THE MODELLING AND OPTIMISATION OF AGGREGATE PLANTS, AND THE USE OF THE APOLLO COMPUTER PROGRAM

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A project report submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the Degree of Master of Science in Engineering.

Johannesburg, 1986

For my wife

Dawn

ABSTRACT

This report is concerned, in general, with the mathematical modelling and optimisation of aggregate plants. In particular, the report describes the use and application of a computer-based model, Apollo, which can aid in determining the most cost-effective way of operating an aggregate plant. To provide the necessary background for the reader to consider the Apollo model in perspective, various mathematical models of the two main components of aggregate processing circuits, namely crushers and screens, are described in detail, and a general linear model of a circuit is developed from first principles. The optimisation of aggregate plants using linear programming is also discussed, this being the technique used in the Apollo model. The report provides a detailed description and explanation of the steps that are taken to set up an Apollo model of a plant, and examples and a case study, illustrating the application of the model, are given. In describing the steps taken in applying the Apollo model and what can be done with it, attention is given to the managerial, engineering and cost-accounting problems that are encountered in implementing such mathematical models in an industrial environment, and much of what is described in this regard may be of value to persons using other process models.

DECLARATION

I declare that this project report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

21 st day of October 1986

PREFACE

The Apollo model, which is essentially what this report is all about, is not my creation. It was originally conceived in 1975 by David Bon of Holderbank Management and Consulting Limited (Switzerland), who considered that an aggregate circuit was mathematically similar to an hydraulic one, with material "flowing" along different paths between connecting "nodes". The person responsible for setting up the model, and for writing the source code of the original computer program, is Dr Hans-Jakob Tobler, an outside consultant to Holderbank. My first contact with the program was in 1982, when an early version of the program was acquired by the company for which I worked, Hippo Quarries Limited (a wholly-owned subsidiary of Anglo-Alpha Limited, Holderbank being the major shareholder of Anglo-Alpha).

I was given the project of co-ordinating the implementation of the program at the 21 Hippo plants, and to this end was involved in the setting up and running of a number of one-day seminars to train the plant managers, and others, in the use of Apollo. By the end of 1984, the Apollo program had been implemented at most of the larger Hippo plants, the modeller in most cases being myself.

The version acquired by Hippo was written in Fortran and ran on a Siemens BS2000 mainframe computer. It was not user-friendly, a problem complicated by the fact that no user manual had ever been written for the program (one of my first tasks when Hippo acquired the program was to learn how to use the program and to write such a manual).

In mid 1984, I was seconded to Switzerland to assist with re-writing the program to run on an IBM PC personal computer. The source code of the new, improved version was written in Pascal, again by Dr Tobler, the author of the source code of the original version. My role in this project was as follows:

- design of the user interface (design of the control menus and design of the input-data screen formats)
- ensuring user-friendliness and simplicity of operation
- program testing and de-bugging
- writing of the DOS set-up routines and driver programs
- writing of the instruction manuals for Apollo (essentially an expanded update of the manual that I wrote in 1982 when Hippo acquired the program, incorporating all the experience and knowledge that I had gained in the subsequent two years)

The instruction manuals that I wrote in Switzerland make up a sizeable part of this report: Chapters 7 and 8 are based on the Apollo Modelling Manual, which describes how to model an aggregate plant using Apollo; and the Appendix is an almost word-for-word copy of the Apollo Operating Manual, which describes how to run the Apollo program on the IBM PC personal computer.

Chapter 9, which is a detailed case-study illustrating a typical application of Apollo, is a condensed account of an actual study that I undertook for Hippo Quarries in 1985.

The report also includes, in some detail, an extract from my undergraduate research project (1980), which was concerned with an investigation into the parameters that influence the output of a crusher and the development of a mathematical description of an aggregate-processing circuit. In retrospect, the circuit model was somewhat clumsy, but the empirical relationships that I developed to describe the output of a crusher are useful, in that they provide valuable insights about the crushing event, and have accordingly been included in this report, albeit in somewhat revised form (Section 3.2).

For similar reasons, I have taken the liberty of including a detailed description of Whiten's (1972) model of a cone crusher (Section 3.3). In this regard it should be noted that the illustrated example and the graphic representatives of Whiten's relationships were developed by myself.

Needless to say, this report reflects the ideas and philosophies of a number of people who have influenced me and whom I wish to acknowledge and thank:

- Mr Andy Kok, who was my superior in the Hippo Management Services Department, where I worked until the beginning of 1985, and who provided me with so much guidance and support.

- Mr Peter Kessler, of Holderbank, who, together with Andy Kok and myself, co-presented a paper on Apollo at the Fifth Holderbank Stone and Readymix Conference, in Lucerne, Switzerland, in 1983, and who originally introduced me to the Apollo model when it was acquired by Hippo.

- Mr Frank Fiore, of Anglo-Alpha, whose philosophy regarding the implementation of process models and the interaction of 'models and managers' is reflected in this report.

- Mr David Bon of Holderbank, who originally conceived the program.

- Dr Hans-Jakob Tobler, for whom no programming task on the IBM PC was too difficult, and who is such a master of the machine that he could, if asked, probably make it fly!

Other people that I wish to thank:

- Miss Donne Gebhard, who typed this report, and who remained unruffled through all my revisions and Oscar Wilde impersonations ("this morning I put in a comma and this afternoon I took it out again!").

- My wife, Dawn, especially, who gave me so much support and encouragement and who proof-read each chapter and provided valuable advice and criticism regarding the content and style of the report.

- My supervisor, Professor John Bicheno, head of the Industrial Engineering Department at the University of the Witwatersrand, for always being available for consultation and guidance (and, especially, for his patience!).

In closing, I could not resist adding the following quotation, which, although somewhat cynical, is probably worth keeping in mind:

"A theory has only the alternative of being right or wrong. A model has a third possibility--it may be right, but irrelevent".
Manfred Eigen, German Scientist.

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CHAPTER 1

INTRODUCTION

Aggregate plants produce the vast quantities of crushed stone used each year for concrete and road-making in the construction industry. In many countries of the world, gravel pits exist where alluvial stones of various sizes can be dug. These then only require some crushing and sorting into correct sizes. However, very few acceptable gravel pits exist in this country, and stone is generally quarried from large open-cast pits, the rock then being crushed and screened into various product sizes.

Crushing plants thus consist primarily of an ordered array of crushers, screens and stockpiles, linked by means of conveyor belts and chutes. The flow diagram of a typical plant, including primary, secondary and tertiary crushers, as well as a sand plant, is shown in Figure 1.1, located at the end of the chapter. The plant, Eikenhof, is one of a number of rock quarries operated by Anglo Alpha Ltd through its subsidiary Hippo Quarries Ltd, the largest producer of aggregates in South Africa.

The primary objective in any operation is to satisfy market demand in the most economic manner. The objective can be expressed in monetary terms as the maximisation of **marginal income**, that is, **sales revenues**, less the sum of the following costs:

- costs of **raw material**
- costs of processing (**crushing and screening**)
- costs due to imbalances between production and sales, i.e.:
  - costs due to **dumping** of surplus products
  - costs due to **running short** of saleable products.

The cost components of the objective indicate the importance of running the plant in a manner that best balances production and demand. An imbalance means costly surpluses of unsaleable sizes and/or shortages of popular products.

There are, of course, a large number of factors which affect the output of a plant and its operating costs, and an experienced operator will readily recognise the significance in the process of the following variables which are under his direct control:

- raw-material size-grading (determined by quarry blasting parameters)
- crusher settings (affecting product size-distributions and crusher capacities)
- screen apertures
- choices regarding how material should be routed in the plant.

Determining the optimum combination of these variables does, however, present an almost impossible task, as even on an average-size plant there exist a large number of choices. And, as with most complex processing systems, optimising any single part does not necessarily optimise the overall system and may, in fact, work to its detriment.

A scientific analysis of material flows, in order to determine the optimum plant-configuration, is usually avoided because of the complex and time-consuming calculations required. Management tends to rely on experience, gut, and just plain trial and error, with the result that the operational configuration of an aggregate plant is often far from the economic optimum.

What was needed, then, was a tool which could:

- calculate the tonnages of material flowing through a given plant circuit, and the amounts of each product produced

- given flexibility in the plant circuit, determine the best routing of material through the circuit, in order to satisfy demand most economically.

Motivated by this need, the computer program, 'Kies', was developed in 1975 by Holderbank Management and Consulting Ltd of Switzerland, the major shareholder in Anglo Alpha Ltd. The program was somewhat crude in application: it was designed as a typical batch program, with data entered by a card reader, and it had to be re-developed for each aggregate plant under consideration.

The latest, completely redesigned version of the program is known as 'Apollo', the name being a loose acronym of **A**ggregate **P**lant **O**pti-misation. It was developed jointly by Dr H Tobler, an outside consultant to Holderbank, and myself. The program runs on an IBM PC personal computer and was made commercially available in 1984. Its design reflects a high level of user-friendliness and flexibility - the program can model almost any aggregate-processing plant. At the date of writing, it represents the state of the art as a "fully-operational computerised static model of an aggregate plant" (Pfohl, 1984).

The remaining chapters are not only concerned with Apollo, however. Apollo is presented against the background of two broad themes, namely, the mathematical **modelling** and **optimisation** of aggregate plants. In other words, before dealing with Apollo, a number of chapters are devoted to these two general themes, in order to allow the reader to consider Apollo in perspective.

Firstly, the mathematical modelling of aggregate circuits is dealt with: In Chapter 2, the reader is introduced to the fundamentals of plant modelling, and in the next two chapters, various mathematical models of the two main components of aggregate circuits, namely, crushers and screens, are discussed. In Chapter 5, these components are incorporated into a general model of a circuit. Using this model, the tonnages flowing in any given circuit, and the amounts of each product made, can be calculated.

Chapter 6 is concerned with the second theme, namely, the economic optimisation of aggregate plants, the aim being to satisfy market demand in the most economic manner.

The Apollo model, which incorporates both these themes into one model, is discussed in detail in Chapter 7, and more advanced Apollo-modelling techniques are described in Chapter 8. A case study of an Apollo application at Eikenhof is given in Chapter 9.

Complete instructions for operating the Apollo computer program on the IBM PC personal computer are given in the Appendix.

A series of photographs showing various aspects of aggregate processing are included in pages 6 to 10. These photographs, which may be of use to the reader who is unfamiliar with aggregate processing, were taken at the Jukskei Quarry, situated north of Johannesburg.

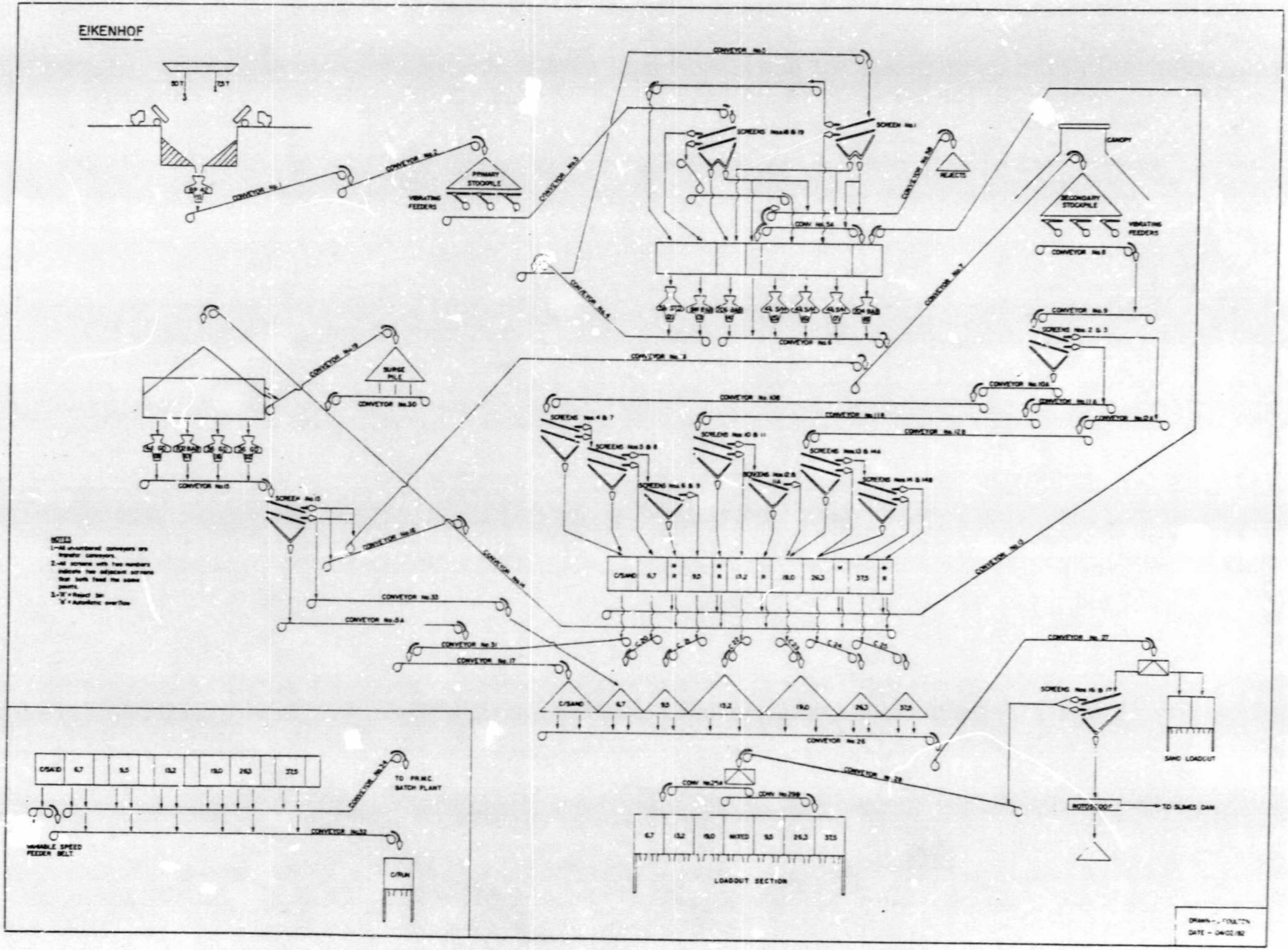

Figure 1.1 Flow diagram of Eikenhof

Above: General view of the Jukskei Quarry. Each bench is about fifteen metres high

Below: Two of the pneumatic drill rigs which are used at Jukskei for drilling the 64 mm diameter holes into which explosive is inserted prior to blasting