CHAPTER 1: INTRODUCTION.

1.1. MOTIVATION.

A worldwide tendency of Basic Oxygen Furnaces (BOFs) being replaced by Electric Arc Furnaces (EAFs) is increasingly experienced in industry. In 1994 EAFs contributed approximately 31.6% to the worldwide steel production, and this figure is expected to rise to 40% by 2010 [1]. The major portion of EAF control is however commonly performed manually, and the efficiency is often highly dependent on operator experience. Large potential benefits exist in the efficient automation of the complete EAF steelmaking process, and in optimising EAF efficiency.

The potential economic benefits of implementing an advanced control strategy on an EAF are investigated in this dissertation by means of a simulation study. The harsh conditions in which EAFs are typically operated, and the accompanying lack of accurate measurements are a major drawback in implementing efficient feedback control schemes. Implementation of a model based control scheme e.g. Model Predictive Control (MPC) has the advantage that unmeasured variables can be estimated by an internal model. Some sub-systems of EAFs for which measurements are readily available or easily derived are commonly controlled, e.g. the positioning of electrodes. Static furnace models are also used extensively to calculate optimal feed additions to furnaces. None of these techniques however account for the high amplitudes of disturbances that typically act on the EAF, the optimisation of the complete EAF steelmaking process or the time dependence of some critical variables.

Steel producers are often required to aim at producing steel of a much higher quality than specified, in order to ensure that all specifications are met in the presence of disturbances. A controller capable of reducing product variations attributable to disturbances would thus increase profit, as expenses in improving steel quality beyond specifications will be reduced considerably. A simulation study incorporating typical disturbances and common EAF operating conditions would provide a useful guide in estimating the feasibility of implementing advanced control schemes on the increasing number of EAFs.

1.2. BACKGROUND.

A large portion of the work done on EAF control focussed on control of subsystems of the furnace, e.g. the electrical system. Position control of electrodes has been a research topic for quite some time. Reuter *et al.* [2] discussed the impedance-based electrode control of submerged arc furnaces. Akimoto *et al.* [3] discussed an optimisation strategy to utilise the available energy sources in the steel works optimally. Chirattananon and Gao [4] described the usage of an energy model of an EAF in determining optimal electrical inputs to the EAF. All of these strategies aim to reduce the energy usage of the EAF or the complete melt shop. The electrical power used by EAFs however accounts only for approximately 10.5% of the total cost of carbon steel production [5], and only a fraction of the total cost of EAF operation is thus influenced by these automatic control schemes.

Bekker, Craig and Pistorius [6] performed a functional evaluation on the control of an EAF off-gas system in a simulated environment. It was found that the off-gas system could potentially be used to improve furnace efficiency and to provide a safer workplace. The off-gas system also serves an important purpose in ensuring that environmental regulations are met. Although many advantages of improved off-gas control do not have large direct economic benefits, the indirect benefits are significant enough to justify inclusion of the off-gas system in the control of EAFs.

Another popular approach is the use of static furnace models to predict the optimal feed additions to the furnace. De Vos [7] developed a static furnace model to calculate the optimal flux additions to an EAF. All calculations are done prior to furnace operation and are not adjusted during a tap. Juuso and Uronen [8] presented a simulation study to optimise production alternatives for a ferroalloy process including an EAF. Deterministic steady state models are used to do predictions, but optimisation is done only at the design stage, and not real time.

For processes with non-linear performance functions or constraints, Bawden and MacLeod [9] showed that a decrease in product variations would increase profit. The performance function of an EAF would consist of the cost of the tap as a function of feed material consumption and of reaching control objectives. Since constraints exist on some of the control objectives and the EAF objective function is mostly non-linear (see Chapter 3), a reduction in product variations would most likely reduce EAF operating cost.

1.3. PROBLEM STATEMENT.

The problem statement consists of four parts:

- Identify the factors contributing to the cost of EAF steelmaking.
- Expand the existing EAF model to ensure that the cost of EAF steelmaking can be modelled accurately.
- Design a controller to minimise the cost of EAF steelmaking.
- Evaluate the efficiency of the control strategy under typical operating conditions.

1.4. CONTRIBUTION.

The EAF model presented by Bekker [6] was used as a basis for the simulation study. Viljoen [10] improved the Bekker model by improving the accuracy of the off-gas temperature model. An additional modelling effort was undertaken to model the slag foam depth inside the EAF, as described in Chapter 2. The slag foam depth is a useful variable in ensuring efficient energy transfer to the melt.

The design procedure of an MPC controller based on economic objectives is discussed in Chapter 5. Although the principle is not new, control objectives are usually based on functional specifications, or on setpoints that proved to be effective in previous control efforts. The transformation of functional control objectives into economic objectives are discussed in Chapter 4 and would ensure that steel of a required quality is produced in an economically optimal way. De Vos [7] reported significant savings using a static furnace model to optimise flux additions to the EAF. It is expected that savings can be increased further, by using a dynamic EAF model and an appropriate MPC controller (utilizing real time feedback and predictions) to reduce EAF operational cost.

Simulation studies are often performed as a preliminary step in controller evaluation, and the accuracy of the simulation model is often limited. The focus of the simulation study conducted in following chapters is to ensure that typical disturbances are modelled, that feedback is only used continuously if the variables are measured continuously, and that unrealistic requirements are not placed on the simulated controller.

The comparison of two controllers is often performed in an inappropriate way, leading to invalid conclusions or statistically insignificant results. A framework for experimental design is presented that ensures that useful data is generated, and the complete evaluation strategy is based on these principles. The complete simulation study thus presents a framework that will help to motivate automation of EAFs.

1.5. DISSERTATION APPROACH.

The logical flow of actions undertaken during the dissertation is depicted in Figure 1.1. A discussion of the actions shown in the figure follows.

The additional modelling effort comprises the slag foam depth model described in Chapter 2. The comprehensive EAF model thus consists of the Bekker model [6], the revised off-gas temperature model by Viljoen [10] and the slag foam depth model by Oosthuizen *et al.* [11].

The closed loop simulation is a preliminary step in ensuring that the MPC controller based on economic objectives meets all functional objectives. A detailed analysis of the economic implications is done in the economic evaluation section.

A comparison of the EAF under manual and MPC control in a noisy environment is done in Chapter 7 as an economic evaluation. Proper testing strategies are utilised to ensure that unbiased results are obtained and statistical significant data are generated. The overall profitability of the EAF is considered, as well as reaching the functional specifications.

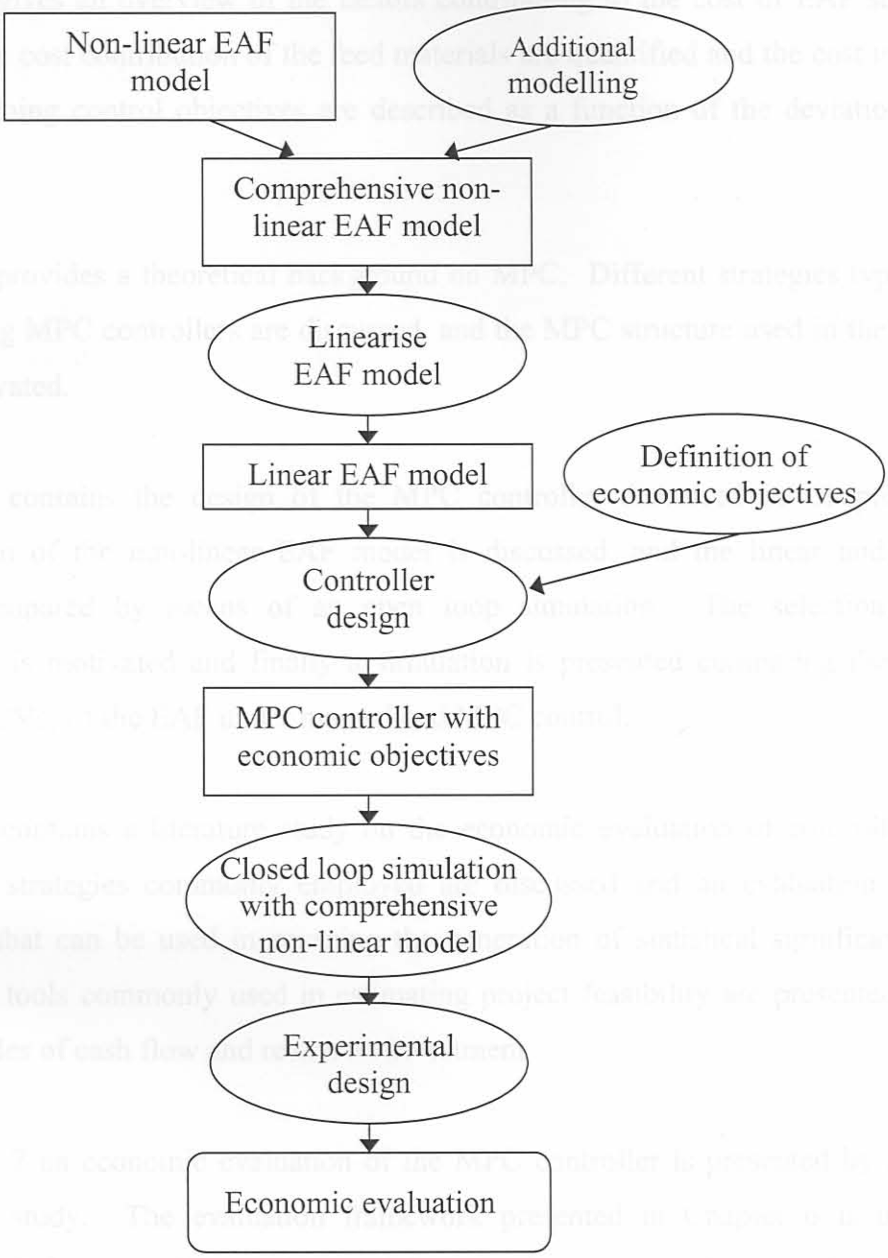

Figure 1.1. Logical flow of actions.

1.5. ORGANISATION.

In Chapter 2 a technical overview of the EAF process and simulation model is given. Control objectives typically used in industry are discussed, and the control objectives for the simulation study are motivated. The modelling of the slag foam depth is also described in this chapter.

Chapter 3 gives an overview of the factors contributing to the cost of EAF steelmaking. The relative cost contribution of the feed materials are quantified and the cost implications of not reaching control objectives are described as a function of the deviation from the setpoints.

Chapter 4 provides a theoretical background on MPC. Different strategies typically used in designing MPC controllers are discussed, and the MPC structure used in the simulation study motivated.

Chapter 5 contains the design of the MPC controller discussed in Chapter 4. The linearisation of the non-linear EAF model is discussed, and the linear and non-linear models compared by means of an open loop simulation. The selection of tuning parameters is motivated and finally a simulation is presented comparing the controlled variables (CVs) of the EAF under manual and MPC control.

Chapter 6 contains a literature study on the economic evaluation of controllers. Some evaluation strategies commonly employed are discussed and an evaluation framework presented that can be used in ensuring the generation of statistical significant data. A number of tools commonly used in estimating project feasibility are presented, based on the principles of cash flow and return on investment.

In Chapter 7 an economic evaluation of the MPC controller is presented by means of a simulation study. The evaluation framework presented in Chapter 6 is used in the experimental design and execution, and hypothesis testing is done to determine if the economic benefits predicted by the simulation study are statistically significant.

Chapter 9 contains a summary of the dissertation contents. Conclusions are made regarding the economic feasibility of advanced control of an EAF, and recommendations are made regarding further work.