CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

This dissertation investigates the automation of manually controlled variables such as fan speed and slip-gap length for the Electric Arc Furnace (EAF) off-gas process. The two above-mentioned variables are part of the off-gas variable set. Automation of these variables may lead to higher efficiency and greater profit. The use of the off-gas variable set in an appropriate control structure is investigated. In order to do this investigation an appropriate process model of the EAF and off-gas system is necessary. The manipulated variables in this case are the forced-draught fan power and the air-entrainment slip-gap width. The possible controlled variables in the EAF are the relative pressure of the furnace gas-phase and the liquid metal temperature. Other variables that have to be controlled are the temperature and composition of the gas that exits the cooling duct.

EAFs produce steel by melting scrap typically using a three-phase electrical supply. By oxygen blowing the concentrations of primarily carbon and silicon can be lowered, while providing an additional energy source. This is important for the type of operation under study, where hot metal (high in carbon and silicon) is charged to the furnace together with scrap. Oxygen is typically blown into the metal bath through one or more side lances, or from the bottom. With the EAF in operation, the roof is closed, and off-gas is extracted through the duct entrance in the roof. Air is entrained at a slip-gap to combust the excess carbon monoxide (CO) and to cool the off-gas. The off-gas is also cooled by forced water and air cooling, before it enters the baghouse filters.

Statistics of a two-month period in 1997 [1] gave total world crude steel production as 121 million metric tons. This translates to worldwide crude steel production of 730 million metric tons for 1997. For the same period South Africa produced approximately 7.5 million metric tons, about 1% of world production. In 1997 approximately 60% of steel production were processed with Basic Oxygen Furnaces (BOFs), and 30% through EAFs [2]. The generally accepted view [2] is that EAFs are slowly but steadily replacing BOFs worldwide. While the steel production by BOFs declines, the steel production by both EAFs and Direct Reduced Iron (DRI) operations is on the increase. The increased use of EAF operations is partly due to the combined use of electrical and oxygen steelmaking in the modern EAF, and partly due to the increased recycling of steel scrap.

During the last decade the emphasis on the operation of EAFs shifted significantly. Not only is it required to operate more efficiently, but also the demand for environmentally friendly operation of EAFs is increasing. The future development of environmental legislation shows a trend towards lower emission limits [3]. EAFs are also increasingly used for scrap recycling.

According to Jones [4] productivity increases are directly related to the increased use of oxygen in the furnace, where the exothermic reaction energy replaces a large amount of the electric energy input. While it does allow significantly shorter tap-to-tap times, it leads to greater demand on the off-gas system. The off-gas system of an EAF not only plays an important role in environmental protection, it also influences the EAF operation strongly. It is used to extract and combust hazardous gases such as carbon monoxide, and influences the steelmaking process. In particular, the rate of gas extraction has a direct influence on the furnace pressure, thus affecting air entrainment, and hence process energy requirement and nitrogen pick-up [5].

1.2 MOTIVATION

In order to investigate the use of the off-gas variable set in an appropriate control structure an appropriate process model of the EAF and off-gas system is necessary. There are only limited references to dynamic EAF models in the literature, as many such models tend to be proprietary. For example Petersohn *et al* [6] derived a dynamic EAF model based on mass and energy balances. They show what the principal measurement points required by a comprehensive model are. The models used in this dissertation were partly developed in Bekker, Craig and Pistorius [7,8].

Other projects on EAF control have focused mainly on electrode control. Reuter *et al* [9] discussed the impedance-based electrode control of submerged arc furnaces. The EAF type considered in this dissertation is of the open-arc type, and current-control is usually applied on this type of EAF. King and Nyman [10] show how neural networks can be used to control the electrode voltages and currents of a single-phase arc furnace. In this dissertation the assumption is made that proper control of the electrical circuits of the electrodes is in place. The choice of control structure for this dissertation stems from an indication, given by a process expert, that the gas pressure in the EAF was not well regulated, which caused several problems. For gas pressure and composition control the off-gas variable set was chosen as the manipulated variables in the control structure.

The control method that was selected for this project is Model Predictive Control (MPC) [11]. The MPC control strategy results from the optimisation of a performance index with respect to a future control sequence, using predictions of the output signals based on an internal process model. An optimisation algorithm is applied to compute a sequence of future control signals that minimises the performance index subject to the given constraints. According to Morari and Ricker [12] MPC displays it main strength when applied to problems with:

- A large number of manipulated and controlled variables;
- Constraints imposed on the manipulated variables;
- Changing control objectives or equipment failures.

1.3 CONTRIBUTION

The main contribution of this dissertation is to demonstrate the feasibility of using the off-gas variables for EAF process control. To do this, the following contributory steps are given:

- Development and combination of models for the off-gas system and EAF processes;
- Verification of these models with the limited plant data available;
- Linearisation of the plant model to obtain the internal model for the controller;
- Initial controller design and time domain analysis for the linearised model;
- Implementation and fine-tuning of the controller on the verified plant model;
- Evaluation of the closed loop performance with respect to the objectives.

Since many unsteady-state models are proprietary, they are not published in the literature. There are a few exceptions [7,13], which give partial model derivations for EAF processes. The model derived in this dissertation, and the publication of it, is therefore seen as an important contribution to the literature. The application of MPC to such a process is also seen as a relevant contribution.

The contributory steps that are listed above follow the guidelines of the General Control Problem (GCP) [14]. Fig.1.1 gives a graphical representation of the GCP as applied in this project.

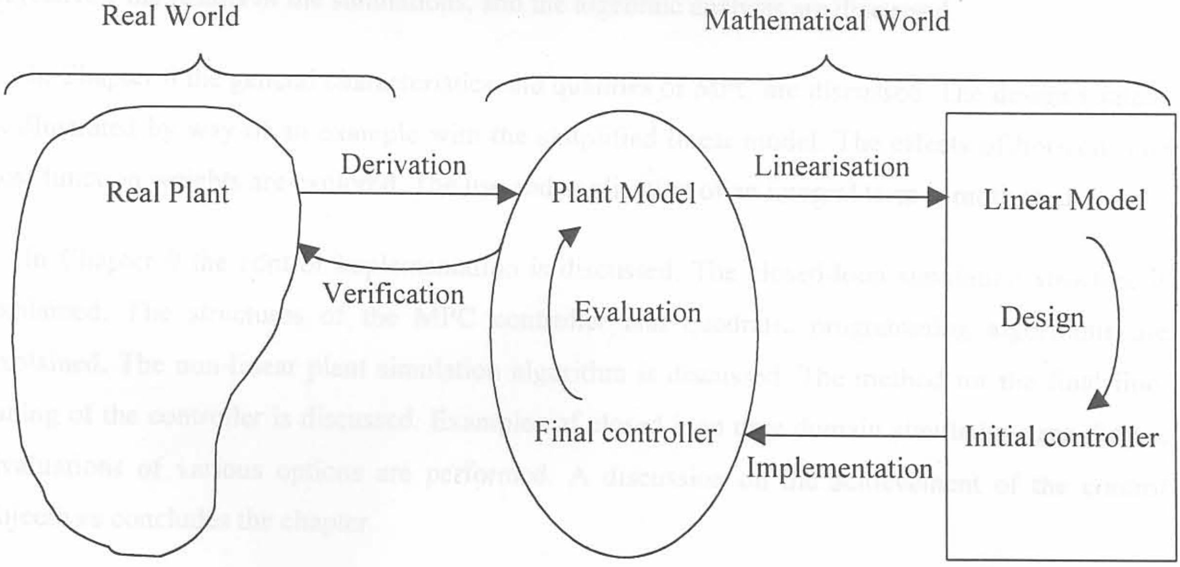

Figure 1.1 General Control Problem applied in this dissertation

1.4 ORGANISATION

In Chapter 2 a technical overview of the EAF process is given. The approach followed in this dissertation is briefly outlined, and the format of the project and its components are discussed.

Chapter 3 contains the derivation of the non-linear EAF plant model. The assumptions and approximations made to derive the EAF model are discussed. The incorporation of the off-gas model into the EAF model is shown. In Chapter 4 the off-gas model derivation is shown. The assumptions and approximations made to derive the off-gas model are given.

Chapter 5 discusses a time simulation of a specific EAF tap. The process conditions that correspond to a set of measured data are discussed. A disturbance model in terms of process conditions is developed. A time simulation with the combined non-linear model is shown. Model adjustment to correspond with the available data by means of parameter adjustment is discussed.

In Chapter 6 the linearisation of the plant model is shown. The approximations to derive the simplified linear state space model are discussed. An example of time simulation with the linear model is shown. The response of the linear model is compared to that of the non-linear model.

Chapter 7 discusses the control objectives in terms of EAF and off-gas parameters. An algebraic analysis of the linear system is given. The control specification, which results from the control objectives, the results of the simulations, and the algebraic analysis are discussed.

In Chapter 8 the general characteristics and qualities of MPC are discussed. The design strategy is illustrated by way of an example with the simplified linear model. The effects of horizons and cost function weights are explored. The use and application of an integral term is motivated.

In Chapter 9 the control implementation is discussed. The closed-loop simulation structure is explained. The structures of the MPC controller and quadratic programming algorithms are explained. The non-linear plant simulation algorithm is discussed. The method for the final fine-tuning of the controller is discussed. Examples of closed loop time domain simulations are shown. Evaluations of various options are performed. A discussion on the achievement of the control objectives concludes the chapter.

Chapter 10 contains a summary of the contents of the dissertation. Finally, a conclusion and recommendations are given.