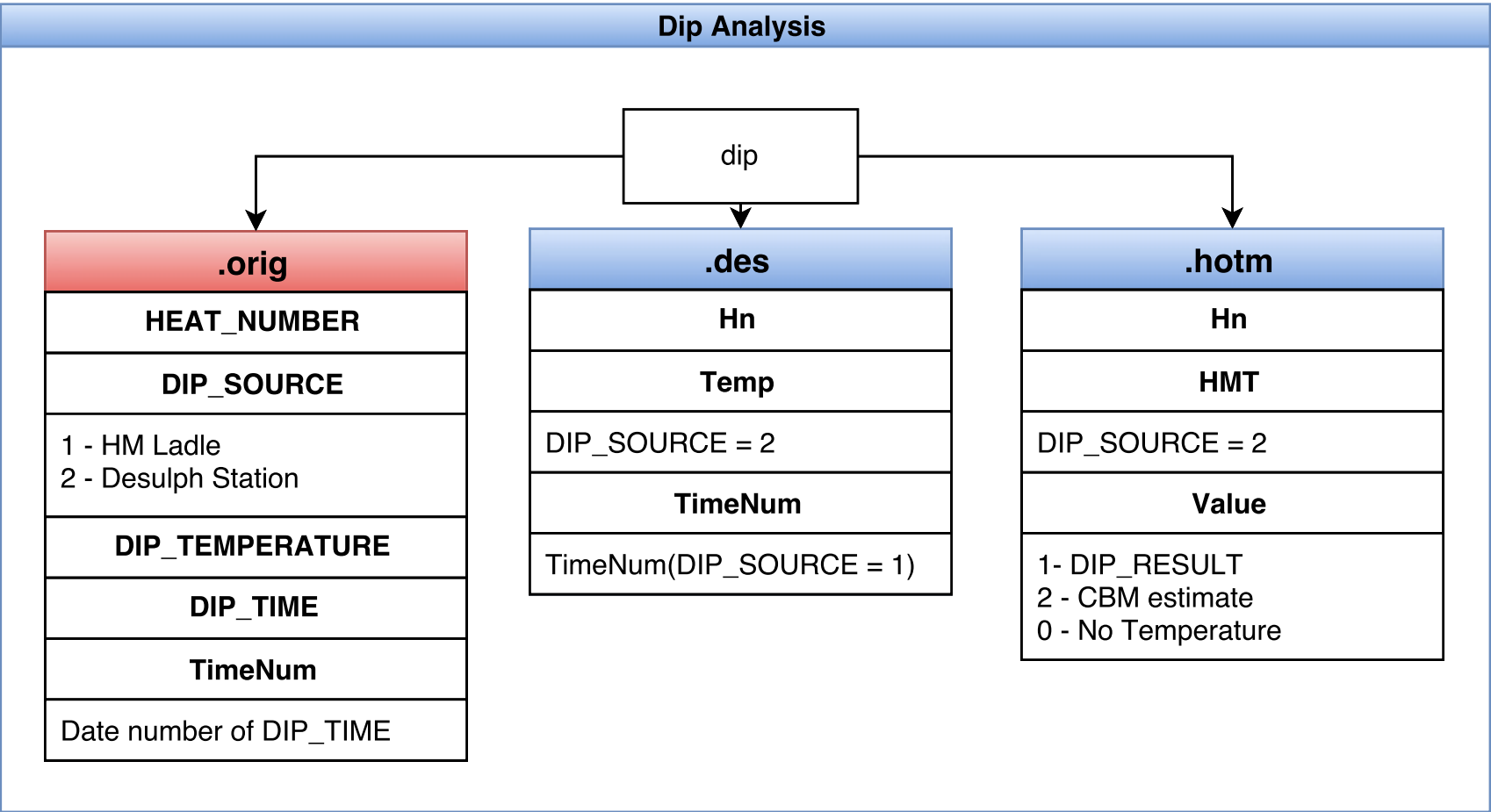
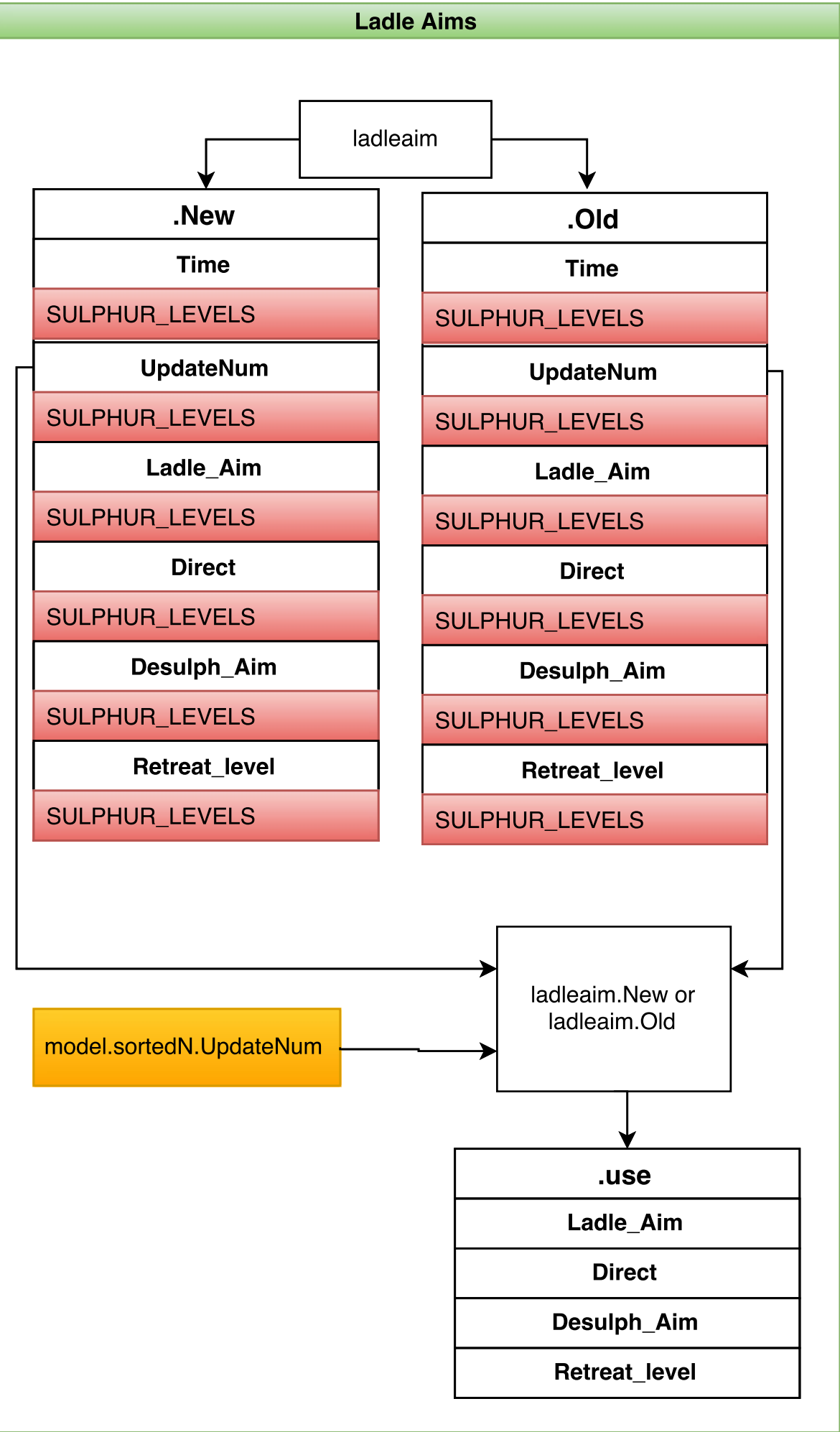
Appendix A

		Yes	C Skull reduced	0	C Skull 50%			Key	Question	
		Alumina	Al2O3 >2.8 for 3/5 heats	1,2	Keep C Skull 50%			No	No	
				3	Al2O3 Improved	Yes	C Skull 75%	Yes		
						No	C Skull, Incin 50%	No of Heats		
				4,5	C Skull 75%	Yes	C Skull 75%	System Output		
						No	Incin Reduced			
							0,1,2	C Skull, Incin 50%		
				6	C Skull 75%	Yes	Al2O3 Improved	Yes		
						No	Reset C Skull			
						No	Incin Reduced	0,1,2		
							3	Al2O3 Improved	Yes	
		No	3/5 occurred	1,2	C Skull Reduced	0	C Skull 50%	NO	Consult Technical	
				3						
				4,5		1,2	C Skull 50%			
				6		3	Al2O3 Improved	Yes	C Skull 75%	
								No	Shouldn't Occur	
						4,5	Keep C Skull 75%			
						6	Al2O3 Improved	Yes	C Skull 100%	
								No	Shouldn't Occur	
				>=7	C Skull 100%					

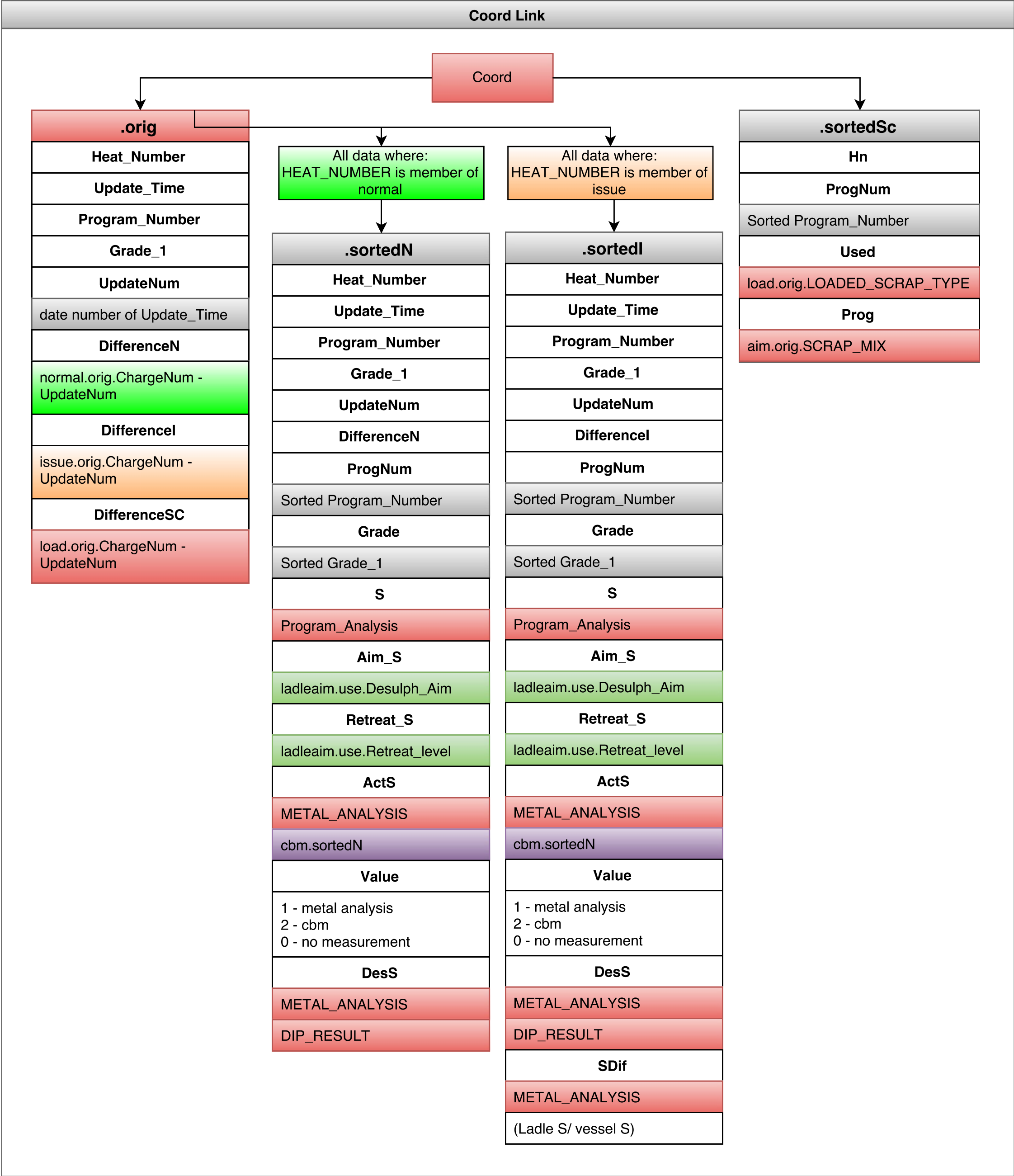
Appendix B

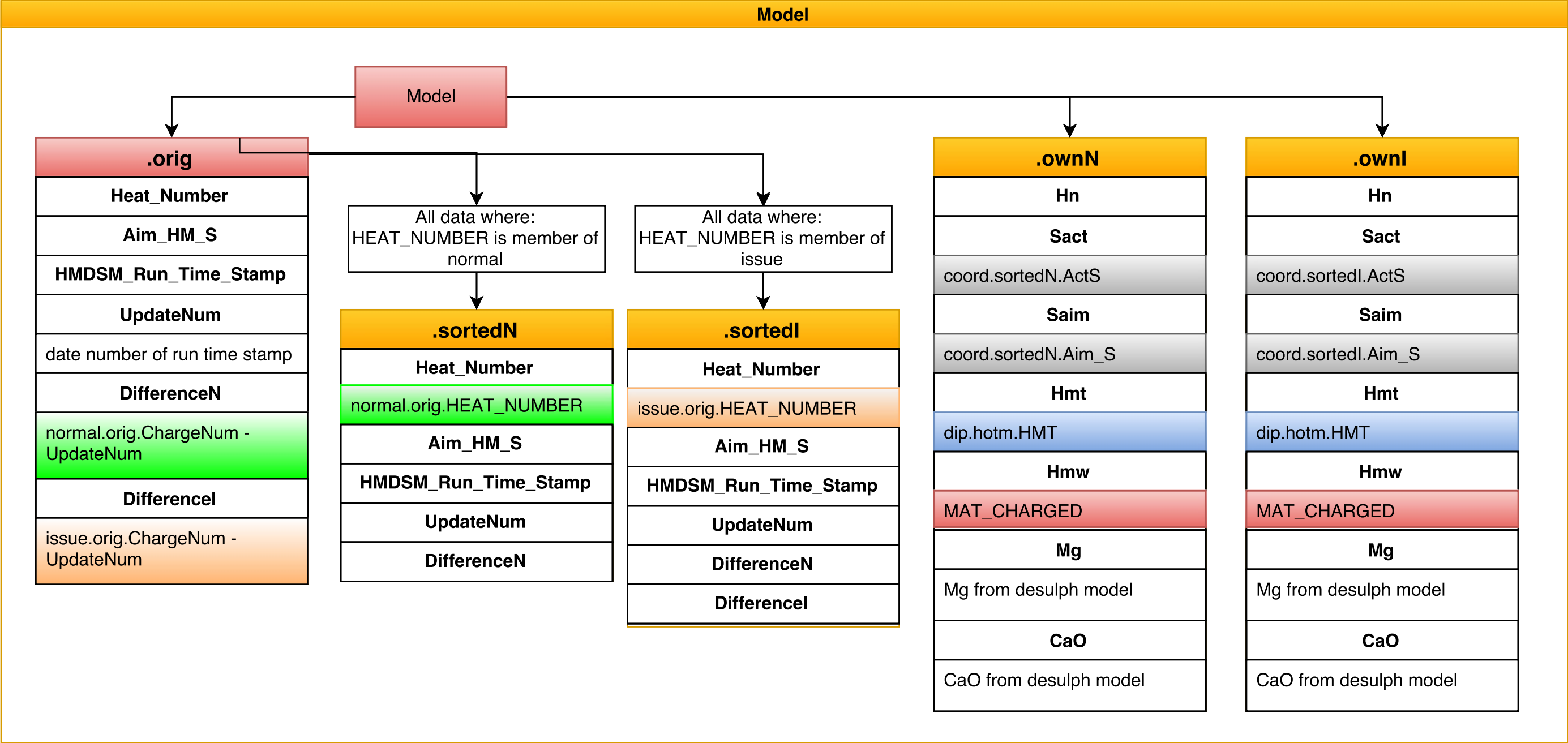
										Key	Question	
											No	
											Yes	
											No of Heats	
											System Output	
Sulphur	Above Ladle Max	Yes	Desulph Reduced	1,2	Desulph At 0%							
				3								
				4,5	Incin Reduced	0,1,2	Desulph, Incin 0%					
				6	Incin Reduced	0,1,2	Desulph, Incin 0%					
						3	Incin 100%, Desulph, Plate 0%					
				7,8								
				9	Plate Reduced	0,1,2	Desulph, Plate 0%					
						3	Consult Technical					
				0	Desulph To 0%							
	3/10 Near Misses	No	3/10 or max occurred	1,2	Desulph at 0%							
				3	Sulphur Improved	Yes	Desulph 50%					
						No	Incin Reduced				0,1,2	Desulph, Insin 0%
				4,5	Desulph at 50%	Yes	Desulph 50%					
						No	Incin Desulph 0%					
				6	Desulph At 50%	Yes	Sulphur Improved				Yes	Desulph 100%
									No	Reset Desulph		
						No	Incin Reduced				1,2	Incin 0%
									3	Sulphur Improved		
						Yes					Yes	Clean Out Scrap Bays
				No					No	Desulph 100%, Incin 50%		
										Incin 100% Plate 0%		
		7,8	Plate Reduced							0,1,2	Incin 100%, Plate 0%	
		9								3	Desulph 100%, Plate 50%	
											Clean Out Scrap bays	
		>=10	All scrap 100%									
		Yes	Desulph Reduced	1,2	Desulph At 0%							
				3	Sulphur Improved	Yes	Desulph 50% 3 Heats					
						No	Incin Reduced				0,1,2	Incin 0%
				4,5	Desulph At 50%	Yes	Desulph 50%					
						No	Incin Desulph 0%					
				6	Desulph At 50%	Yes	Sulphur Improved				Yes	Desulph 100%
								No	Reset Desulph			
						No	Incin Reduced				1,2	Incin 0%
								3	Sulphur Improved			
					Yes					Yes	Clean Out Scrap Bays	
					No					No	Desulph 100%, Incin 50%	
											Incin 100% Plate 0%	
		7,8	Plate Reduced							0,1,2	Incin 100%, Plate 0%	
		9								3	Sulphur Improved	
										Yes	Clean Out Scrap bays	
										No	Desulph 100%, Plate 50%	
		0	Desulph To 0%								Consult Technical	

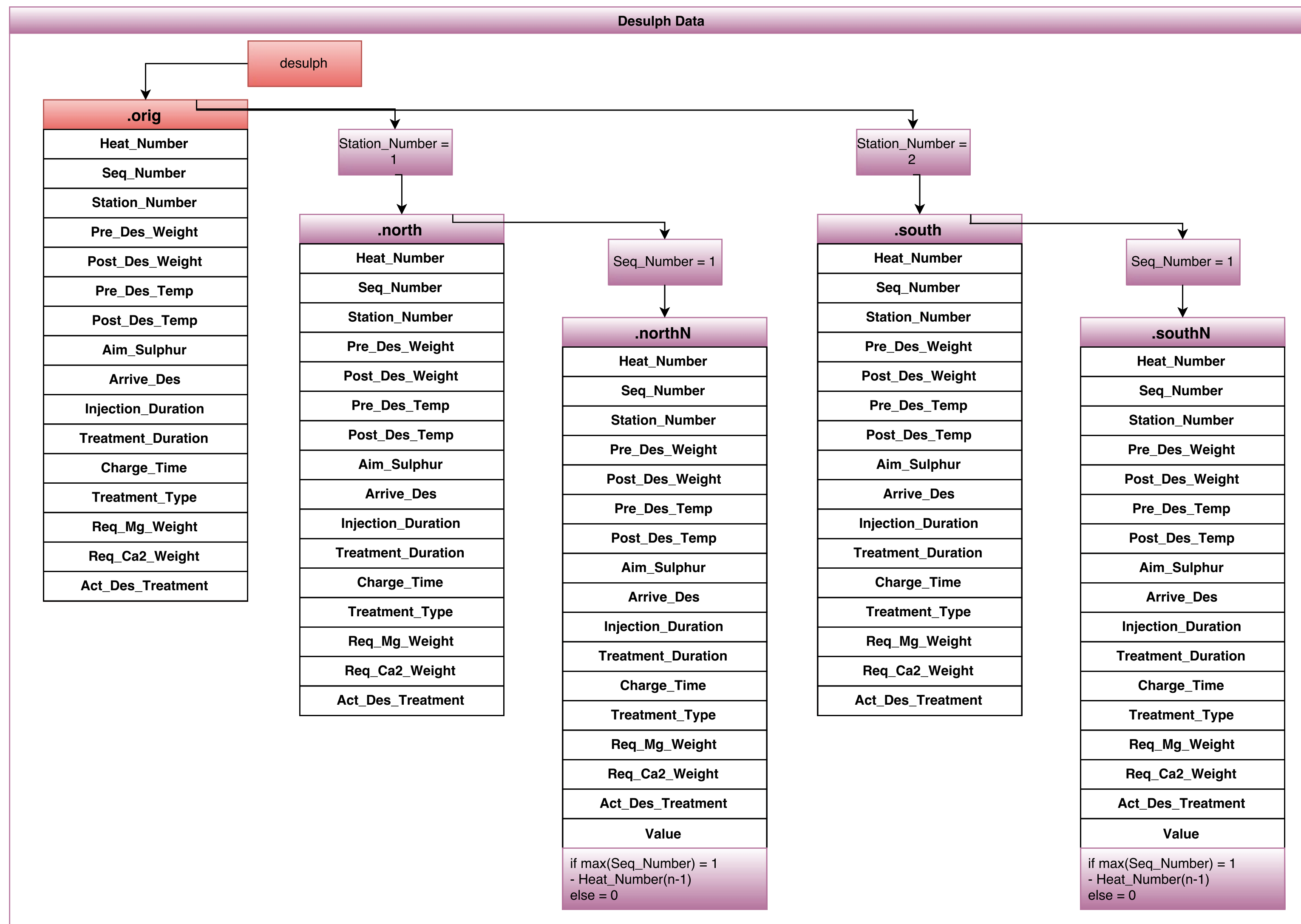


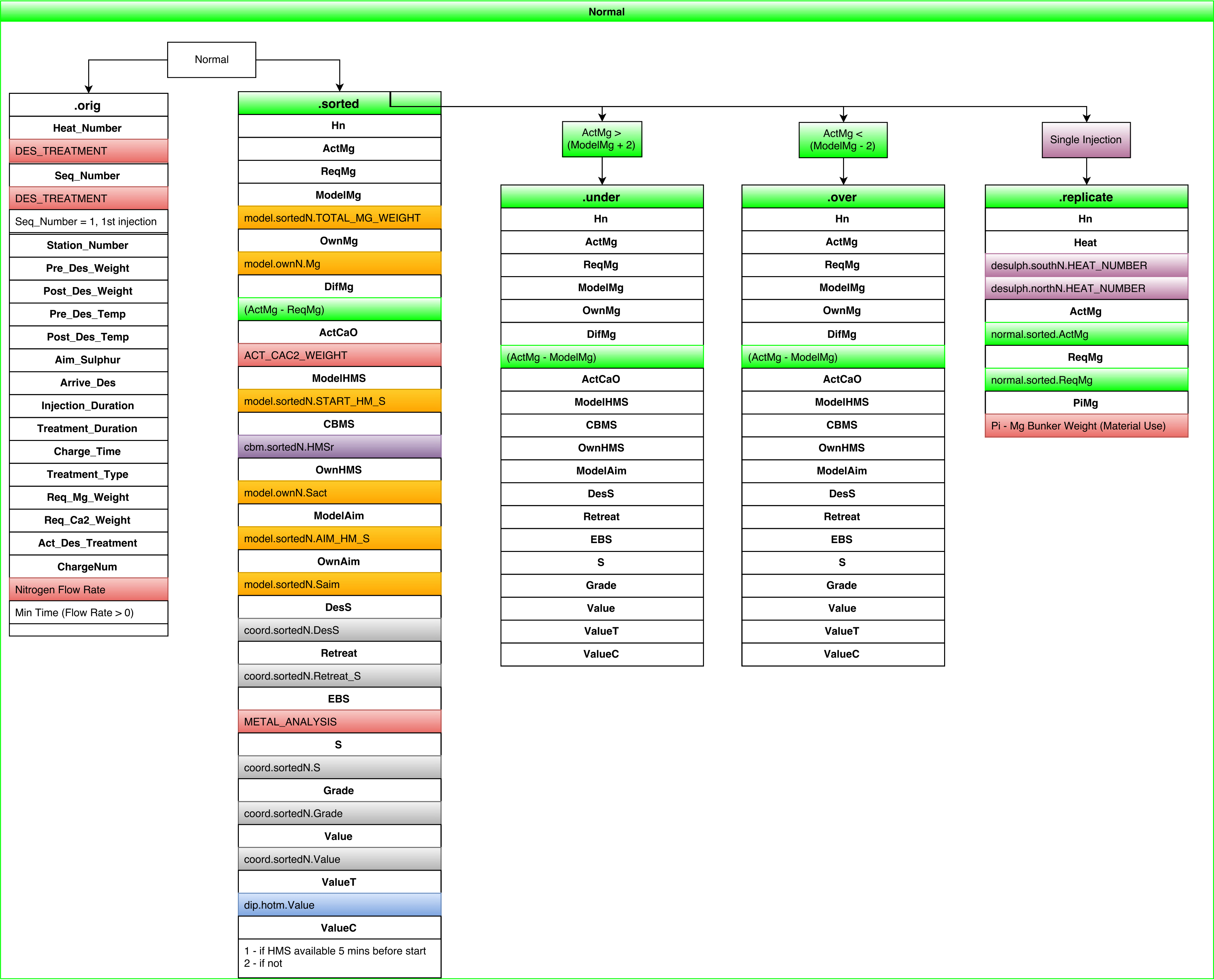




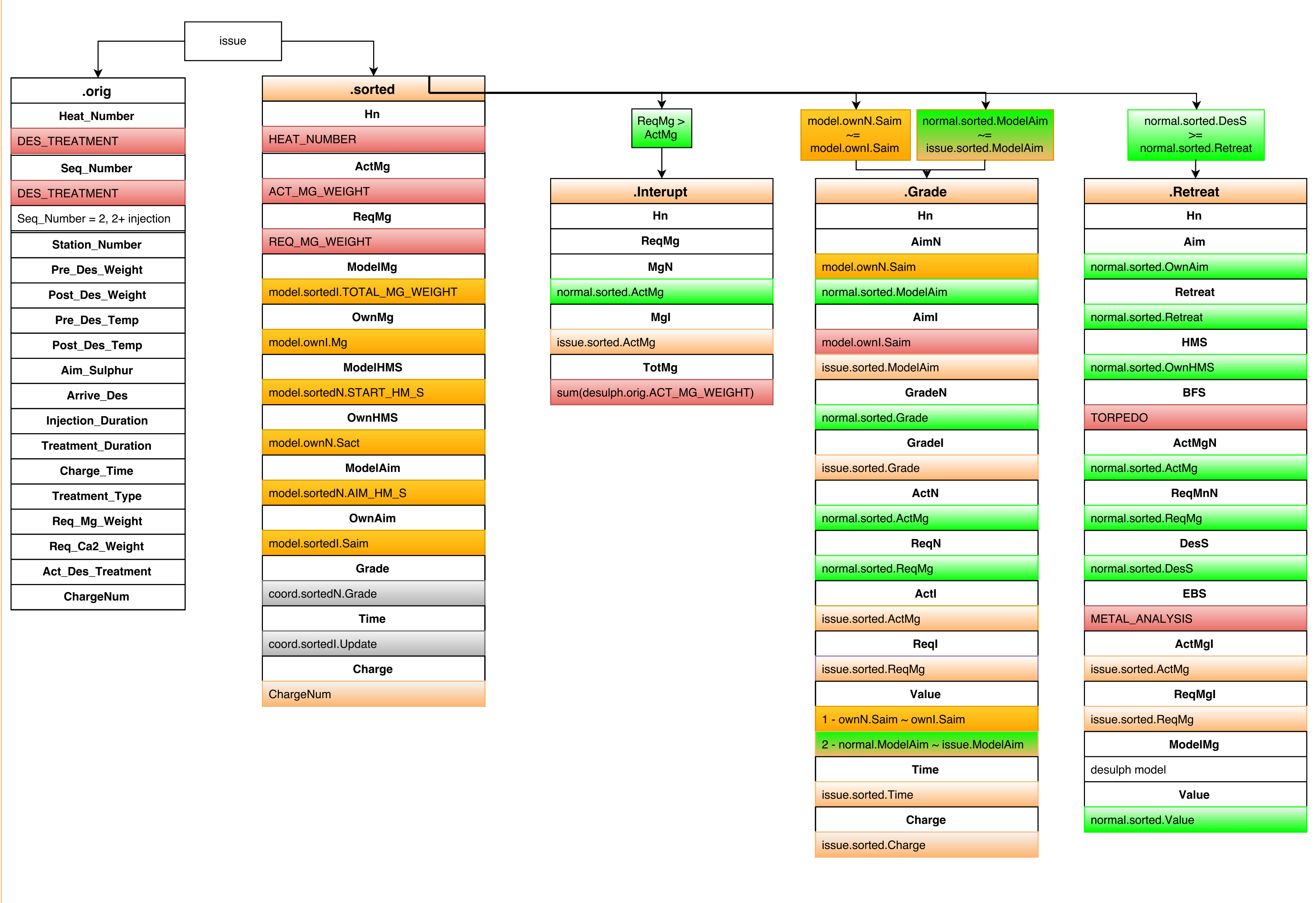






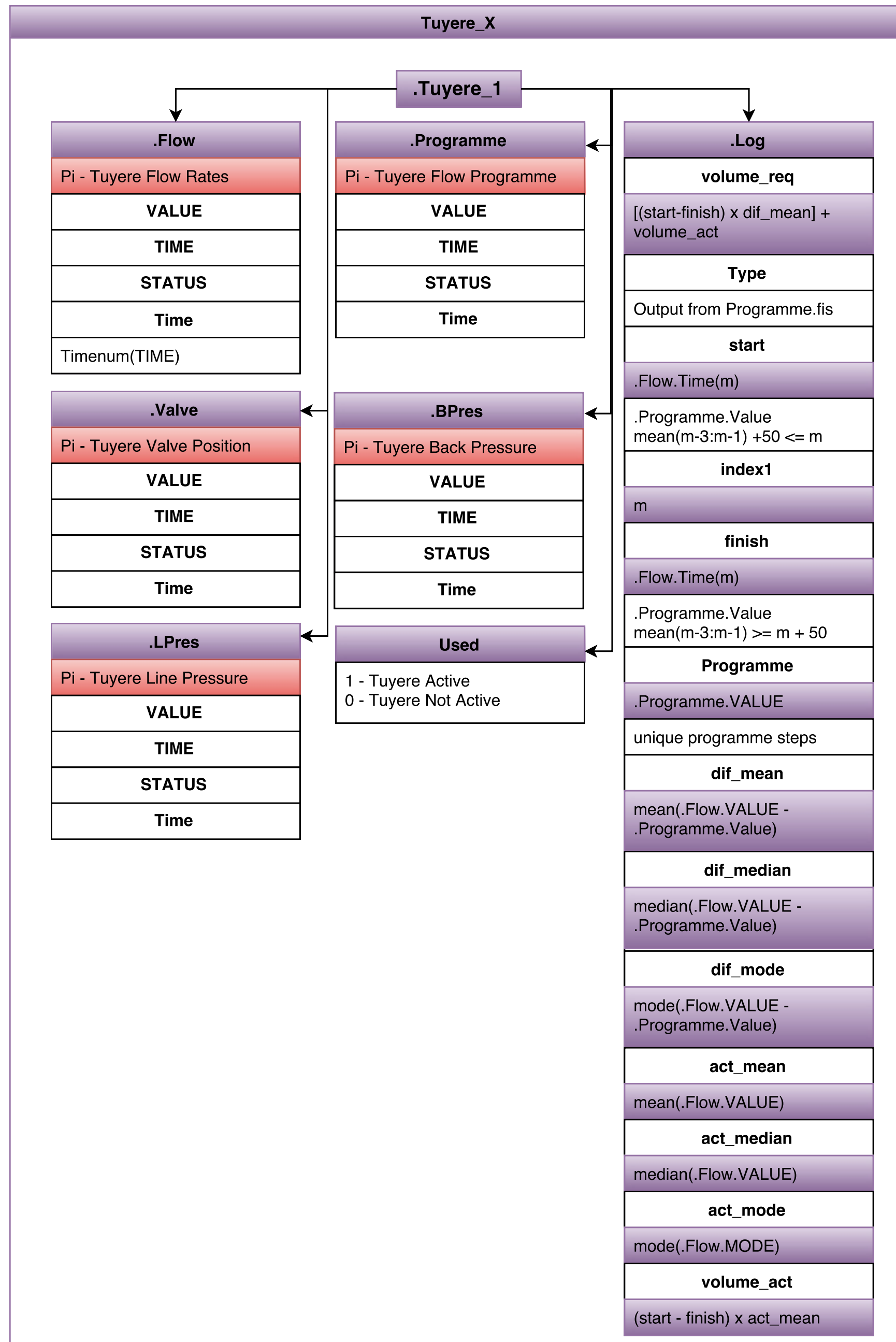


Multiple Treatments	
1	2
3	4
5	6
7	8
9	10
11	12
13	14
15	16
17	18
19	20
21	22
23	24
25	26
27	28
29	30
31	32
33	34
35	36
37	38
39	40
41	42
43	44
45	46
47	48
49	50
51	52
53	54
55	56
57	58
59	60
61	62
63	64
65	66
67	68
69	70
71	72
73	74
75	76
77	78
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87	88
89	90
91	92
93	94
95	96
97	98
99	100



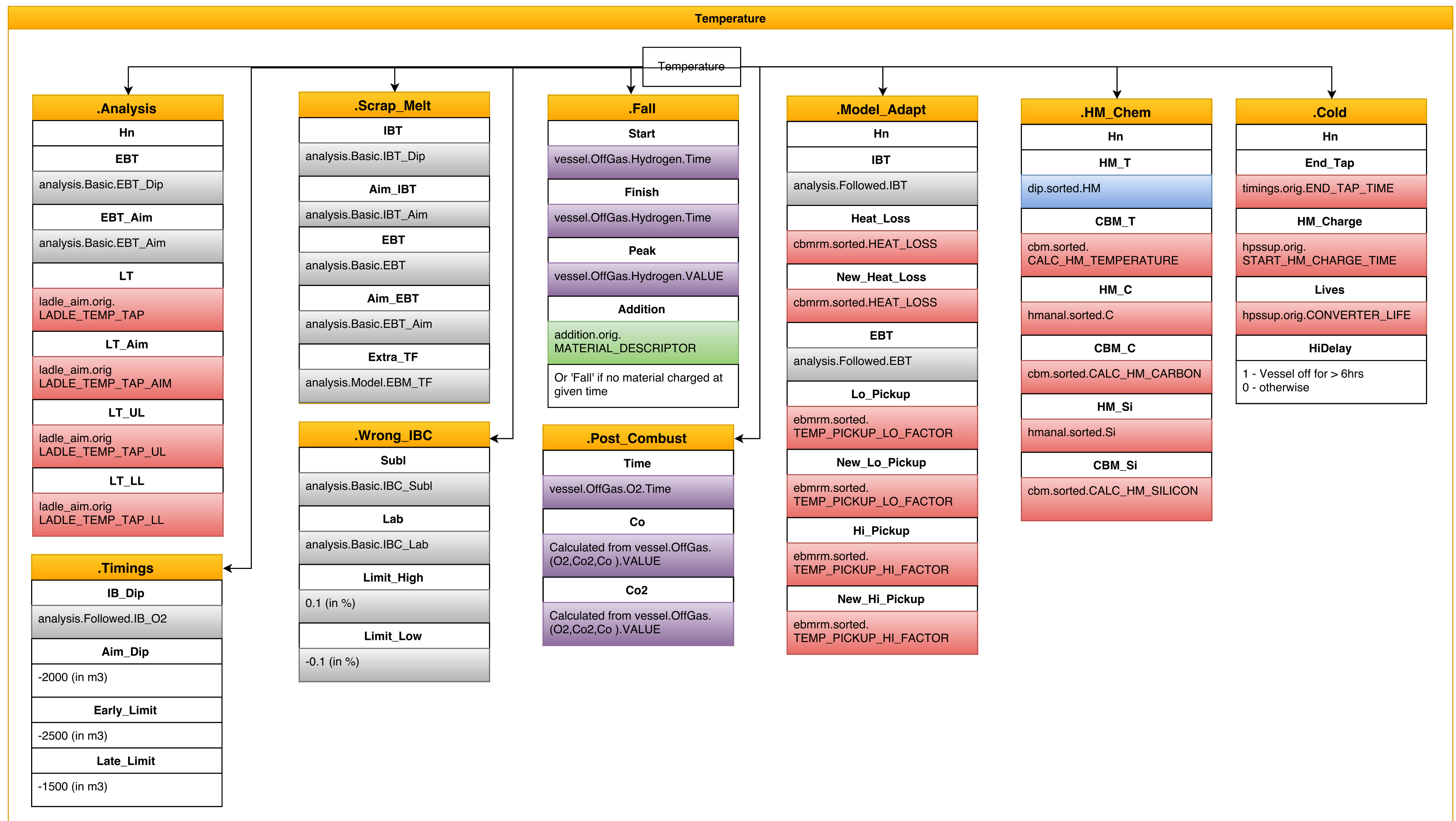
## Appendix E

Collection		
PSSUP	PSMET	Pi
HEAT_ALL_TIMES_VIEW	EXPERT_ADHERENCE	<b>Tuyere</b>
PSSUP1_LOGICAL	SUBL	Flow Rate
CBM_VESSEL_RM	META_ANALYSIS	Valve Position
HM_LADLE_TRIP	HEAT_PSSUP	Programme
EBM_VESSEL_RM	MAT_CHARGED	Back Pressure
	DIP_RESULT	Line Pressure
	CBM_DISPLAY_ANALYSIS	Argon/Nitrogen
	CBM_ADAPT_FACTORS	<b>Sub Lance</b>
	CRANE	Height Counter
	LG2_CONVERTERS	TSC Attached
	COORD_LINK	TSO Attached
	PROGRAM_ANALYSIS	Slew To Conn
	EBM_DISPLAY	Slew To Measure
	SLAG_ANALYSIS	Steel Temperature
	HEAT_BOSMET	Setpoint Height
		Actual Height
		<b>Off Gas Analysis</b>
		Hydrogen
		CO
		CO2
		O2
		<b>Oxygen Lance</b>
		Height
		O2 Flow
		O2 Used
		<b>Skirt</b>
		Skirt Height

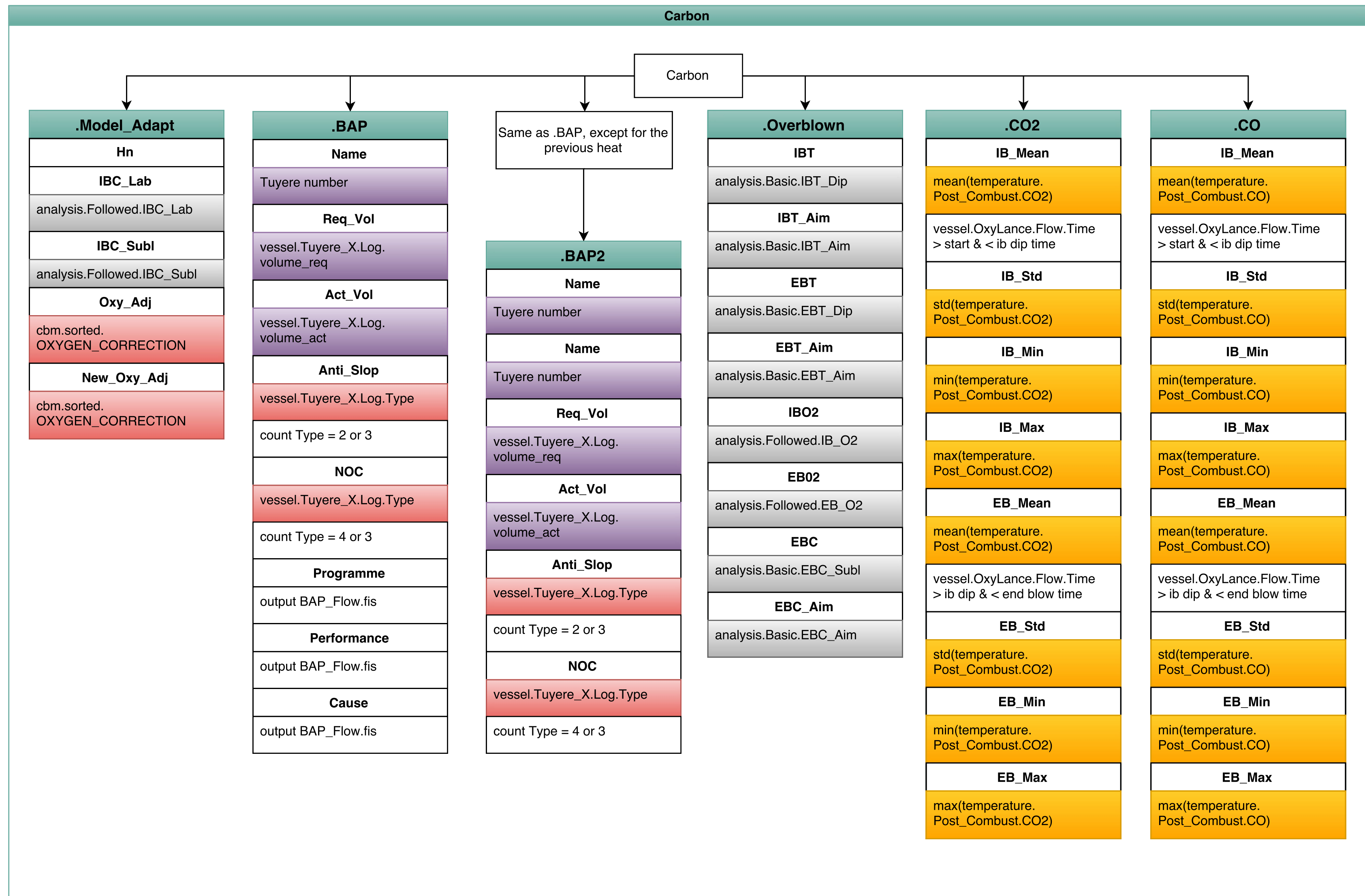












Appendix F

Hard / Soft Blowing

\*

P	O	H	H	O	H	H	O	O
Fe	O	O	H	H	H	O	H	O
Mn/C	O	O	O	O	H	H	H	H

L	L	O	L	L	O	O
O	L	L	L	O	L	O
O	O	O	L	L	L	L

- Up Up (P) Down Up (P) Up - -

- - - - - - -

\*

x

x

P	L	L	L
Fe	H	H	O
Mn/C	O	H	H

H	H	O
L	L	L
O	H	H

H	H	O
H	O	H
L	L	L

L	L	H
L	H	L
H	L	L

Down Down -

Up Up -

- Up Down - Down Up

unlikely

H High  
O Ordinary  
L Low

Start Date: 21/09/2016

OK

Model

Model Advice	Date / Time
27702, -6Kg Of Mg Requested, HMS Analysis Late, Start S Lowered From [0.028] To [0.027]	21/09/2016 07:37:44
27708, 78Kg Of Extra Mg Requested, Aim S Lowered From [0.012 To 0.003], Grade [3617]	21/09/2016 07:37:44
Cleaner Scrap Mix Used For This Heat At The Vessel	21/09/2016 07:37:44
27711, 42Kg Of Extra Mg Requested, BF S Estimate Used [0.042], Sample Available [0.032] At 03:53 Treated At 03:56	21/09/2016 07:37:44

Treatment

Treatment Advice	Date / Time
27703 Apparent Undertreatment, Injection Data Identical To 27701	21/09/2016 07:37:44
Pi Trace Indicates 0Kg Mg Used, For Required 156Kg	21/09/2016 07:37:44

Data Availability

Data Availability Advice	Date / Time
Poor Availability Of Desulph S Samples, Measured For 0 Of 21 Heats, Of Which 0 Had Desulph Temperature	21/09/2016 07:37:44
Poor Availability Of Desulph Temperature, Measured For 1 Of 21 Heats	21/09/2016 07:37:44