NAME OF AUTHOR/NOM DE L'AUTEUR: MARIUS VILIS NEIMANTS

TITLE OF THESIS/TITRE DE LA THÈSE: SCHEDULING IN THE COPPER CONVERTER AISLE

UNIVERSITY/UNIVERSITÉ: CARLETON

DEGREE FOR WHICH THESIS WAS PRESENTED/GRÂDE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE: M. ENG.

YEAR THIS DEGREE CONFERRED/ANNEE D'OBTENTION DE CE Degré: 1980

NAME OF SUPERVISOR/NOM DU DIRECTEUR DE THÈSE: C. M. WOODSIDE

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

DATED/DATE: Nov. 29/79 SIGNED/SIGNÉ: M. V. Neimanis

PERMANENT ADDRESS/RÉSIDENCE FIXÉ: 2400 CARLING AVE, APT. 806, OTTAWA, K2B-7H2
NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

Ottawa, Canada
K1A 0N4

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, S.R.C. 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVÔNS RECUE

Ottawa, Canada
K1A 0N4
SCHEDULING
IN
THE COPPER CONVERTER AISLE

by
Maris Vilis Neimanis, B.Sc., M.Sc.

A thesis submitted to the Faculty of Graduate Studies in partial fulfilment of the requirements for the degree of Master of Engineering

Carleton University
Ottawa, Ontario
November, 1979
The undersigned recommend to the Faculty of Graduate Studies acceptance of the thesis

SCHEDULING

IN

THE COPPER CONVERTER AISLE

Submitted by Maris V. Neimanis in partial fulfilment of the requirement for the degree of Master of Engineering.

..............................
J. J. Brandon
CHAIRMAN, DEPARTMENT OF SYSTEMS ENGINEERING

..............................
C. M. Linder
THESIS SUPERVISOR
ABSTRACT

This thesis describes a technique for generating converter aisle schedules in a copper smelter to maximize the material processing rate. The first step in the procedure is the development of a mathematical model of the flow of materials in the aisle in the absence of process upsets or equipment failures. Then, based on this description, a problem of matte allocation to the converters to maximize overall matte consumption is formulated and solved. The resulting schedule is validated on an interactive computer model of the converter aisle. Finally, similar techniques are employed to develop transient schedules to reach this ideal mode of operation starting from any arbitrary converter aisle status which could arise due to disruptions.
ACKNOWLEDGEMENT

The help and direction of my supervisor, Professor C.M. Woodside, not only in this work, but throughout my graduate work at Carleton University is sincerely appreciated.

The assistance provided by Dr. U.P. Graefe and Mr. L.K. Nenonen of the National Research Council of Canada in this study is gratefully acknowledged.

The co-operation of Noranda Mines personnel in providing data for this study is appreciated. As well, financial assistance by Noranda Mines Ltd. in work related to this thesis is appreciated. This assistance was provided under an arrangement between Noranda Mines Ltd. and N.R.C.
# TABLE OF CONTENTS

Chapter 1  Introduction  
Chapter 2  Scheduling Literature  
  2.1 Introduction  
  2.2 A Scheduling Problem  
  2.3 Industrial Scheduling  
  2.4 Basic References  
Chapter 3  A Description of the Scheduling Problem  
  3.1 The Flow of Materials in the Converter Aisle  
  3.2 Practical Scheduling of the Plant  
  3.3 The Noranda Smelter  
  3.4 Previous Optimization Research of the Copper Smelter  
Chapter 4  The Scheduling Technique  
  4.1 Introduction  
  4.2 Determination of Model Parameters  
  4.3 An Overview of the Optimization Problem  
  4.4 Overall Matte Allocation for Maximum Production  
  4.5 Allocation of Matte Ladles to Blowing Period  
  4.6 Determination of Best Time Spacing Between Converter Cycles  
  4.7 The Determination of the Best Timing of In-Blow Converter Tasks  
  4.8 Summary  
Chapter 5  Validation on the Interactive Model  
  5.1 The N.R.C. Interactive Smelter Model  
  5.2 Description of a Validation Run  

Page numbers:  
1  
5  
5  
6  
8  
12  
15  
16  
26  
31  
36  
45  
45  
46  
58  
60  
69  
70  
75  
82  
86  
86  
94
**TABLE OF CONTENTS (CONT'D)**

5.3 Summary of Results 102

Chapter 6 Reaching the Optimal Cycle 105

6.1 Introduction 105

6.2 Steps in Calculating the Transient Schedules 105

6.3 Practical Implementation of this Scheduling Approach 118

Chapter 7 Conclusions 120

References 124

Appendix A 128

Appendix B 131

Appendix C 135

Appendix D 143
LIST OF TABLES

Table 4.1: Matte Addition Limits per Blow
Table 4.2: Average Matte Processing and Handling Times for Each Converter
Table 4.3: Maximum Matte Capacities for Various Converter Charge Cycle Times
Table 4.4: Converter Matte Allocations for the 8 Hour Cycle
Table 4.5: Service at End of Blows in the Case Study Schedule
Table 4.6: Service at End of Blows for In-Blow Deterministic Study
Table 4.7: All my Schedules
Table 6.1: Meshed Transient Cycle
# List of Illustrations

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>The Perce-Smith Copper Converter</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>General Flow of Materials</td>
<td>22</td>
</tr>
<tr>
<td>3.3</td>
<td>Sequence of Events in a Typical Converter Charge Cycle</td>
<td>25</td>
</tr>
<tr>
<td>3.4</td>
<td>Smelter Layout</td>
<td>32</td>
</tr>
<tr>
<td>3.5</td>
<td>Material Flow Chart</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>Flowchart for Calculating Material Results Due to the Addition of a Ladle of Matte</td>
<td>48</td>
</tr>
<tr>
<td>4.2</td>
<td>Gantt Chart for Sequence of Converter Operations</td>
<td>77</td>
</tr>
<tr>
<td>4.3</td>
<td>Gantt Chart for the very First Case</td>
<td>78</td>
</tr>
<tr>
<td>4.4</td>
<td>Demand for Crane Service</td>
<td>80</td>
</tr>
<tr>
<td>4.5</td>
<td>General Flow Chart for Determining Optimal Aisle Operation</td>
<td>83</td>
</tr>
<tr>
<td>5.1</td>
<td>Smelter Display Unit</td>
<td>90</td>
</tr>
<tr>
<td>5.2</td>
<td>Smelter Display Unit: Information Format</td>
<td>91</td>
</tr>
<tr>
<td>6.1</td>
<td>Times Associated with Transient Schedules</td>
<td>107</td>
</tr>
<tr>
<td>6.2-6.5</td>
<td>Detailed Converter Charge Cycle Times for Optimal Cycle Prior to Time Shifts</td>
<td>112-113</td>
</tr>
<tr>
<td>6.6-6.9</td>
<td>Transient Schedules for the Individual Converters</td>
<td>115-116</td>
</tr>
<tr>
<td>Plate 1</td>
<td>Smelter Display Unit</td>
<td>89</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Copper smelting using the reverberatory furnace and converter with material transfer by cranes has been a standard procedure since the early part of this century. The process chemistry has not changed essentially. A standard reference on the physical chemistry of copper smelting was written by R.W. Ruddle in 1953. [34] Recently, the Japanese have developed a technique of continuous material transfer by flow, thus eliminating the need for crane service. [35] Moreover, in such smelters the material inputs and metallurgical compositions are computer controlled. If existing smelters are to be competitive with such new ones, increased plant efficiency is highly desirable.

This thesis deals with scheduling in a copper smelter aisle at Noranda, Quebec and describes an approach for computing a cyclical schedule in which the operation of four converters is properly spaced in time to avoid conflicts in crane demand and to maximize production. Chapter 2 discusses the principal types of mathematical
techniques used in optimization with a view toward scheduling. The techniques used in this thesis are discussed in more detail. Other techniques are merely referenced since optimization is such an all-encompassing field. Chapter 3 describes the particular scheduling problem in the converter aisle. The physical and chemical environment of the converter aisle is discussed. Previous attempts at optimization in this reference frame are noted. Chapter 4 discusses the scheduling technique in detail. The actual mechanics of the procedure are illustrated by means of a completely calculated sample schedule. Various other schedules with different values for the parameters are also mentioned. Listings of the appropriate computer programmes can be found in the appendices. Chapter 5 deals with the validation of these schedules on the interactive smelter model at the National Research Council. Some practical problems in this verification are included as well as a brief description of the operation of the model. A sample model run with comments is included in the appendices. Chapter 6 describes a technique for attaining an optimal schedule from an arbitrary converter aisle status. A sample schedule is included to illustrate the mechanics of this procedure. Finally, a few pertinent remarks are made regarding the practicality of such scheduling. The concluding chapter summarizes the work done and suggests various extensions. Parts of this work have been published.[15],[24],[25]
The research described in this thesis was done over a period of some four years, mainly during the summers. The initial impetus was provided by the study of the National Research Council's (N.R.C.) hybrid computer model of a converter aisle as an example of applied simulation. A preliminary effort at scheduling was attempted by programming a module of the model to report the material contents of each converter versus the 'ideal' material contents whenever a major event occurred in the converter aisle. (Refer to Section 5.2) During the summer of 1975, the analysis of the scheduling problem was detailed by decomposing the structure into the following steps:

(A) Calculation of process times per unit raw material
(B) Determination of an ideal cycle time
(C) Maximization of material flow for the converter system
(D) Calculation of end point times for individual converter cycles
(E) Staggering of converter cycles to avoid crane conflicts
(F) Investigation of in-blow task insertions

Computer codes were written for tasks (A), (D), (E) and (F) while an available code was used to solve problems (B) and (C). Results showed the material throughput to be relatively constant subject to the volume constraints of the converter. Thus the length of a working shift - 8 hours - was chosen for the cycle length. A visit to the Noranda smelter was also made during this time period to verify some parameter values with operating personnel and
to measure others. The schedules were validated on the N.R.C. interactive model during the summer of 1976. It was a laborious process because the model was not often used and had been originally designed to be run with different computers. Eventually, however, the schedule showed an increase in matte turnover rate of some 33% which implied an in-plant increase in converting potential of up to 25%. The schedules were shown to be feasible even when the model was run in non-deterministic mode with air-flow rate deviations and deviations in cuprous sulphide allocation policy. The smelter personnel reacted positively to these results. Subsequently several months were spent in generating schedules under new plant operating conditions which showed how the same workload might be handled by fewer number of converters. These schedules were verified by senior plant operations personnel. Unfortunately, the values of the parameters which were originally supplied by Noranda Mines Ltd. were questioned as well as certain operating practices of the N.R.C. model which had previously been judged to be impeccable for some five years. It is emphasized that a change in operating policy only amounts to a change in the value of the control parameters and the schedule generating methodology remains unchanged. Finally, during the summer of 1977 a technique was developed for generating transient schedules to reach the ideal mode of operation starting from any arbitrary converter aisle status.
CHAPTER 2

SCHEDULING LITERATURE

2.1 Introduction

Control over the detailed operations of large industrial processes has become a subject of basic research. An important aspect of industrial control is deciding upon the precise use of manufacturing facilities at each instant of time. Many factors have to be taken into account in making these decisions. It is this kind of decision making, the allocation of resources over specified time periods, that will be called 'scheduling' in this thesis.

The literature survey which follows was undertaken at the start of this research and is therefore somewhat dated. This survey is by no means exhaustive, but rather is merely an indication of the most widely used tools. It is included mainly for completeness, although with the approach taken in this thesis, the scheduling problem did not fit into any one established technique. Rather, the schedule generation methodology is a blending of process knowledge, common sense and a little mathematical programming.
The lack of success of scheduling theory in solving practical problems may be attributed to the gap between the theoretical developments in scheduling theory and the nature of the practical problems. Scheduling research suffers from an over-emphasis on the rigorous mathematical development of the problem and too little emphasis on the realism of the formulation of the problem. See for example [32], where the difficulty of modeling an industrial process is shown by detailed analyses of specific processes. Also, [5] indicates that theory deals with generic models which might be too much of a simplification of real life. The elegant formal machinery developed in scheduling is of no appreciable use to practising schedulers who are thus forced to use the old technique of trial and error.

2.2 A Scheduling Problem

The mathematical analysis of optimal operating conditions presumes the existence of a reliable mathematical model of the system. The techniques of optimization are therefore model-dependent.

That there is no uniquely satisfactory scheduling method will now be illustrated by reference to three similar problems in resource allocation. Time, space and manpower will be the resources considered subject to
availability constraints. The underlying structure of these three problems in basically the same.

In turn, we look at examination timetabling, classroom allocation and the assignment of workers to shifts.

The author of this thesis has modified the work of Broder, [4] from a Monte Carlo technique to a heuristic rule for breaking ties in a student conflict matrix. Using this approach, a computer programme yields an examination timetable for one thousand seven hundred students taking ninety courses. Using fifteen available writing slots, the number of student conflicts is less than twenty. Subsequently I have discovered that my heuristic rule is called the FFD (First-Fit Decreasing) algorithm in Bin packing. [5]

Appleton [1] describes an interactive computer simulation of room usage at the University of Newcastle Upon Tyne to allocate rooms efficiently to classes and to plan new buildings. Interaction between the computer and user frequently makes results more acceptable since it allows the use of personal experience and expertise, i.e. heuristic scheduling. The programme, written in ALGOL, has submodules to perform reallocations, print out timetables, update student numbers, add new rooms, change existing
rooms, update the timetables and gather statistics. A sample terminal session is included as part of the paper.

Linear programming has been used to generate garbage collection schedules in New York City in order to minimize weekly collections missed, subject to union regulations and man-power and track constraints. [18]

Thus heuristics (or job-shop scheduling), simulation and linear programming have been used to solve three very similar timetabling problems.

2.3 Industrial Scheduling

Three basic approaches to scheduling include networks, the construction of schedules with the aid of linear programming and simulation. Reference will now be made to some of the most commonplace techniques used in scheduling and allied problems in industry.

The two major methods of attack in network approaches are the critical path method (C.P.M.) and program evaluation and review technique (P.E.R.T.). They differ in that P.E.R.T. is used for projects for which there is job time uncertainty whereas the critical path technique is used on relatively well-known job times, as might occur in
building a house. In a pair of papers, Kelley [19], [20] laid the mathematical foundations of the critical path method and suggested some uses for P.E.R.T. Widely diverse kinds of projects lend themselves to analysis using these methods, such as:

1. The assembly line
2. Mobilization, strategic, and tactical planning
3. Budget planning
4. The construction of a building, highway, new plant, ...
5. Maintenance projects such as the operation of an oil refinery
6. Installation of a computer system

Each of these projects has several characteristics that are essential for analysis by these methods:

1. The project consists of a well-defined collection of jobs which, when completed, mark the end of the project.
2. The jobs may be started and stopped independently of each other, within a given sequence.
3. The jobs are ordered - that is, they must be performed in a given sequence.

In the field of project scheduling, P.E.R.T. and its descendants have established themselves as excellent, feasible, money and time-saving methods. This is shown by the vast number of diverse projects where the technique has been used with considerable success.
Schedules may be constructed using linear programming and integer programming. A few examples will suffice to indicate the wide variety of uses. These techniques are limited only by the ability of the analyst to translate the problem into this framework.

A linear programming model is used by Bennett, Curr and Haywood [3] to develop schedules to optimize the commercial parameters for transfer of fish between trailers in a fleeting system. This was forced due to the fact that the fish were far from home base and freshness of the catch is a factor in market price. The conclusion is that the transfer at sea system has been satisfactory and has contributed significantly to the profits.

The practical solution of large mixed integer programming problems is reported by Forrest et al. [11]. The algorithm employed, coded as UMPIRE, uses linear programming as the main fathoming device. UMPIRE has solved many problems of the generally combinatorial type. These have included the generation of schedules in the field of construction and production and distribution of resources. Some of these models involve less than five hundred constraints or have only a few dozen integer or special ordered set of variables. However, UMPIRE has solved a number of very large problems with up to eight thousand constraints and several thousand integer variables. The
paper includes two tables of computational efficiency of the algorithm corresponding to the two types of problems. It is concluded that large scale integer programming is a viable economic proposition.

Simulation is intrinsically valuable since it allows non-experts to visualize the results. A paper by Ashour and Bindingnave [2] analyzes the flow of hot ingots from the steel works through to the rolling mill. Even though soaking pits are nonproductive units in the process, they could create serious bottlenecks in production if their capacities were not properly determined before installation. The paper represents the pit-mill complex as a queueing system and develops a simulation model to predict the improvement in the capacity of the system attainable through the addition of more pits and to predict the effects of breakdowns and maintenance and the shutdown of a pit. The simulation was written in GASP-IIA. Two sets of runs were done varying the service queueing discipline (FIFO and LIPO), for the arriving ingots. The critical factor economically is the idling of the mill. The simulation experiments suggest that even a small reduction in mill idle time will offset substantial costs for pits and increased capacity until the optimum is closely approached.
Freeman, Hoover and Satia [12] discuss the elimination of machine interference by simulation. The parameters of the problem include task characteristics, machine characteristics and scheduling rules. The scheduling rules include an assignment of interruptability characteristics in terms of task priorities. They discuss the three traditional techniques of assigning operators to machines: namely; interference tables, queueing analysis and expected work load analysis. The shortcoming of interference tables is that this technique suffers from the necessity of oversimplification of the problem. Rather severe assumptions and semi-empirical approximations are required to apply queueing theory analysis. Work load analysis fails to recognize the impact of high variability in arrival or performance times in causing interference. The paper describes input and output for their machine interference simulator. Included is a sample run for a family of three and six machines. The simulator has been used in both batch and time shared modes. It was found easier to input the data and perform sensitivity analysis in the time shared mode.

2.4 Basic References

A good introduction to scheduling methods is via one of the following books:
The 'Scheduling Handbook' by O'Brien [30] is a useful reference for a person who wishes to apply a particular method to a real-life problem. The level of mathematics is quite unsophisticated and the book abounds with a plethora of practical examples. The book is reviewed as containing every known method of scheduling except the rhythm method.

Ray and Szekely [32] have published a textbook which illustrates various techniques of scheduling and optimization with detailed real-life applications. The text is suitable for a graduate level course while techniques of optimization are drawn from chemical and metallurgical industries.

'Industrial Scheduling' by Muth and Thompson [23], although somewhat dated, gives an excellent insight into various types of scheduling methods. The general emphasis is on the illustration of theory by means of simple examples. The book is recommended as a light introduction to someone unfamiliar with the ideas behind some of the basic theory.

'Computer and Job-Shop Scheduling Theory' by Coffman et al. [5] expounds on the theory of one important type of scheduling which is practically applied, namely, the job shop. Job shops deal with the manufacture of discrete units processed either as single entities or in small batches.
Scheduling is generally controlled by a shop order process rather than by an assembly-line system. In the past, routing sheets controlled manufacturing through a series of operations, each group consisting of a job. This resulted in the term 'job shop'. Examples of the use of job-shop techniques include mail-sorting, textile machine works, manufacture of machinery and shipbuilding. The intent of this book is to provide students and researchers in specific areas with a means of staying moderately up to date in scheduling theory as a whole, without having to peruse extensive literature. From a mathematical point of view, the book is not light reading. The focus is on generic models of simple structure whose combinatorial complexity and analysis resembles that of various structures encountered in a wide variety of disciplines. The treatment is wholly mathematical, with very little recourse to discussions of pragmatics.
CHAPTER 3

A DESCRIPTION OF THE SCHEDULING PROBLEM

In order to have a clear understanding of the operation, a brief description of the processes involved in copper smelting is given.

The copper smelting process description and model parameter values are based on discussions with and reports from Noranda Mines Ltd. personnel. During the summer of 1975 a two day visit was made to the smelter during which operations were observed and discussions took place with all relevant operating personnel. Much valuable insight was also provided by Mr. L.K. Nenonen and Dr. U.P. Graefe, who have modelled and simulated copper-smelting operations for more than a decade. An eighteen page survey of the values of operating parameters was provided by a Noranda Mines' conventional converter technician in February, 1975. This included pickup and dumping times of materials, weights, distances and assay values of materials. In cases where values were not available, the opinions of people in these departments were collected. These estimated values were considered to be representative. In addition, data was also
provided in the following ways. Discussion of operating practices and parameter values was carried on when a smelter metallurgist in charge of converting and a senior converter aisle foreman visited the National Research Council's simulation model in September, 1975 and October, 1976. A visit by the director of the Noranda Research Center in August, 1976 provided further insight. During the summers of 1975 and 1976, there were numerous communications with the smelter technical superintendent.

3.1 The Flow of Materials in the Converter Aisle

The Physical Components

In this thesis, the operation is viewed in terms of material handling by the cranes and matte processing by the converters. The equipment in the converter aisle consists of reverberatory furnaces, converters, anode (or holding) furnaces and gantry cranes.

The reverberatory furnaces supply the raw material and accept the converter waste. The converters operate on an oxidation/flotation principle so that waste products float on the surface and may be poured off. Anode furnaces accept the finished product from the converters for further refining.
In order to facilitate the description, the following is a glossary of commonly used terms. Sizes and capacities refer to the Noranda Smelter. British units of measure are used instead of the SI system because at the time of the case study schedule (1974) the smelter was using this system of measure. It is hoped that such a system might be of more benefit should this material be referenced by Noranda Mines Ltd.

Anode Furnace: holding furnace for pyrometallurgical refining of blister copper. Typical capacity of 150 tons.

Blister Copper: almost pure liquid copper, the end product of the converting process.

Blow: a period of time during which air is blown into the mass of molten metal and slag in the converter.

Converter: a cylindrical brick-lined container capable of holding some 125 tons of molten matte and fluxing ore at temperatures of 1200 degrees Celsius. As can be seen in Fig. 3.1, the converter lies on a roller support which is motor driven to rotate the converter so that it may pour out slag.
Cranes:-Overhead cranes run on a common track with no siding or bypass to avoid interference. Forty tons is a typical crane carrying capacity. Cranes achieve speeds of 200 ft./min.

Fluxing ores:-some seventy per cent silicon oxides .. the remainder assumed to be inert materials which enter the slag

Ladies:-containers of some 150 cubic feet capacity capable of holding twenty tons of molten material .. transported by the cranes

Matte:-liquid ore in the reverberatory furnaces (eutectic mixture of iron and cuprous sulphides)

Reverberatory Furnace:-large (100 ft. x 50 ft.) boxlike brick structure holding matte and slag at 1300 degrees Celsius

Slag:-liquid mixture of fayalite and gangue (earthy particles in ore)

Tuyeres:-pipes through which air enters the converter .. must be repeatedly opened with a puncher (Fig. 3.1)
White Metal: almost pure cuprous sulphide .. the contents of the converter at the start of the copper blow

The Process Chemistry

Reverberatory matte is poured into the mouth of a converter from a ladle which is manipulated by an overhead crane. The converter then rolls into the stack, i.e. the blowing position with its mouth under the hood, submerging the tuyeres below the surface of the molten bath, and air is blown into the bath.

There are basically two parts to the converting process, the slag phase and the copper phase. Although the chemistry is quite complex, I will follow Nenonen and Pagurek [29] in assuming that essentially the process can be summarized by the following two exothermic reactions.

**Slag Phase**

\[ 2\text{FeS} + 3\text{O}_2 + 2\text{SiO}_2 \rightarrow 2\text{FeO} \cdot 3\text{SiO}_2 + 2\text{SO}_2 \]

Fluxing ore is continuously added to the converter by a belt system and slag floats to the surface. During converting, flue gases are exhausted by an overhead hood fan.

**Copper Phase**

\[ \text{Cu}_2\text{S} + \text{O}_2 \rightarrow 2\text{Cu} + 2\text{SO}_2 \]
During this stage more white metal may be added by crane service from other sources. For cooling purposes, cranes transport chunks of solid copper called 'pigs'. At the end of this stage, the blister copper is either transported to the anode furnaces by the cranes for further refining or, if need be, poured into sand moulds to cool into pigs.

A general overall flow of materials is indicated in Fig. 3.2.

**Operational Sequence**

The operations which define the length of a converter charge cycle are:

1. Transportation of matte from reverb to converter, including cycle interruption times when matte is added during a blow.

Molten matte pours out into a ladle which is on a handcar on a track beside the reverb. This location is referred to as the matte tunnel. The hole is then closed with a clay plug. The car is pushed to the converter aisle where a crane is waiting. The ladle has jutting arms on either side and the crane connectors are oval-shaped. The time to pick up a ladle of matte takes less than one minute but is dependent on the experience of the crane operator. Travel
Fig. 3.2 General Flow of Materials
times can range from ten seconds to a minute depending on the relative location of the converter and the reverb. The pouring of matte takes about one half a minute. Then the ladle must be deposited somewhere, preferably back at the matte tunnel where it came from.

2. Oxidization of ferrous sulphide to slag during the matte blow phase

3. Removal of slag and its transportation to a reverberatory furnace

The procedure is essentially the same as procedure 1. but reversed. Slag is 'skimmed' when a converter rotates out of its stack and pours the top layer of its contents into a ladle.

4. Addition of pigs for cooling purposes during the copper blow

'Pigs' are five ton lumps of copper crusted with sand from the mold they are cooled in. There is a hook imbedded in each copper pig so that the crane may pick it up, and an auto-release crane hook which releases when the pig enters the converter bath.
5. Oxidization of cuprous sulphide during the copper blow

6. Removal of blister copper from the converter and transportation to an anode furnace or pig bay

Tapping of copper takes about half an hour. The charge is generally allowed to settle in the converter and a skull is added to form a crust on the surface. (A skull is the cooled residue of crust from a ladle and is formed when the ladle is bumped and its contents are dumped on the floor to cool.) Copper is tapped for twenty minutes and five to ten minutes are required to add reverberatory matte in preparation for a new cycle. The blister copper is dispatched in the same manner as was the slag. If it is dumped in the pig bay about four pigs can be formed from a ladle of copper which then take about three hours to cool.

The converter cycle is illustrated by the (ferrous sulphide:cuprous sulphide) vs. time profile in Fig. 3.3. The cycle is divided into blows because of the physical volume capacity of the individual converters as well as limitations to effective oxidation depending on the depth of the bath. See, for example, [9]. Therefore, more matte may be added as slag is removed.

With the exception of blow #1, service prior to a matte blow consists of skimming slag and addition of matte.
In the profile, the horizontal segments followed by sawtooth peaks, during matte blows, indicate times of matte addition. Skimming is allowed during the last slag blow (called the going high blow) in order to distribute the demand for crane service. These slag skimming periods are represented by the horizontal segments in that particular blow's profile. The longer horizontal segment represents the task of collar pulling i.e. removing the crust deposit around the mouth of the converter due to spillage and dumping it into the converter. Crane service prior to the copper blow consists of skimming of all residual slag followed by the addition of flue dust. During the copper blow, the short horizontal segments indicate the addition of copper pigs for cooling purposes.

The purpose of this study is to design a converter schedule for optimal crane deployment with minimal crane interference.

3.2 Practical Scheduling of the Plant

Based on this description of the process, let us examine in more detail the problems of production scheduling.
The converter aisle foreman tries to achieve a maximal constant rate of matte flow from the reverberatory furnaces. In order to do this, he must continuously maintain a material demand-supply function on a macroscopic scale. Each unit in the converter aisle may be assigned such a function. To maintain a balance, the demands of one unit must be met by the supplies of another. At any instant, therefore, the foreman must be aware of the state of these functions for all units. Then the demands must be sequenced in order of time priority in conjunction with the total production of the whole system. Finally a non-conflicting crane assignment must be made to perform the operations in descending order of priority. Where choices are possible, he tries to determine the best feasible procedure maximizing productivity. To do this he generally tries to schedule the converter cycles so that their end-points are evenly spaced in time. Such an even spacing requires a detailed knowledge of blowing rates and efficiencies, matte grades, converter capacities, matte availability, traffic conflicts, etc. Such current data can only be collected accurately by some form of automatic data acquisition system and, to provide predictions, some form of computer system may be required. At any time three levels of information must be available:

1. The status
2. The priorities
3. A crane schedule to satisfy the priorities
The converter cycles must mesh with the reverberatory furnace cycles and the anode furnace cycles, otherwise, the material balance cannot exist since there would be a shortage/surplus of reverberatory matte and/or blister copper.

Clearly, decision-making by the converter aisle foreman is a difficult process which may be satisfactorily approximated only after a lifetime of experience. Even then, the decisions can only be intuitive not quantitative. Under present circumstances, a bottleneck in material demand, and thus crane demand, invariably occurs.

In practice, each converter foreman attempts to take a certain number of ladles of matte from the reverberatory furnaces during his shift. Striving to meet this goal on one shift can cause difficulties on the following shift. The most serious schedule disruption occurs when two converters come down simultaneously at the end of a blow. If two converters come down simultaneously at the end of a copper blow, the situation is compounded. Not only is there an impossible crane demand, but subsequently there will be a matte shortage. In effect, one can safely say that one of the converters has lost about an hour.

Physical obstruction by a crane can also delay a schedule. An example of this is a crane performing a
collar pulling task. Collar pulling is the task of cleaning the mouth of a converter. The actual time required for this operation depends very much on the experience of the craneman and also the state of the mouth. In the meantime, some converter on the other side of this working crane from the free crane may require service at the end of a blow or in-blow service such as pig addition during a copper blow. Invariably time will be lost. Either the collar pulling will be interrupted which is not desirable, or else the other task may be delayed until the collar pulling is completed.

The synchronization of the converter and anode cycles is of prime importance. The anode furnace cycle is of approximately a twenty-two hour duration. Should all the anode furnaces be busy casting, there would be no place (other than the limited demand of the pig bay) to transfer the blister copper.

Prior to passing any judgment on the performance of the converter aisle foreman, we must consider his environment. He works in temperatures often in excess of 100 degrees Fahrenheit, with noise level around the pain threshold (he wears ear plugs) in clouds of noxious gases (all workmen wear gas masks). Under these circumstances, it is not surprising that there is an occasional error in communication between the foreman, crane-operator and the
swamper. (A swamper is a workman on the floor of the converter aisle who directs crane movements by hand signals.)

Every shift has its share of unexpected disturbances. A converter is temporarily held up due to mechanical trouble caused by material from the hood falling between the shell and rotating mechanism. A converter comes down due to an empty silica chute. A malfunction in the air flow system occurs, such as: punchers needing repairs, valves or punching bars sticking in the tuyeres.

The cranes must be serviced periodically. Overhead tracks must be inspected, causing a stoppage or at least a diminuation of crane service. The tuyeres become periodically clogged with matte which causes a great deal of fluctuation in the air flow rate. The converter lining tends to be thinned with wear with the result that near the end of its life a converter can not be used on a copper blow. Instead the white metal must be transferred to some other converter which is in the copper blow.

The times of end points of blows in a smelter may be very non-deterministic because of reasons such as the following. Scrap material added to the converter includes items such as television chassis, telephones, cables, oily motors etc. Moreover, the building is open and thus the outside temperature affects the rate of chemical reactions.
3.3 The Noranda Smelter

Physical characteristics

The smelter includes the following equipment arranged as shown in Fig.3.4, the overhead schematic diagram of the converter aisle:

1. Three reverberatory furnaces
2. Five Peirce-Smith copper converters
3. One fixed and two rotary anode furnaces
4. Three gantry cranes operating on the same track above the converter aisle

Reverberatory Furnaces

In the mode of operation illustrated in Fig.3.4, there were two dry (or hot) charge furnaces and one wet-charge furnace, each of dimensions 110 ft. by 35 ft. Whereas a hot-charge furnace is fed with calcine from roasters, the wet-charged furnace accepts concentrates with a certain moisture content. Concentrate is charged to the furnaces from storage bins by a shuttle conveyor on each side of the furnace.

Typical metallurgical and production features of such furnace operations are:
DESIGNATIONS:
C = CONVERTERS
A = ANODE FURNACES
R = REVERBERATORY FURNACES

ORDER OF CRANES
I, 2, 3

SCALE = FEET
0 20 40 60 80 100

ANODE WHEEL
# 3

CONVERTER COTTRELL

STACK 2

Noranda process
Continuous smelter

Pig pile

Scrap copper
storage

Pre-heater

Pig bay

Bumping block

Matte tunnel #2

Wet R 3

Dry R 2

Dry R 1

Matte tunnel #1

Fig. 3.4

SMELTER LAYOUT
CHARGE COMPOSITION

<table>
<thead>
<tr>
<th>Matte Type</th>
<th>Cu</th>
<th>Fe</th>
<th>S</th>
<th>Rate (dry tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Charge</td>
<td>32%</td>
<td>33%</td>
<td>28%</td>
<td>600</td>
</tr>
<tr>
<td>Dry Charge</td>
<td>40%</td>
<td>28%</td>
<td>25%</td>
<td>1200</td>
</tr>
</tbody>
</table>

Converters

There are four 13 ft. x 30 ft. Peirce Smith converters. Converter #7 is larger being of dimensions 14 ft. by 32 ft. It is equipped with Kennecott 48 punchers with automatic sequential firing. The punchers are arranged in two banks of 25 each and are fired once a minute, taking four to five seconds to fire a 25 puncher bank. The machines are removed once every twenty-four hours to ream the tuyeres manually. An average converter life is 180 days with a production rate of one hundred tons per day. Theoretical upper limits for the charge sizes are 17 ladles of matte for the four converters of equal size and 20 ladles of matte for converter #7. In practice, 12 ladles of matte is a typical charge size.
Anode Furnaces

There are two rotary anode furnaces of dimensions 13 ft. by 35 ft. and 13 ft. by 30 ft. and one stationary anode furnace, similar in design to the Gaspe anode furnace reported in [22]. The stationary furnace capacity is 145 tons, copper being tapped at 40 tons per hour into a casting wheel with a capacity of twenty 625 pound anodes.

Other Converter Aisle Details

Matte and slag ladles are 180 cubic feet in volume. Copper ladles are limited to 130 cubic feet due to crane capacity. Approximate weights of matte and slag transferred are eighteen and twelve tons per ladle respectively. Slag and matte ladles can be used interchangeably, depending on their condition. Although matte ladles could be larger, slag ladles are limited to the present size by space restrictions when dumping slag into the reverb furnaces.

Collar pullers are stored on a rack near reverb #2.

Matte skulls are kept by the bumping block. These skulls are cooled residuals of ladle crust which forms so that every once in a while the ladle has to be bumped. The skulls are used to form a surface crust on a converter's contents at the end of a copper blow.
Pigs are poured in sand molds on the floor at the pig way and require some three hours to cool. The pig pile is an emergency storage place in case of pig shortage which would be disastrous to say the least.

Workmen collect flue dust in wheelbarrows and dump it into ladles located near each of the converters.

Operating Mode for the Case Study

During the summer of 1974, four of the five converters were in operation while the other one was down for rebricking. Although there are three cranes designated, only two were used for operation at any one time. The third crane is a smaller crane (CR#2) and is located at the north end of the smelter where it performs housekeeping chores such as unloading trucks. It is only used in production when one of the other cranes is out for repairs or servicing.

In this mode of operation no one kept track of what type of matte was added to a converter. Hence there was uncertainty about the exact content of a converter at any fixed time and added unpredictability of blow end point times, especially the definitive high blow and copper blow end points.
The material flow chart for these operating conditions is illustrated in Figure 3.5 (ignore the continuous smelter input).

3.4 Previous Optimization Research of the Copper Smelter

Research to date of optimization in the copper smelter has been largely in the area of metallurgical variables in the individual processes to minimize heat and material losses and to maximize production rates. There has been little in the way of scheduling of the operation of the individual processes and of the flow of material between them to maximize smelter production.

Research on Copper Converter Process Optimization

Foreman [9] developed a computer model that would yield a dynamic record of reaction rates and predict endpoints. He specifies in detail the model development which consisted of a Fortran program. The company was to proceed with a pilot installation of an on-line computer for the development of control criteria applicable to converter features. Foreman mentions that converter aisle throughput is directly related to the optimum operation of individual converters and scheduling of converter crane moves. He concludes that the present goal is to develop an integrated smelter process control system. In the later paper [10],
Fig. 3.5
MATERIAL FLOW CHART

RAW MATERIAL

REVERB FURNACE

SLAG

MATT SKULL

LADLES

SLAG SKULL

SKULL

LADLE COOLING

SKULL

CU SKULL

MATTE TRANSFER

CONVERTER

MATTE BLOW

MATTE

CONVERTER

CU BLOW

BLISTER CU

PIGS

PIGS

CONTINUOUS SMELTER

INPUT

PIG BAY

PIG PILE

ANODE FURNACE

CU OUTPUT

REVERB SLAG

DUST

FLUE DUST STORAGE

FLUE DUST INPUT

LOW CU SCRAP

HIGH CU SCRAP

CU SCRAP STORAGE

SCRAP INPUT

REQUIRE CRANE SERVICE
some results are reported. The importance of depth of blowing was confirmed as a process control variable and a method for blister copper end-point control was developed. Results indicated the value of computer process control and the need for a full scale development program. Predicted information has been used as a guide for overall operations scheduling; for example, matte grade fluctuations have been minimized. He proposes a simulation program to provide improved charge calculation and operations scheduling information based on all available material on hand and current reverberatory conditions.

Nenonen and Pagurek [29] employed a conjugate gradient method to determine the optimal rate of flux addition to a calibrated mathematical model of the converter for various levels of enriched oxygen.

Simulation of Effect of Plant Changes

Eastwood et al. [8] describe changes in the smelting practice of the Nchanga Consolidated Copper Mines' Rokana Smelter, due to a GPSS model. The model simulated many weeks of smelter operation in a short computer run and evaluated the effects of any change. The model endorsed a number of earlier decisions taken regarding plant additions and was able to simulate operations over a range of production levels to show the effect on plant capacity of
changes in operating technique, and positive contributions to revision in the converter aisle. Included in the additions to the plant during this period were an anode casting furnace, a converter, an overhead gantry crane and increased reverberatory furnace slag handling equipment. Continuation of this work has lead to increased aisle mechanisation to reduce overhead crane involvement with the more arduous of the aisle operations.

In a subsequent paper, Davies and Thixton [6] report on further equipment changes due to this simulation. Larger ladles were purchased since the simulation indicated that an increase of the order of 6% in smelter throughput could be expected. The provision of extra bumping blocks was shown to have but a marginal effect on production under the prevailing conditions. The investigation did, however, stimulate thought on the question of crust breaking and a device was designed and installed which breaks a hole in the crust of a ladle without the need for bumping. Other additional changes due to the simulation include the purchase of housekeeping equipment so that there would be reduced crane interference, and a choice of location for the installation of a slag settling furnace to receive all the slag from the converters.

DeMaire [7] describes a simulation of a copper casting alloy plant using GPSS in order to evaluate the
effect of plant expansion on the workload of a large single crane. Each crane task was detailed by sub-dividing it by breakpoints into sub-tasks. Through cooperation with operating personnel, a matrix was developed that fixed which events could not happen simultaneously. Since many of the crane tasks were relatively long in duration and consisted of several distinct steps, it was decided to allow the crane to be pre-empted at any breakpoint in a major task if a higher priority task was waiting. The major conclusion drawn showed that there was negligible loss in capacity due to increased crane interference. Further sections of this paper discuss simulation in quality control and standards for patrolling operators. The simulation resulted in a 20% reduction in the standard labour requirements with corresponding salary savings to the company.

Marchant et al. [21] report on a General Purpose Smelter Simulation System (GPSSS). This simulation system was designed to evaluate the effect that various smelting processes, gas capture methods and dispersion systems have on environment, production and operation of a copper smelter. New environmental laws forced The Kennecott Copper Corporation to do this research. One significant conclusion was that low level emissions have a disproportionately large effect on ambient concentrations in the area immediately surrounding a smelter.
Scheduling in the Converter Aisle

Aside from the National Research Council model, which this thesis considers in detail, there have been only two papers published dealing with this type of scheduling; one, [36], is theoretical and incomplete, the second, [6], is the GPSS simulation of Davies.

The difficulty lies in the setting up of an adequate mathematical model of the plant which is acceptable to non-mathematician management, so that they would put their trust in any conclusions drawn and implement changes in the plant.

The simulation approach is to develop a mathematical model of the plant which accurately imitates the behaviour of the real-life operation. The GPSS simulation is a set of rules which describes the behaviour of the plant, together with statistical information concerning plant variables. The Rokana Smelter simulated by Davies [24] consists of five reverberatory furnaces, six converters and four anode furnaces. Material handling is almost exclusively by the five gantry cranes. The model was used to estimate that a production increase of about 3% could be achieved if there was an alternate way of delivering cold copper pigs to the converters during the copper blow. Unfortunately that problem remains unsolved. The
simulation also investigated the possibility of staggering the cycles so that one converter would always be down for crane service. A second less-detailed simulation was run to account for the effects of converter overhauls. Many years of smelter operation were simulated in this manner and long term average production rates could thus be established for the various converter operating strategies.

The only other actual effort at scheduling in the converter aisle is reported by Nenonen and Graefe [27]. A planning pegboard arrangement was used by Noranda Mines Ltd. which worked reasonably well for routine operation but was of no help to the foreman when he wished to adjust plans following an unexpected disturbance. The planning horizon for the pegboard was to be three hours.

Templeton and Hankley [36] provide a theoretical analysis of the converter aisle. The paper indicates how the system may be formalized into a state variable model. However, the system they consider consists of a single crane, one reverberatory furnace, one anode furnace and three converters. Furthermore, their model describes the system only during the slag blow phase and only while the converters are actually blowing.

The authors then compare direct optimization vs. partitioning of the problem.
For direct total system optimization, continuous variables are quantized in time and combined with discrete decision variables to form one large discrete time model. They comment on three techniques of optimization. First, they considered dynamic programming. The number of calculations required varies exponentially as a function of the number of state variables. In the case investigated, the number of variables is so large that the authors decline to present a model. In a realistic case, this approach becomes unmanageable. Second, gradient search may not be used because it requires that the system performance function vary continuously with each control variable and that the control vector be independent of its value at any other time. Third, random search is unlikely to be useful because of the number of variables involved.

For the partitioned version, the paper considers the following hierarchy of control subproblems:

1. Given material requirements of the converters, find an optimum crane routing which will minimize the service time for each converter service.

2. Given fixed services and fixed service times for each converter, find an optimum converter schedule which will minimize the charge cycle time for each converter.
3. Given a schedule of converter services, find optimum inputs to each converter furnace which will achieve that schedule and satisfy the physical constraints of the converting process.

The first problem is solved by dynamic programming. The converter furnace control is solved by a gradient search in the space of control functions as by Nenonen and Pagurek [29]. A method is described to compose these solutions into a solution to the original problem.

This work was surveyed subsequent to the structure arrived at in this thesis. The concept of partitioning the main problem into a series of subproblems is the same. However, this thesis examines a more complex situation in greater detail. (Refer to Section 4.3) Templeton and Hankley perform a more theoretical analysis of a generic model avoiding such details as crane interference, different grades of matte and service at the end of blows.
CHAPTER 4

THE SCHEDULING TECHNIQUE

4.1 Introduction

We now examine how the scheduling approach is applied to the process described in Chapter 3. Each converter goes through a cycle beginning with the addition of several ladles of matte (this cycle has been describe in Section 3.1). The establishment of a steady state cyclical schedule for the entire converter aisle is logical for the following reasons. A cyclical schedule ensures that at any time the status of all machines is specified. Furthermore, it is a natural way to ensure a constant material flow and to avoid an extreme out of kilter status whereby the whole of production is delayed. It will also be shown that there is an easy way to return to a given cyclical schedule from an arbitrary state.

A work load analysis of the converter aisle is performed. The scale of modelling is macroscopic; i.e. batch times are allocated to events which need not be considered in detail. It is hoped that a level of detail has been established that is sufficiently gross to keep the
model simple yet specific enough to produce accurate results.

The following sequence of decisions is made in the construction of the schedule. A time is calculated to complete a stage in the refining process using the parameters of the machine as well as transportation times. The maximum total production turnover is calculated for the plant for a given fixed time under the constraints of machine capacity and raw material availability. A detailed schedule is then mapped out for each machine (converter) using this maximum turnover as data. Then, these machine schedules are staggered in time to avoid conflicts in crane service demand.

The approach involves four general steps which are now discussed in detail using the particular schedule which involved four converters serviced by two cranes and operating with two dry and one wet matte reverberatory furnaces; the operating conditions at the Noranda smelter in 1974. This example is being used because it is realistic and it explains the scheduling technique.

4.2 Determination of Model Parameters

The purpose of this section is to define the mathematical model for scheduling. The model will
represent the length of a converter cycle as a function of the type and quantity of matte added.

It is possible to estimate the total time to process and handle the matte, slag, blister copper and copper pigs during a typical converter cycle on a "per ladle basis" i.e. minutes per ladle of matte in the absence of crane or other conflicts. Furthermore, separate values can be determined for the hot charge matte, wet charge matte and reactor matte due to the separate locations from which they are picked up by the cranes (matte tunnels 1 and 2 and the north end of the plant) and due to their differing grades and consequentially different processing times in the converter. Finally, these times will differ for each converter due to the differing blowing rates of each converter and due to the differing distances from the matte tunnels, reverb furnaces, anode furnaces and pig storage areas.

Material Content in a Converter Due to and Resulting From the Addition of a Ladle of Matte

The weights of ferrous sulphide, cuprous sulphide, free iron, free copper and slag formed as a result of the addition of one ladle of matte ore are calculated. For a detailed definition of the symbols representing these quantities, refer to Fig. 4.1.
Figure 4.1 Flow Chart for calculating quantities of ferrous sulphide, cuprous sulphide, slag, free iron, free copper (tons) in a ladle of matte of weight W tons and proportions of iron, copper, sulphur of F, C, S respectively.
During the slag phase, the principal chemical reaction is given by:

\[ 2\text{FeS} + 3\text{O}_2 + \text{SiO}_2 \rightarrow 2\text{FeO} \cdot \text{SiO}_2 + 2\text{SO}_2 \quad (1) \]

Any free copper entering with input materials oxidizes instantaneously according to equation (2) and any free iron according to (3), then the resulting FeO combines with the silica to form slag according to (4).

\[ 4\text{Cu} + 2\text{FeS} + \text{O}_2 \rightarrow 2\text{Cu}_2\text{S} + 2\text{FeO} \quad (2) \]

\[ 2\text{Fe} + \text{O}_2 \rightarrow 2\text{FeO} \quad (3) \]

\[ 2\text{FeO} + \text{SiO}_2 \rightarrow 2\text{FeO} \cdot \text{SiO}_2 \quad (4) \]

During the copper phase, incoming oxygen reacts with cuprous sulphide according to equation (5).

\[ \text{Cu}_2\text{S} + \text{O}_2 \rightarrow 2\text{Cu} + \text{SO}_2 \quad (5) \]

Given the proportion by weight of iron, sulphur and copper (Fe, S, Cu) in a ladle of matte, we can calculate the resultant products formed during the converting process. The atomic weights of the elements are:

\[ \text{O} - 16.0 \quad \text{Si} - 28.1 \quad \text{S} - 32.1 \quad \text{Fe} - 55.8 \quad \text{Cu} - 63.5 \]
Case (i) If all the iron enters as ferrous sulphide, we have the condition that there is excess sulphur, the ratio being in excess of that found in the formula FeS i.e. $(S : P) > (32.1 : 55.8) = 0.575$, or $S > 0.575P$. So the proportion of ferrous sulphide present can be expressed in terms of the proportion of iron present by $FS = (32.1 + 55.8) \div 55.6 \times P$ or $F = 1.57F$.

Case (ii) Otherwise, there is no cuprous sulphide as sulphur shows a greater affinity for iron than for copper. All the copper entering is then free copper. The proportion of free iron, $FF$, is given by the total proportion present minus the amount in the ferrous sulphide, i.e. $FF = P - 55.8/(55.8 + 32.1) \times PS = F - 0.64FS$. Now the free copper reacts according to equation (2), consuming the ferrous sulphide in the ratio of $(32.1 + 55.8)/(2 \times 63.5) \times FC$. Therefore, $FS = FS - 0.691FC$. In addition to the original proportion of slag (or waste material) present, fayalite is produced when ferrous oxide combines with the silica flux according to equation (4). The ferrous oxide is partly a result of chemical reaction of free copper and free iron according to equations (2) and (3). So the total proportion of slag present, $SL$, equals the original slag plus these by-products;
1.e. $SL = SL + (2 \times 71.8 + 0.1) / (2 \times 55.8) + (2 \times 71.8 + 60.1) / (4 \times 63.5) \times FC$

   $= SL + 1.825 \times FF + 0.801 \times FC$

If Case (i) is true, $S > 0.575F$; $FS = 1.57F$ and two cases ensue depending on whether all the copper enters as cuprous sulphide or not. The condition that it enters solely as cuprous sulphide is given by $S > 0.575F + (32.1/127)C = 0.575F + 0.252C$. If this is true, there is no free copper or free iron and the proportion of cuprous sulphide present is given by $CS = (127 + 32.1) / 127 \times C = 1.25C$. If it is not true, then some of the copper enters as free copper and all the sulphur has combined to form cuprous sulphide and ferrous sulphide. Hence, the amount of free iron present is n.i. The proportion of cuprous sulphide present is given by $CS = (S - 0.575F) \times (127 + 32.1) / 32.1 = 4.96 \times (S - 0.575F)$ and that of free copper present by $FC = C - (S - 0.575) \times 4.96 \times 127 / 159.1$

   $= C - (S - 0.575) \times 3.96.$

The calculations are summarized in an accompanying flowchart (Fig. 4.1). A similar flowchart was provided by L.K. Nenonen, but the above calculations have been derived independently.
Travel Times of Cranes

Crane travel times are of utmost importance in the model as these times lengthen the converter cycle time when the converter is down at the end of a blow and waiting for the conclusion of service.

Crane travel times were obtained by measuring respective distances on a scaled floor-plan (Fig. 3.4) and dividing by the average crane speed. These crane speeds were verified by observation in the plant itself.

At the start of each converter cycle, reverb matte is added to the converter. The addition limits are specified in Table 4.1. Two ladles of matte (three for converter 7) are required to start blow 1 whereas all other blows require only one ladle of matte to start. The operation of adding reverb matte consists of the following crane tasks: picking up matte, travelling to the converter, pouring matte, travelling to the matte tunnel, depositing ladle. Assuming that each converter receives quantities of hot and wet matte in the same ratio as their respective production rates, the average matte transport addition time for each converter is calculated. Note that the "optimal" ratios of hot to wet charge matte for an individual converter will not necessarily correspond to the matte production ratio. Their calculation is based on best a priori estimates of
<table>
<thead>
<tr>
<th>NCV</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>TOTAL MATTE ALLOWED</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4.1 Matte Addition Limits per Blow
matte transport time. In this particular case the difference in travel times was insignificant. Generally, this calculation procedure would have to be iterative.

The following is an important model approximation. Since the initial positions of the cranes at an individual time can not be found deterministically, allowance is made for increase in cycle time due to crane interference by assigning a full task time when only a partial time would suffice. As an example, suppose converter 4 requires two ladles of matte to start blow #1. The time for adding reverb matte and returning the ladle is 112 seconds plus travel time. If the ratio of the production rate (in ladles) of hot charge matte to that of wet charge matte is c, the time for the operation to take place is: time to add matte + (c x time to travel from converter to matte tunnel 1 and return to converter 4 + time to travel to converter 4 to matte tunnel 2 and return to converter 4) +(c + 1). Assuming c=2, the expression is equal to 112 + (2x78 + 54)/3 = 182 seconds. A likely sequence of events could now be the following. Crane #3 picks up a ladle of wet matte at matte tunnel 2 which takes an estimated 45 seconds, travels to converter 4 in 27 seconds, dumps in the ladle of matte in 37 seconds, and takes 10 seconds to move out of the way of crane #1 (see Fig. 3.4). In the meantime, crane #1 has picked up a ladle of dry matte at tunnel #1 and moves in to pour it into converter 4.
in 37 seconds. The converter then rotates into the stack to start blow #1, using 5 seconds. Thus, converter 4 would be down for 161 seconds and crane service time allowed is 182 seconds, i.e. the two cranes are busy for 182 seconds.

Assuming that slag is returned in equal proportions to each reverberatory furnace, and using operating statistics on the occasions in the converter cycle when it is skimmed, the average times to skim and transport the slag produced per ladle of hot and wet charge matte added to each converter is determined.

The time to tap and transport the blister copper produced per ladle of hot charge and wet charge matte is calculated. Again there is assumption that the blister copper is evenly distributed amongst its possible receivers, namely, the anode furnaces and the pig bay.

Calculation of In-Blow Processing Times

The processing time of materials is now considered. The timing of the chemical reactions, expressed in tons/min., can be summarized by the following three rate equations found in Neonen, Graefe, Stroele [28]:

Consumption of ferrous sulphide = .000016 x AIR x EFF
Production of slag = .000013 x AIR x EFF x (1 + .419 x FRAT)
Oxidation of cuprous sulphide = .0000434 x AIR x EFF
where AIR and EFF measure the air flow entering a converter in standard cubic feet per minute and the proportion of oxygen which actually reacts on its way through the converter. A coefficient FRAT is introduced to approximate the actual rate of silica addition as a factor of the stoichiometric rate. For a complete discussion of this, one may consult Appendix C of the previously mentioned reference.

The number of ladles of slag produced per ladle of matte

\[ \text{Rate FeS consumed} \times \text{Wt ladle slag} \]

\[ = (\text{SLG} + 0.81 \times (1 + 0.419 \times \text{FRAT}) \times \text{FeS}) \times 19/11.9 \]

From plant statistics for the month of December, 1974, it was determined that 14% of the slag is skimmed during the going high (or final slag) blow and the rest during end points.

Miscellaneous Cycle Interruptions

Other than equipment breakdown and servicing, there are some interruptions which are independent of the quantity of matte added to a converter. Notably there is the process of collar pulling which takes about 12 minutes and is dependent on the location of the converter with respect to the collar pulling location. The time taken to
add a skull is similarly dependent. The flue dust addition also lengthens the cycle and adds to the amount of blister copper produced at the end of the cycle.

Operations which increase the cycle time and are dependent on the amount of matte added include skimming of slag during the going high blow (see comment in section 5.1) and the addition of pigs for cooling during the copper blow. Copper pigs are added at the rate of approximately one pig per twenty tons of cuprous sulphide present. There is also, of course, interruption of blow for the addition of matte during the slag phase. In other schedules, there is interruption of the copper blow for the addition of reactor matte which is almost pure white metal.

**The Total Time**

The processing rate for each converter I can be expressed in terms of TH(I) and TW(I), the average times in minutes to process and handle materials contained in one ladle of hot charge matte and wet charge matte respectively. Summing the operations described in this section one can approximate the cycle time as follows:

\[ T(I) = TW(I)NW(I) + TH(I)NH(I) \quad \ldots \quad (6) \]

where

- NW(I) = no. ladles of wet charge matte in converter I
- NH(I) = no. ladles of hot charge matte in converter I
A computer programme which calculates the coefficients $TW(I)$ and $TH(I)$ is included in Appendix A. Refer to variables $VNWM(J)$ and $VNDM(J)$ in the output statement. For the case study presented in detail, the results of these calculations are shown in Table 4.2.

4.3 An Overview of the Optimization Problem

Since it was found that the matte processing rate was independent of the charge cycle length (see Section 4.4), a cyclical schedule was adopted as ideal for the converter aisle as a whole. In conjunction with an on-line computer this could lead to practical implementation involving a short range planning horizon.

The optimization problem is heuristically decomposed into the following layers:

1. The converter aisle matte turnover rate is maximized for a fixed converter charge cycle time, treating the converters as separate non-interfering entities.
2. Wet and hot charge matte are allocated to each converter on a per blow basis.
3. Converter charge cycles are sequenced in time so that the peak demand for crane service due to end of blow operations is kept at or below the availability level.
4. In-blow crane tasks are scheduled so that the other demands for crane service are dispersed.
<table>
<thead>
<tr>
<th>Converter</th>
<th>T</th>
<th>HI</th>
<th>Dry Charge</th>
<th>Wet Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Size</td>
<td></td>
<td></td>
<td>Matte 41% Cu</td>
<td>Matte 32% Cu</td>
</tr>
<tr>
<td>4' 13x30</td>
<td></td>
<td></td>
<td>34.1</td>
<td>39.3</td>
</tr>
<tr>
<td>5 13x30</td>
<td></td>
<td></td>
<td>35.4</td>
<td>40.9</td>
</tr>
<tr>
<td>6 13x30</td>
<td></td>
<td></td>
<td>34.8</td>
<td>40.1</td>
</tr>
<tr>
<td>7 14x32</td>
<td></td>
<td></td>
<td>31.7</td>
<td>36.6</td>
</tr>
</tbody>
</table>

Table 4.2: Average Matte Processing and Handling Times for Each Converter
The non-applicability of the work-shop approach to the particular scheduling problem discussed in this thesis stems from the difference in the factors determining the length of a job. In the job-shop, job duration is a fixed time, though jobs may be pre-empted. In the model derived here, job times are functions of the present and previous contents of the machines. Additionally, job duration may depend on interference with other machines. This branch of theory is thus non-applicable to the model as derived in this thesis.

4.4 Overall Matte Allocation for Maximum Production

The first stage is to determine the number of ladles of hot charge matte $NH(I)$ and wet charge matte $NW(I)$ to be added to converter I such that the overall matte processing rate is maximized, subject to various constraints imposed by smelter operation. In mathematical terms, the maximization problem can be stated as follows:

$$\text{Max } Z = \sum_{I} (NW(I) + NH(I))$$  \hspace{1cm} (7)

for fixed cycle times, reverberatory matte production rates and converter volume capacity constraints. Note that the index I has been assigned values corresponding to the converter numbers used in the actual smelter (Fig. 3.4).

To maintain steady-state smelter operation, the charge/cycle times $T(I)$ for all converters must be equal.
By nature of converter operation, all cycle times can be made to equal some value $T$ minutes only by the addition of slack or converter down time $\Delta T$ as required. $\Delta T$ is the maximum allowable difference between the longest and shortest cycle generated by this optimization. It is undesirable, for example, to have one converter stand idle for half an hour while another is continuously in operation. This situation would result in numerous conflicts at stage (3) of the optimization (Section 4.3) where the individual converter cycles are to be sequenced into a single production cycle. Therefore, if the common cycle time is to be $T$ minutes and the maximum permissible slack time is $\Delta T$ minutes, the corresponding mathematical constraints are:

\[ TW(I)NW(I) + TH(I)NW(I) \leq T \quad (8) \quad I=4,5,6,7 \]

\[ TW(I)NW(I) + TH(I)NH(I) \geq T - \Delta T \quad (9) \quad I=4,5,6,7 \]

Matte must be drawn from the hot charge and wet charge reverberatory furnaces in the same ratio as their respective production rates. If $c$ is the ratio of the production rate of hot matte to that of wet charge matte, this constraint can be expressed mathematically as follows:
\[ \sum_{I=4}^{7} c \times \sum_{I=4}^{7} NW(I) \leq k \] (10)

where \( k \) could be a small positive integer such as 1.

Since \( \sum_{I=4}^{7} NH(I) = c \times \sum_{I=4}^{7} NW(I) \), inequality (10) is simply a statement of the fact that the consumption rate of reverb matte might vary from the production rate by a small integral number of ladles over the duration of the cycle. Translated into smelter operation, this means that the rate of matte production could be altered slightly, which is substantiated by plant operating data.

Converter capacity constraints are expressed as follows:

\[ NW(I) + NH(I) \leq N(I) \] (11) \( I=4,5,6,7 \)

where \( N(I) \) is the capacity in ladles of converter \( I \).

Gomory's all integer programming algorithm [13], coded as GOMGEN, was employed to obtain the numerical solutions to this problem. GOMGEN was supplied courtesy of the Carleton University Computing Centre.

Analyzing the Numerical Results with \( T = 8 \) hours

The problem has been formulated as:

\[ \text{Max } Z = \sum_{I=4}^{7} NH(I) \]

subject to the following constraints:
341NH(4) + 393NW(4) \leq 4544
341NH(4) + 393NW(4) \geq 4444

354NH(5) + 409NW(5) \leq 4580
354NH(5) + 409NW(5) \geq 4480

348NH(6) + 401NW(6) \leq 4617
348NH(6) + 401NW(6) \geq 4417

317NH(7) + 366NW(7) \leq 4598
317NH(7) + 366NW(7) \geq 4498

NH(4) + NW(4) \leq 17

NH(5) + NW(5) \leq 17

NH(6) + NW(6) \leq 17

NH(7) + NW(7) \leq 20

\sum_{I=4}^{7} NH(I) = 2 \times \sum_{I=4}^{7} NW(I)

Note that the time coefficients and constants here are expressed in tenths of a minute, for convenience in a simulation with an integral time variable. A reasonable value for \( \Delta T \) was considered to be 10 minutes. The time coefficients are the results of a computer programme of the
process described in Section 4.2 (See Table 4.2). The limits on the converter capacity constraints can be found in Table 4.1. In actual practice, the variable NH(4) was eliminated using as the production constraint the last equation listed above. This corresponds to the choice of \( c = 2 \) and \( k = 0 \) in equation (10).

The time of certain operations such as collar pulling and skull addition are independent of the ladles of matte added to a converter. However, these differ amongst the converters because of each converter's physical location in the aisle. Thus, the time constraint bounds are different for each converter.

Also, the number of blows per cycle must be originally assumed because these time bounds are functions of the number of slag blows. Thus the process of optimization, here, was an iterative one. Because of these factors, several solutions were obtained in the nominal time region.

Two such solutions are listed in Table 4.4 and will be analyzed. The computer printouts are in Appendix B. It is to be noted, however, that the total matte turnover in the cycle was found to be 51 ladles of matte in every case. A linear programming approach using the same data gave a maximum of 51.2 ladles (Appendix B). Therefore, an
<table>
<thead>
<tr>
<th>Cycle Time</th>
<th>Total Ldles of Matte</th>
<th>Turnover Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hrs.</td>
<td>Mln.</td>
<td>(Ldles/hour)</td>
</tr>
<tr>
<td>8 00</td>
<td>51</td>
<td>6.38</td>
</tr>
<tr>
<td>8 30</td>
<td>54</td>
<td>6.35</td>
</tr>
<tr>
<td>9 00</td>
<td>57</td>
<td>6.33</td>
</tr>
<tr>
<td>9 30</td>
<td>60</td>
<td>6.32</td>
</tr>
<tr>
<td>9 55</td>
<td>63</td>
<td>6.35</td>
</tr>
<tr>
<td>10 25</td>
<td>66</td>
<td>6.33</td>
</tr>
<tr>
<td>11 00</td>
<td>69</td>
<td>6.27</td>
</tr>
</tbody>
</table>

Table 4.3: Maximum smelter capacities for various converter cycle times as determined using a maximization algorithm.
<table>
<thead>
<tr>
<th>CONVERTER</th>
<th>LADLES OF MATTE</th>
<th>BLOWS (ASSUMED)</th>
<th>SLACK TIMES (MINUTES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY</td>
<td>WET</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>C5</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>C6</td>
<td>13</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>C7</td>
<td>11</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CONVERTER</th>
<th>LADLES OF MATTE</th>
<th>BLOWS (ASSUMED)</th>
<th>SLACK TIMES (MINUTES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY</td>
<td>WET</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>11</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>C5</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>C6</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>C7</td>
<td>11</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4.4: CONVERTER MATTE ALLOCATIONS AND SLACK TIMES GIVING MAXIMUM MATTE THROUGHPUT FOR A NOMINAL CONVERTER CHARGE CYCLE OF 8 HOURS
absolute maximum was realized under the prevailing constraints.

Results for a cycle time of 8 hours are given in Table 4.4. Note that two sets of results are given, the first table allowing for a total of four slag blowing periods for converter 4, the second table allowing for five slag blowing periods for converter 4. The solution with five slag blowing periods was chosen as a basis for further work for the following reasons:

1. During the GOMGEN runs it was frequently found that the number of blows initially assumed for each converter was not compatible with the total numbers of ladles of matte handled by the converter. This problem can only be resolved through an iterative scheme. For example, referring to the first solution in Table 4.4, converter 4 handles 12 ladles of matte during four blows, whereas in practice at most 11 ladles are handled in four blows (see Table 4.1).

2. A comparison of slack times indicates a maximum difference in the cycle length of 2.1 minutes for solution 2 as compared with 6.1 minutes for solution 1.

3. It was considered desirable to assign some matte of each kind to each converter. Intuitively, such a scheme should smooth out the demand for each grade of matte.
Although, the resultant matte distributions shown in Table 4.4 are by no means obvious, they do reflect the coefficients of the processing constraints. Converter 7 should be assigned as much dry matte as possible because this is by far the smallest coefficient, i.e. 317 tenths of a minute per ladle of dry matte. This is due to the fact that it has the highest blowing rate and is closest to the reverberatory and anode furnaces. The maximum ladles of dry matte it can process is (4590/317) or 14. However, due to the additional constraint that the ratio of total dry matte to total wet matte must be 2, (i.e. c=2) the solution is eleven dry matte and three wet matte, which is still the maximum total ladles which converter 7 can process in the specified time. Converter 5 is the least efficient mainly because it has the lowest blowing rate. The blowing rates and the locations in the converter aisle for converters 4 and 6 are not significantly different. For this reason, while the distributions of matte for converters 5 and 7 remain the same for solutions #1 and #2 for the reasons given previously, those for converter 4 and converter 6 vary considerably, reflecting the relative insensitivity of the smelter performance to the matte allocations to these two converters.
4.5 Allocation of Matte Ladles to Blowing Period

Having calculated the number of ladles of wet and hot charge matte, NW(I), NH(I), respectively, to be processed by converter I, and using much of the process knowledge from the first stage (Section 4.2), it is possible to determine the number of blowing periods in the converter cycle and their start and end times relative to the starting time for the converter cycle. Understandably, the matte delivery times are now exactly specified which results in modifications to the slack times of Table 4.4. A uniform wet matte turnover rate was ensured using the following heuristic rule. If the total number of ladles of wet matte allocated to a converter is less than or equal to the number of blows, one ladle of wet matte is added at each blow until all wet matte is consumed. If the number of ladles of wet matte is greater than the number of blows (and less than twice the number of blows) two ladles are added to each blow until the number of remaining blows equals the number of remaining ladles of wet matte to be allocated. Then one ladle of wet matte is added per remaining blow. The output of the computer programme CYCLE is a sequence of times indicating the start and end times of each blow for each converter (see Figs. 6.2 - 6.5).
4.6 Determination of the Best Time Spacing Between Converter Cycles

Production delays can arise when crane interference or excessive demands for crane service occur. Effects of crane interference were included in an approximate way in the analysis and computation. This was done by allowing full crane task times where only partial ones were needed to start a blowing period. The problem of limiting the maximum demand for crane service is considered in this section.

Since demands for crane service are highest at end points of converter blowing periods, the maximum demands for crane service can be minimized by proper choice of the time spacing between starting times for each converter charge cycle. Let \( t_4, t_5, t_6 \) be the lengths of time between the start of the cycle for converter 7 and those of converters 4, 5 and 6 respectively. For any given value of \( t_4, t_5, \) and \( t_6, \) crane demand \( n(t) \) as a function of time can be determined by the summation

\[
    n(t) = \sum_{I=4}^{7} n(I, t)
\]

In mathematical terms, the problem is to find the values of \( t_4, t_5, \) and \( t_6 \) which will minimize the maximum demand for crane service:

\[
    \min_{t_4, t_5, t_6} \max_{0 \leq t \leq T} n(t) \quad (12)
\]
where $T$ is the common cycle length. The value of $\max n(t)$ was found by scanning a superposition of the four crane demand functions. To accelerate convergence, it was found useful to modify the criterion function of (12) by adding a counter of .01 every time a crane demand of 4 is encountered. Thus the number of such demands was reduced.

The Optimization Algorithm

Of the variety of methods available, the sequential technique called the Constrained Rosenbrock Hillclimbing Technique was used, coded as ROSY, because the objective function and the constraints were of the exact form so that no transformation of variables was required. The technique is discussed in detail, including flow charts, in Chapter 4 of Rosenbrock [33].

Here is a brief description following the reference. The technique assumes a global maximum; hence, for a general unfamiliar function such as FN several computer runs of ROSY have to be made. Starting values and step sizes must initially be specified by the user for each of the variables. Each variable in turn is increased and if the value of FN improves the move is termed to be successful and the step size is increased by a factor larger than 1. On the other hand, if the value of FN is increased, the step size is decreased by a factor between 0
and 1 and the direction of the step is reversed. If the current point lies outside the feasible region, the objective function FN is modified according to equations (38) and (39) of the reference. The function value is replaced by the best current value in the feasible region. After the search encounters a success and a failure for each variable, the axes are rotated to align them in the direction of the largest optimal change according to equations (24) and (25) of the reference. These steps constitute one stage in the search. The purpose of the rotation is to rapidly align the first axis with a 'ridge' of the performance function. The direction of the second axis tends to align itself in the best direction normal to the first, and so on. The last direction is mutually orthogonal to the others. The search is now continued in each of the new directions. The procedure terminates either when the problem has converged (i.e. the difference in FN from one stage to the next is less than some specified value) or when the maximum number of function evaluations has been exceeded.

**Application of the Algorithm and Results**

The number of interference points was recorded by a counter which adds .01 to the value of FN every time a value of 0 is encountered. In this way the number of interferences is reduced. Only crane demands at end points
of converter blows were included, the crane demand being calculated at two minute time intervals over the cycle time \( T \). At time intervals where the minimized crane demand function exceeded two, additional slack time was introduced into the converter charge cycle, the overall cycle time \( T \) extended and the minimization repeated. An alternative procedure to this would be the reallocation of matte types in a blow to use these as decision variables in order to extend or contract a blow time. However, subsequent implementation of schedules under non-deterministic conditions on the interactive model has convinced the author of this thesis that these could be used as decision variables to return to the ideal schedule in case of slight disruptions.

The initial time spacing was assumed to be such that the copper blow end points were uniformly distributed in the cycle. An iterative scheme was employed whereby the end point of a solution was used as the initial point in the next computer run. The convergence to a good solution was fairly rapid, typically requiring some ten iterations. Referring to Figure 4.2 for maximum matte turnover, under the previously specified conditions, the charge cycles for converters 4, 5 and 6 should start 328, 413 and 170 minutes respectively after that of converter 7. The schedule is outlined in terms of times of service at the start and end blows in Table 4.5. Converter 7 was chosen as the basis
for the fixed cycle for two reasons. First, it had the least amount of slack time available in its cycle. Second, it differed from the other converters in its physical size and also its number of blows per cycle.

4.7 The Determination of Best Timing of In-Blow Converter Tasks

Various additions and removals are made during converter blowing periods where the converter is rotated out of stack only long enough to make the addition or removal. In most cases, these operations can be performed at any time within a limited time interval, permitting their execution while cranes are available. Particular in-blow tasks included in this analysis were; the addition of copper pigs for cooling during the copper stage, addition of matte during slag blows and the removal of converter slag during the going-high (final slag) blow. The same Rosenbrock algorithm was used to determine the best times for executing these in-blow tasks and to minimize the time during which both cranes were in use. For the particular operation considered, the timing of forty-four in-blow tasks was determined. In cases where in-blow tasks could not be inserted without exceeding the demand for crane service, either slack time was inserted into the converter charge cycle, or, in the case of matte additions, the addition was rescheduled for the beginning
of the blow. As a result, for the example used in this thesis, the period of time during which in-blow tasks were executed and both cranes were in use was reduced from 126 minutes to 78 minutes.

This analysis was only performed on the very first model for reasons which will be subsequently discussed. The first model differed from the case study discussed to date in the time and duration of the collar pull. Subsequent changes were performed to agree with smelter operation as in the case study. The Gantt chart for this in-blow study case is found in Fig. 4.3 and the corresponding schedule is found in Table 4.6. Figure 4.4 shows the levels of crane service demanded during the time interval 250-350 minutes for this schedule. The corresponding ROSY listing is appended (Appendix C). Given that these results concern steady-state or undisturbed smelter operation, a number of desirable performance characteristics are noted:

1. Demand for only one crane during the execution of in-blow slag removals and matte additions during the time interval 270 to 290 minutes.

2. No crane demands during the interval 320 to 355 minutes, leaving both cranes free for a 15 minute interval to carry out other miscellaneous duties such as bumping ladles, moving pigs from the pig bay to the pig pile, etc.
Fig. 4.2 Gantt Chart for Sequence of Converter Operations
Fig. 4.3 Gantt Chart for the Very First Case

- B1: Slag Blow No. 1
- COPPER: Copper Blow
- HIGH: Final Slag or Going High Blow
- : Crane Service and Slack Times
<table>
<thead>
<tr>
<th>TIME (min./hr)</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>164</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>204</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>244</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>284</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>324</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>364</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>404</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>444</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>484</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>524</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>564</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>604</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>644</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>684</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>724</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>764</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>804</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>844</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>884</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>924</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>964</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1044</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1084</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1124</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1164</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1204</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1244</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1284</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1324</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1364</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1404</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1444</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1484</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1524</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1564</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1604</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1644</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1684</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1724</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1764</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1804</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1844</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1884</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1924</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2044</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2084</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2124</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2164</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2204</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2244</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2284</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2324</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2364</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2404</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2444</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2484</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2524</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2564</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2604</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2644</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2684</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2724</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2764</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2804</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2844</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2884</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2924</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2964</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3044</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3084</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3124</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3164</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3204</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3244</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3284</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3324</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3364</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3404</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3444</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3484</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3524</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3564</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3604</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3644</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3684</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3724</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3764</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3804</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3844</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3884</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3924</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3964</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4044</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4084</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4124</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4164</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4204</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4244</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4284</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4324</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4364</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4404</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4444</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4484</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4524</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4564</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4604</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4644</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4684</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4724</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4764</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4804</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4844</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4884</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4924</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4964</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 9.5: Timing of Converter Operations for Maximum Converter Production with No Crane Interference**

**Note:** Charge cycle time for all converters = 497 minutes.
A: Service to start new cycle on C4
B: Service for copper blow on C5
C: Skim during high blow on C7
D: Addition of matte to C4 during B1
E: Pig addition to C5
F: Skim during high blow on C7
G: Service to start B3 on C6
H: Service to start B2 on C4
I: Addition of 2 pigs to C5 and matte to C4 and C6
J: Service for copper blow on C7

Fig. 4.4 DEMAND FOR CRANE SERVICE
3. Total delay or slack times of 6% involving converters 4 and 5.

The slack times of converters 4 and 5 could be eliminated by adding wet charge matte rather than dry charge matte to those converters, thus extending their respective blowing periods by about five minutes, hence delaying the demands B and H for crane service (Fig. 4.4). However, if such set matte additions were made, subsequent demands for crane service would be affected in the following undesirable ways:

1. Crane service for the copper blow of converter C5 (segment B, Fig. 4.4) would be delayed by five minutes and no cranes would then be available for the previously scheduled skimming of converter C7, during the going high blow period (segment C, Fig. 4.4).

2. Crane service needed to start blow B2 in converter 4 (segment H, Fig. 4.4) would be delayed by five minutes and no cranes would then be available to add pigs to converter 5 and matte to converter 6.

The schedule implied by this analysis is much more rigid than that employed in practice. For example, while the analysis is based on a fixed policy regarding the accumulation of ferrous sulphide in the converter during the slag blowing periods, in practice, converter operators
effectively vary this policy to cope with problems such as momentary unavailability of cranes, etc. This type of analysis would only be relevant in a purely deterministic system. Since the determination of in-blow tasks is expensive from a computing viewpoint because of the large number of variables and since such a finely detailed schedule would be impossible to implement on a non-deterministic model, this aspect of the analysis was judged to be only useful as an academic exercise and abandoned in the calculations of future schedules.

4.8 Summary

A flow chart of the scheduling technique can be found in Fig. 4.5.

Comparing the results of Table 4.4 with corresponding figures from actual smelter operation, the actual production could, in the limit, be increased somewhat in excess of 25%. It is realized that this is a theoretical deterministic figure and that breakdowns and random variation would reduce the amount of matte produced. Nevertheless, it is felt that a considerable production increase could be realized.

As the smelter operation changed to reverber matte and reactor matte, a schedule was worked out for these
**INPUTS**
- Weight of a ladle of matte
- Matte composition
- Times taken to deliver matte, remove slag, remove copper
- Blow rates, efficiencies

**OUTPUT OF NORANDA**
Total time to process each ladle from the time of removal from reverb to the time of deposit in smelting furnace or pig bay

**OTHER INPUTS**
- A corrected cycle time
- Ratio of wet/dry matte
- Allowable maximum slack time
- Maximum number of ladles per converter

**OUTPUT OF QOMGEN**
Number of ladles of wet and dry matte for each converter to maximise total number of ladles of matte

**OTHER INPUTS**
- Weight of a ladle of matte
- Matte compositions
- Times to deliver matte, remove slag, copper
- Blow rates, efficiencies
- Sequence of maximum allowable number of ladles per blow for each converter

**OUTPUT OF CYCLE**
Sequence of times for start and end of converter blows (transferred to functional form for input to ROST2)

**OUTPUT OF ROST2**
Relative time shift between converter cycles so that the maximum crisis demand is at most 3

**OTHER INPUTS**
- Times for the addition of matte and pigs during blows and skimming while on high blow with estimates of upper and lower time limits

**OUTPUT OF ROST2**
Times for the performance of these various tasks so that the number of times of crisis demand of 3 is minimised

**FIGURE 4.5 GENERAL FLOW CHART FOR DETERMINING OPTIMAL ALELE OPERATION**
operating conditions. A schedule was formulated and validated which would allow the four converter operation in the smelter to be replaced by a three converter operation.

A summary of all the different modes of operation which have been scheduled is listed in Table 4.7.
<table>
<thead>
<tr>
<th># of converters</th>
<th># of cranes</th>
<th>Nominal Cycle Time (hrs.)</th>
<th>Wet Matte</th>
<th>Hot Matte</th>
<th>Reactor Matte</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>8</td>
<td>Yes</td>
<td>Yes</td>
<td>No*</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>7</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>8</td>
<td>Yes</td>
<td>No</td>
<td>Yes*</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>5</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
</tbody>
</table>

*Table 4.7: Classes of Schedules Generated

* Indicates that the schedule was fully validated on the N.R.C. model.*
CHAPTER 5

VALIDATION ON THE INTERACTIVE MODEL

Validation is the process of establishing the accuracy with which the optimization model resembles the system under study. Inferences made in establishing the model are checked by observing if the model behaves as expected. Since a simulation model of this system was available, it was an effective way of showing smelter personnel that the schedules generated were more than a mere academic exercise.

5.1 The N.R.C. Interactive Smelter Model

The copper conversion process is partly discrete, as typified by batch material additions and removals, and partly continuous, as indicated by the chemical conversion process. Therefore, a hybrid computer approach has been used by Graefe, Nenonen, and Strobel [28] to set up an interactive hybrid computer simulation model of the Noranda smelter. Analog computers are used for solving all differential equations associated with the continuous part of the model, while the digital computer handles the discrete event part of the model as well as controlling the analog portion of the model.
Considerable time was spent by the author in running the model to test his optimization and in assisting in the debugging of the model since the original digital computer had been replaced and the analog computer model had been changed from a single analog to two analog computers in slave-master mode. Thus some insight was gained into the operation of the model. In the on-line interaction and display situation, programming oversights could be immediately detected visually and unforeseen model behaviour could be recognized.

The simulation of the smelter comprises the following components:

1. Executive program adapted from GASP
2. Analog-digital and purely digital submodels of the various processes, and material handling facilities.
3. Smelter display unit
4. Operator command entry system

GASP was modified to make it possible for the analog portions of the models to run in continuous time between successive discrete events. During the simulation, time advances twenty times as fast as real time. Each discrete event is assigned an event number which acts as a pointer to the corresponding subsection of a model where actions appropriate to that event are executed. If an end point of a continuous process occurs or if a discrete event occurs which affects the process, the simulation is frozen while
initial or end point conditions are changed in a digital subprogram associated with the analog model of that process.

The author makes no pretense of fathoming the hardware or software of the system which is completely described in N.R.C. report LTR-CS-107 authored by Neenonen, Graefe and Erobele. Emphasis is placed here on the actual operation of the system to verify the optimization techniques employed.

The display board of the model is a scale replica map of the Noranda smelter. Plate 1 and Figure 5.1 were provided by courtesy of the model builders. Three servo-driven crane models show the position and status of the cranes at any instant of time. The status of the converters, reverberatory furnaces, matte tunnels, anode furnaces and reactor plant is indicated by a myriad of coloured lights which cover the display unit (Fig 5.2). In addition there are reactor plant status lights and lights to indicate the availability of cool pigs at the pig bay and pig pile and the status of ladles at the bumping block.

System commands are entered via a teletype. A subprogram decodes the input commands to the model and translates these into corresponding events. Additional smelter information is available from the line printer or
CONVERTERS

1. Matte stage
2. Copper stage
3. At an end point, not blowing
4. Material to be added
5. Empty ladle required
6. Material to be removed

REVERBERATORY FURNACES AND MATTE TUNNELS

1. High slag level
2. High matte level
3. Matte available
4. Matte on matte car
5. Empty ladle needed
6. Full ladle of matte on floor

ANODE FURNACES

1. Blister copper required
2. Full, ready for refining
3. Refined, ready for tapping

* Indicator lights

FIG 5.2 SMELTER DISPLAY UNIT: INFORMATION FORMAT
partial information on the teletype; e.g. the status of the matte tunnels. Information regarding upcoming events in the simulation can thus be obtained. Two digital voltmeters display the simulation time and beeps are used as operator alarms when immediate attention is required, e.g. at the end of a blow. In the event of a bell, the simulation is stopped so that the operator can take time at leisure to make the best decisions for future commands.

A strip chart recorder may be used as a peripheral device and it gives blow profiles similar to Figure 3.3 as well as elapsed simulation time. A copy of such a chart is included with one of the sample schedule validations found in Appendix D.

The simulation model has been validated by experienced converter foremen who directed the operation of the model and, using the display unit, checked that the various operations responded in a manner similar to that of the real smelter. After a short while they were able to give instructions to simulate several shifts in which realistic matte, slag and copper production figures were obtained. The ease with which non-computer oriented people have used the model, with the converter aisle display unit, indicates that the model is a useful tool for the training of new foremen and for allowing experienced foremen to experiment with new operating strategies without making
costly mistakes in the plant. The development of a programme for the further training of foremen along these lines was, at one time, considered.

Other published works describing the operation of the model include: Pannel, Nenonen, Graefe and Strobele [31]; Graefe and Nenonen [14]; Graefé, Nenonen and Strobele [16], [17]; Nenonen and Graefe [27].

An Important Model (and Optimization) Assumption

The end point of a matte blow should be determined from metallurgical considerations. "Slag is usually skimmed at 2250 degrees Fahrenheit where viscosity is suitable." [27] In smelter practice, end points are largely determined by the mood of the converter foreman. Some foremen skim at fixed time intervals, no matter what the contents of the converter may be. The model and optimization do not operate on temperature considerations. Rather, a fixed percentage of the total amount of iron sulphide present during a matte blow is blown. This percentage has been determined to satisfy the observations of several senior plant converter aisle personnel. Of course, there is no choice during the going high (or last) slag blow as all the ferrous sulphide gets converted to slag. Similarly, during the copper blow all the cuprous sulphide is oxidized. Moreover, theoretical studies have
revealed that the rate of oxidation is approximately linear and therefore independent of the amount of FeS/Cu₂S present [27].

5.2 Description of a Validation Run

This section describes the operation of the simulation model. Included is a detailed description of a portion of one of the validation runs.

A glossary of the N.R.C. model system commands is found in Appendix D prior to two validation runs of the case study. The first run is in deterministic mode. The second allows for a standard deviation of .05 in the blowing rates of the converters and the length of matte blows. Both runs are for a duration of one cycle i.e. 8 hrs, 11 minutes simulation time.

A glance at Figure 4.2 will verify the fact that all aspects of the operation would be included by a study of the first two hours and fifty-one minutes of the cycle, i.e. at the end of which converter 6 should start on blow #1. The first (deterministic) run will be scrutinized.

The starting time in the simulation is one minute before the start of blow #1 in converter 7. The minute of simulation time, free of assigned tasks, allows the user to
move crane #2 out of the way. Recall that this is the third crane not used in the actual converter cycle operation.

The notes are separated by the event of a converter coming down at the end of a blow. These places are marked on the corresponding listing found in Appendix D.

Note 1: - The date is a fictional one. ENTER is the cue for the user to enter a command. INFOGP asks for information of upcoming GASP events to be printed out on the line printer. Note that comments during the run are included as "orders" followed by CC to cancel the "order" given in the previous line. So it is determined that converter 4 is coming down at the end of blow #3 at time 5 minutes, 1 minute early. TTY SAYS PERTURBED FES POLICY ONLY is a message to remind the N.R.C. personnel of a print malfunction as the run is being made in the deterministic mode. INFOM1 provides information about the matte tunnels which is printed. -1 matte on car indicates that empty ladles are needed both at matte tunnel 1 and 2. WAIT2,PP, commands crane #2 to go to the pig pile and wait for further instructions. This crane is not used in the simulation and has been effectively removed from the board at the north end of the smelter. Refer to Figure 3.4 for a better understanding of the manoeuvres. Crane #3 is ordered to go to converter 4 and wait as converter 4 is coming down
shortly (WAIT3,C4,). EVENT 44 signifies that a full ladle of dry matte has arrived at matte tunnel #1. Crane #1 is told to pick the matte off the car and place it on the floor adjacent to matte tunnel #1.

Note 2: - EVENT 286 signifies that converter 4 has come down at the end of matte blow #3. There are 3 ladles of slag to be skimmed as indicated by the printout. Crane #3 is instructed to pick up slag from converter 4, dump it into reverb 3 and return to converter 4 by PDSL3,C4,R3,. The instructions to crane #1 are somewhat different. Recall that it is occupied in lowering a ladle of matte to the tunnel floor. Subsequently, it will go to converter 4 and pick up a ladle of slag (PKSL1,C4) and dump it in reverb 2' (DPSL1,R2,). In the meantime, crane #3 will finish the slag skim on converter 4 (PKSL3,C4,). While this is going on, crane #1 can pick up some dry matte at matte tunnel #1 (PKM1,M1,) and go to converter 4 to wait for crane #3 to finish skimming the slag (WAIT1,C4,). When crane #3 is finished, it moves aside to allow crane #1 to dump the matte into converter 4 so that it may begin blow #4 (DPMT1,C4,). Afterwards, crane #3 will dump the slag into reverb #3 (DPSL3,R3,). The advantage of this procedure is that converter 4 can begin its blow without having to wait for crane #3 to dump the slag. While all this is going on, a message is typed out that there is now only one ladle of matte on the floor at matte tunnel #1.
We are also told that converter 4 contains 3 ladles of copper and could go on its high blow. However, this is not on our schedule so, we refuse the offer and begin blow #4 on converter 4. A message arrives that converter 4 is due for a collar pull. This will be attended to presently by crane #3 so that crane #1 will still be free to attend to converters 5 and 7 even though it will be blocked out from converter 6 by crane #3 collar pulling (PULL3,C4). EVENT 45 signifies the arrival of a ladle of wet matte. Crane #1 is told to pick it off the car and dump it on the floor at matte tunnel #2 (PDM1,M2,M2). EVENT 91 simply signifies that converter 4 is not completely filled for a matte blow and could use another ladle of matte. On the board this fact is indicated by converter light #4 being on (Figure 5.2). At 18 minutes another ladle of dry matte arrives at matte tunnel #1 and is picked up and placed on the floor by Crane #1 (EVENT 44;PDM1,M1,M1). In the future, only new commands and events will be given in code. At time 20 minutes, Crane #3 finishes the collar pull. It then picks up one ladle of dry matte and dumps it into converter 4 which is now filled for blow #4. More dry matte arrives at 32 minutes and is placed on the floor by crane #1. Crane #3 dumps a ladle to cool at the bumping block so that another skull may be formed for later use (DPLD3, BB). Crane #3 then bumps a ladle to form a skull (BUMP3, BB). GASP says that converter 6 is due to come down at the end of its going high blow at time 36 minutes as scheduled.
Crane #3 is dispatched to wait at converter 6 so that it is ready to skim slag.

Note 3: - EVENT 288 signifies that converter 6 comes down at the end of its high blow. Crane #3 skims the slag. Crane #1 picks up the flue dust from a nearby bin (PKFD1,F6,) and dumps it into converter 6 (DPFD1,C6,). Converter 6 starts its copper blow 2 minutes early. A second ladle of slag is skimmed by crane #3 because all residual slag must be removed since this was the end of the final slag blow. Meanwhile, at time 39 minutes, converter 5 has come down at the end of blow #2. Three ladles of slag are to be skimmed. Crane #1 dumps two of these three ladles into reverb 1 while crane #3 dumps one ladle into reverb 3. Notice that the final skimming done by each crane has again been fragmented to avoid a wasted trip back to converter 5. Instead, each crane is ready to proceed from the respective reverb to another task. Crane #3 picks up a ladle of wet matte from matte tunnel #2 and dumps it into converter 5. Converter 5 starts blow #3 at time 51 minutes, 1 minute behind schedule. A ladle of wet matte arrived at 42 minutes and a ladle of dry matte arrived at 45 minutes.

Note 4: - Converter 7 comes down at 51 minutes at the end of blow #1. Three ladles of slag are skimmed. Crane
#1 dumps two ladles of slag into reverb 1 and crane #3 dumps the other into reverb 3. Crane #1 picks up a ladle of wet matte. It dumps it into converter 7 to start blow #2 at time 1:00 hours. Crane #1 then adds 1 ladle of dry matte to converter 5 to fill it for blow #3. It then dumps in two ladles of dry matte into converter 7 to fill it for blow #2. At 1:04 EVENT 268 signals the need for a copper pig in converter 6 which is in its copper blow. Crane #3 picks up a pig at the pig bay and adds it to converter 6 (PDPG3, PB, C6,).

Note 5: - Converter 4 comes down at the end of blow #4 at 1:07. Crane #3 dumps the two ladles of slag, one ladle into each of reverb furnaces 3 and 2. Crane #1 adds one ladle of dry matte to start the next blow. Converter 4 resumes its blow at 1:16. More matte arrives at the tunnels at 1:14 and 1:16. Crane #3 dumps a ladle of wet matte to the tunnel floor, then adds a pig to converter 6. Crane #1 adds a dry matte to converter 4 which is not allowed to proceed with its going high blow. More dry matte arrives at 1:30. Information on matte tunnels reveals no dry matte and two wet matte on the floor. One more ladle of matte is added to converter 7 to fill it for blow #2. PAUSE 00001 is an indication of a software problem which required the resetting of some logic switches. A ladle of wet matte arrives at 1:43.
Note 6: - At 1:44 converter 5 comes down at the end of blow #3, three minutes early. Crane #3 dumps one ladle of slag into reverb 3 while crane #1 dumps the other into reverb 2. A ladle of dry matte arrives at matte tunnel #1 at 1:45. Crane #3 adds one ladle of wet matte and crane #1 adds one ladle of dry matte to converter 5. There is little to choose between the cranes here. Perhaps crane #1 should have been assigned this task so pigs could be delivered by crane #3 to converter 6 when requested. A ladle of dry matte arrives at 2:00 and is placed on the floor by crane #1. The nature of the model is such that no new matte will be generated while there is matte on a car. Hence, the choice was made for the collar pull as is. After finishing the collar pull on converter 5, crane #3 delivers a pig from the pig bay to converter 6.

Note 7: - At 2:02 converter 7 comes down at the end of blow #2, 3 minutes early. Three ladles of slag are dispersed in the following manner. Crane #1 dumps two ladles into reverb 1 while crane #3 dumps the other into reverb 3. A check is made at this time of the matte available. An erroneous message leads to another PAUSE message. A ladle of dry matte arrives at 2:10. After the mistaken messages are cleared, two ladles of dry matte are added by crane #1 to converter 7 which starts blow #3 at 2:14, on time, with a request for a collar pull. EVENT 94 is merely a request for more dry charge reverb matte as the
Crane operations by crane #1 have not yet been carried out. Obviously, crane #1 is assigned the task for collar pulling on converter 7. Crane #3, meantime, skims converter 4 which is in its high blow and adds a pig to converter 6 which is in its copper blow. Wet matte arrives in the tunnel at 2:23 and dry matte at 2:26. At the end of the collar pull crane #1 dumps a ladle of dry matte to the tunnel floor.

Note 8: - Converter 6 comes down at the end of its copper blow at 2:28, two minutes late. There are 6 ladles of copper to be dispersed. Crane #3 picks up a skull at the bumping block and dumps it into converter 6 (PDSK3,BB,C6). One ladle is poured into pigs at the pig bay by crane #3. One ladle is taken to anode furnace 5 by crane #1. Four ladles of copper are delivered to anode #6, two each by each of the cranes. As soon as converter 6 is cleared, a status report is typed out on the converters. A ladle of dry matte arrives at 2:42. Crane #3 dumps in two wet matte and crane #1 dumps in two dry matte into converter 6 to start a new cycle at 2:48, three minutes early.

And so it continues ..., for a cycle length of 8 hours 11 minutes.
5.3 Summary of Results

The following is a summary of two deterministic simulation runs using the case schedule for a simulation time of one cycle. The first set of data apply to the appended simulation copy. The differences between run A and run B are mostly finger trouble at the keyboard, since each run involved hundreds of keyboard entries over five or six hours. The numbers represent times in minutes; '+' indicates ahead of desired schedule, '-' indicates behind schedule, '0' indicates dead on time.

<table>
<thead>
<tr>
<th>Converter</th>
<th>Time at End of First Blow in Simulation</th>
<th>Time at End of Last Blow in Simulation</th>
<th>Net Change in Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run A</td>
<td>Run B</td>
<td>Run A</td>
</tr>
<tr>
<td>#4</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>#5</td>
<td>+4</td>
<td>+5</td>
<td>-4</td>
</tr>
<tr>
<td>#6</td>
<td>-1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>#7</td>
<td>-1</td>
<td>0</td>
<td>+3</td>
</tr>
</tbody>
</table>
Also, a non-deterministic run was done with a random variation of 5% in both the blow rates and percent ferrous sulphide oxidized per blow. From the run listing in Appendix D, we see that in all cases the converters gained time; the respective gains being twelve minutes, one minute, nine minutes, and six minutes for converters 4, 5, 6 and 7 respectively. In addition other runs were made by Dr. Graefe and Mr. Nenonen which substantiated the implementation of the schedule on the model.

Thus a stable matte turnover of 51 ladles per cycle has been attained. The previous best matte turnover rates achieved with the model, using operator knowledge of the process, were of the order of 40 ladles per 8 hour shift with the resulting subsequent shift being left in a semi-chaotic state.

A schedule was worked out and implemented on the N.R.C. interactive model involving a cycle length of 6 hours operating with 3 converters and 2 cranes using reactor matte as well as dry and wet charge reverberatory matte. At the time the Noranda smelter was obtaining the same turnover with 4 converters. It was shown that under the assumptions of the model, which after all had been verified by smelter personnel over a period of some six years, not only could the turnover be handled by 3 converters but there was, additionally, slack in each converter cycle of
one-half hour, one-half hour and forty-five minutes to account for delays due to random disruptions. This schedule was also validated with runs of twelve hour duration both in the deterministic and in the variable mode.
CHAPTER 6

REACHING THE OPTIMAL CYCLE

6.1 Introduction

To get onto the known cycle from an arbitrary state is a very important part of this analysis because the smelter will not have the initial values suggested in the simulation. It will be assumed that there is some semblance between the smelter operation and the optimization. In particular, it will be assumed that the converter can be identified as being at a particular time in the optimal cycle from its past history of material inputs, number of blows in the current cycle and its time in the current blow. Then during the transient schedule, the converters will converge to a common ideal time by control of the addition of type and quantity of matte. The same type of analysis will hold if one of the converters should radically fall out of phase from its optimal schedule.

6.2 Steps in Calculating the Transient Schedules

To expedite the formulation of transient schedules, the following terminology is defined:
$T_f$: common optimal cycle length

$T(I)$: the time since the start of its cycle for converter $I$.

$T_i(I)$: the initial converter phase time for converter $I$ relative to the start of the converter aisle optimal cycle.

$T_f$: the phase time within the optimal cycle corresponding to the end of the transient schedule.

For illustrative purposes, the following times were chosen at random:

$T_i(4) = 364$

$T_i(5) = 19$

$T_i(6) = 0$

$T_i(7) = 112$ (see Fig. 6.1).

These times correspond to an initial state with:

- converter 4 near the end of blow #1
- converter 5 midway through blow #2
- converter 6 towards the end of the going high blow
- converter 7 near the end of blow #2

**Step 1: Assignment of a value for $T_f$.**

The average of $T_i(I)$ is taken to be $T_f$.

i.e. $T_f = \frac{1}{4} \sum_{I=4}^{I=7} T_i(I)$
Times associated with a transient schedule.
In the example transient schedule, $T_f = 124$. Thus referring to Fig. 6.1 once again we see that converter 4 must lose considerable time and all other converters must gain. However, converter 7 needs to gain only 12 minutes.

The average value is chosen to be the target time because:

1. Matte losses by one converter are translated into time gains. These lades of matte may then be translated into time losses for the other converters by their addition. Thus, one preserves matte balance during the transient schedule.

2. The average time represents the least amount of total shift in the individual converter cycles, i.e. it minimizes $\min_{I=4}^{7} (T_f - T_i(I))$.

The length of the transient cycle is chosen to be $T$ for the following reasons. If the optimal cycle is attained by matte exchanges among the converters during time $T$, we know that one can not improve on the processing rate during this time interval. If one aims at the endpoints corresponding to $T_f$, there is good probability that there will be no interference among crane demands in this neighborhood. In any case, the lower limit for the length of a transient cycle must exceed the combined times for the copper blow and going high blow because once a converter has started its going high blow the end of its charge cycle is fixed. This lower time limit is of the
order of one-half $T$. So the problem becomes one of matte juggling.

**Step 2:** Matte juggling to attain $T_f$.

The schedule which the juggling of matte ladles attains is a standard cycle starting at the given converters' starting phase.

Referring to Table 4.2, one can only change the time for converter $I$ in units of $T(H(I))$, $T(W(I))$ and $(T(W(I)) - T(H(I)))$. The degree of accuracy is considered to be satisfactory if the difference between the target time and the indicated time of convergence is of the order of $T(W(I)) - T(H(I))$. Recall that these time coefficients are not exact, but are a function of the number of blows per cycle as well as the type and quantity of matte added.

The order of time juggling is in increasing values of magnitude of $|T_f - T_i(I)|$. If this value is less than $T(H(I))$ and such that $T(H(I)) - (T_f - T_i(I)) > T(W(I)) - T(H(I))$, the addition is performed entirely in units of $T(W(I)) - T(H(I))$. Otherwise, check if $(T_f - T_i(I)) \mod T(W(I))$, or $(T_f - T_i(I)) \mod T(H(I))$ is of the order of $T(W(I)) - T(H(I))$. If this is the case, the matte re-distribution is solved. Otherwise, take the least of the above values in magnitude and correct for the remainder of time in units of
TW(I) - TH(I). Finally, the largest value of Tf - Ti(I) should correspond to the negatives of matte changes in the other converters.

The transient cycle requirements for the sample schedule are summarized in the following table:

<table>
<thead>
<tr>
<th>Converter</th>
<th>Initial Position</th>
<th>Final Position</th>
<th>Tf-Ti(I) minutes</th>
<th>Matte Changes</th>
<th>Equivalent Time Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>7 min. to end of B#1</td>
<td>62 min. to end of High</td>
<td>-240</td>
<td>+ 1 dry</td>
<td>-34 -197=</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>24 min.to end of B#2</td>
<td>54 min. to end of B#4</td>
<td>+105</td>
<td>- 3 dry</td>
<td>+106</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>36 min. to end of High</td>
<td>22 min.to end of CU</td>
<td>+124</td>
<td>- 3 wet</td>
<td>+120</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>12 min. to end of B#2</td>
<td>At end of B#2</td>
<td>+12</td>
<td>- 2 wet</td>
<td>+10</td>
</tr>
</tbody>
</table>

It is clear that converter 4 cannot continue in a single charge cycle because it has to lose 240 minutes and the addition of so much matte would violate the volume constraints specified in Table 4.1. The six extra ladles of matte must be carefully distributed over the transient cycle to avoid excessive crane demand. In fact, there is a
lot of flexibility in this and conflict with other converter end of blow points may be easily avoided.

Note that converter 4 is out from its final ideal position by 9 minutes. However, the time it must gain is 4 hours and the coefficients obtained from Step 2 are based on an average per ladle process time.

**Step 3: Shift to avoid crane conflicts**

The optimal cycles before shifting, are included as Figures 6.2 - 6.5. Note that natural slacks exist here which one can use during the transient cycles. Also, matte distribution for each blow is indicated as well as the number of ladles of copper produced in each cycle. The times here are in tenths of a minute.

Transient cycles were now generated using the computer programme CYCLE. Converter 7 was given a ladle of hot matte instead of wet matte for blow #3 and similarly for blow #1 to start its next charge cycle. As can be seen from Fig. 6.6, the transient cycle has seven and a half minutes of slack.

Converter 6 is in its high blow, so there is no choice but to end its present charge cycle. The transient cycle is obtained by omitting 3 ladles of wet matte and
Fig. 6.2

BLOW #1 STARTS AT T = 30
BLOW #1 ENDS AT T = 456

BLOW #2 STARTS AT T = 552
BLOW #2 ENDS AT T = 1109
BLOW #3 STARTS AT T = 1207
BLOW #3 ENDS AT T = 1704

BLOW #4 STARTS AT T = 1804
BLOW #4 ENDS AT T = 2361

BLOW #5 STARTS AT T = 2459

END OF GOING HI BLOW OCCURS AT T = 3470
COPPER BLOW STARTS AT T = 3532

END OF CU BLOW AT T = 4668
COPPER = 5.72609

END OF CYCLE FOR CONVERTER #4 OCCURS AT T = 4841

THE AMOUNT OF BLACK TIME IN THIS CYCLE IS 69 TENTHS OF A MINUTE

Fig. 6.3

BLOW #1 STARTS AT T = 22
BLOW #1 ENDS AT T = 501

BLOW #2 STARTS AT T = 577
BLOW #2 ENDS AT T = 1162
BLOW #3 STARTS AT T = 1258
BLOW #3 ENDS AT T = 1823

BLOW #4 STARTS AT T = 1899
BLOW #4 ENDS AT T = 2532
BLOW #5 STARTS AT T = 2607

END OF GOING HI BLOW OCCURS AT T = 3571
COPPER BLOW STARTS AT T = 3625

END OF CU BLOW AT T = 4702
COPPER = 5.27069

END OF CYCLE FOR CONVERTER #5 OCCURS AT T = 4839

THE AMOUNT OF BLACK TIME IN THIS CYCLE IS 51 TENTHS OF A MINUTE
NDBLO(1) = 2
MBLLO(1) = 2
NDBLO(2) = 2
NMBLLO(2) = 1
NDBLO(3) = 1
NWBLO(3) = 1
NDBLO(4) = 1
NMBLLO(4) = 1
NDBLO(5) = 0
NWBLO(5) = 1

Fig. 6.4

BLOW #1 STARTS AT T = 32
BLOW #1 ENDS AT T = 492
BLOW #2 STARTS AT T = 503
BLOW #2 ENDS AT T = 1173
BLOW #3 STARTS AT T = 1274
BLOW #3 ENDS AT T = 1816
BLOW #4 STARTS AT T = 1917
BLOW #4 ENDS AT T = 2528
BLOW #5 STARTS AT T = 2627
END OF GOING HI BLOW OCCURS AT T = 3552
COPPER BLOW STARTS AT T = 3616
END OF CU BLOW AT T = 4650
COPPER = 5.27069

END OF CYCLE FOR CONVERTER #6 OCCURS AT T = 4829
THE AMOUNT OF BLACK TIME IN THIS CYCLE IS 81 TENTHS OF A MINUTE

NDBLO(1) = 4
MBLLO(1) = 1
NDBLO(2) = 3
NMBLLO(2) = 1
NDBLO(3) = 2
NWBLO(3) = 1
NDBLO(4) = 2
NWBLO(4) = 0

Fig. 6.5

BLOW #1 STARTS AT T = 71
BLOW #1 ENDS AT T = 521
BLOW #2 STARTS AT T = 596
BLOW #2 ENDS AT T = 1245
BLOW #3 STARTS AT T = 1358
BLOW #3 ENDS AT T = 2111
BLOW #4 STARTS AT T = 2186
END OF GOING HI BLOW OCCURS AT T = 3403
COPPER BLOW STARTS AT T = 3475
END OF CU BLOW AT T = 4622
COPPER = 6.28925

END OF CYCLE FOR CONVERTER #7 OCCURS AT T = 4805
THE AMOUNT OF BLACK TIME IN THIS CYCLE IS 105 TENTHS OF A MINUTE
going high on blow #3. This isolated transient cycle provides some 20 minutes of slack time (Fig. 6.7).

Similarly, Figs. 6.8 and 6.9 reveal slack times of 20 minutes and 10 minutes respectively for converters 5 and 4. The transient cycle for converter C4 can be juggled somewhat if need be, because it consists of parts of two regular charge cycles and the end point of the first charge cycle is therefore flexible.

The process of forming a transient cycle for all the converters together is simply to start with the one with the least slack, i.e. converter 7, and then superimpose the others in order of increasing slack. If this procedure should fail, one can always recalculate a different transient cycle for converter 4. The nice feature about this is that this transient schedule is optimal since no more matte than this can be processed in the given time interval as was shown previously by the linear programming approach. The meshed transient cycle schedule showing times of crane service at the end of blows is shown in Table 6.1. The slack times at the end of the transient cycle are:

<table>
<thead>
<tr>
<th>Converters</th>
<th>Slacks (in minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 4</td>
<td>10</td>
</tr>
<tr>
<td># 5</td>
<td>13</td>
</tr>
<tr>
<td># 6</td>
<td>20</td>
</tr>
<tr>
<td># 7</td>
<td>4</td>
</tr>
</tbody>
</table>
Fig. 6.6

BLOW #1 ENDS AT T= 70
BLOW #2 STARTS AT T= 145
BLOW #2 ENDS AT T= 240
BLOW #3 STARTS AT T= 044
END OF GOING HI BLOW OCCURS AT T= 2038
COPPER BLOW STARTS AT T= 2125
END OF CU BLOW AT T= 2891
COPPER = 4.07445
END OF CYCLE FOR CONVERTER #4 OCCURS AT T= 3037
MDBL(1) = 2
MDBL(1) = 1
MDBL(2) = 2
MDBL(2) = 0
MDBL(3) = 1
MDBL(4) = 1
MDBL(4) = 1
BLOW #1 STARTS AT T= 3067
BLOW #1 ENDS AT T= 3390
BLOW #2 STARTS AT T= 3446
BLOW #2 ENDS AT T= 3840
BLOW #3 STARTS AT T= 3914
BLOW #3 ENDS AT T= 4342
BLOW #4 STARTS AT T= 4416

THE AMOUNT OF SLACK TIME IN THIS CYCLE IS 102 TENTHS OF A MINUTE

Fig. 6.7

BLOW #2 ENDS AT T= 240
BLOW #3 STARTS AT T= 315
END OF GOING HI BLOW OCCURS AT T= 1427
COPPER BLOW STARTS AT T= 1717
END OF CU BLOW AT T= 2531
COPPER = 4.07445
END OF CYCLE FOR CONVERTER #5 OCCURS AT T= 2444
MDBL(1) = 1
MDBL(1) = 3
MDBL(2) = 2
MDBL(2) = 1
MDBL(3) = 1
MDBL(3) = 1
MDBL(4) = 1
MDBL(4) = 1
MDBL(5) = 0
MDBL(5) = 1
BLOW #1 STARTS AT T= 2488
BLOW #1 ENDS AT T= 3195
BLOW #2 STARTS AT T= 3271
BLOW #2 ENDS AT T= 3891
BLOW #3 STARTS AT T= 3967
BLOW #3 ENDS AT T= 4627
BLOW #4 STARTS AT T= 4703

THE AMOUNT OF SLACK TIME IN THIS CYCLE IS 195 TENTHS OF A MINUTE
END OF GOING HI BLOW OCCURS AT T = 360
COPPER BLOW STARTS AT T = 424

END OF CU BLOW AT T = 1458
COPPER = 5.27069

END OF CYCLE FOR CONVERTER #6 OCCURS AT T = 1637

NDBLO(1) = 2
NDWLO(1) = 2
NDWLO(2) = 2
NDWLO(2) = 1
NDWLO(3) = 2

NDWLO(3) = 0

BLOW #1 STARTS AT T = 1669
BLOW #1 ENDS AT T = 2129

BLOW #2 STARTS AT T = 2230
BLOW #2 ENDS AT T = 2810
BLOW #3 STARTS AT T = 2913

END OF GOING HI BLOW OCCURS AT T = 4052
COPPER BLOW STARTS AT T = 4139

THE AMOUNT OF SLACK TIME IN THIS CYCLE IS 201 TENTHS OF A MINUTE

NDBLO(1) = 4
NDWLO(1) = 1
NDWLO(2) = 3
NDWLO(2) = 1
NDWLO(3) = 3

NDWLO(3) = 0
NDWLO(4) = 2
NDWLO(4) = 0

BLOW #2 ENDS AT T = 124
BLOW #3 STARTS AT T = 217
BLOW #3 ENDS AT T = .945
BLOW #4 STARTS AT T = 1020

END OF GOING HI BLOW OCCURS AT T = 220A
COPPER BLOW STARTS AT T = 2278

END OF CYCLE FOR CONVERTER #7 OCCURS AT T = 3608
NDWLO(1) = 5
NDWLO(1) = 0
NDWLO(2) = 3
NDWLO(2) = 1
NDWLO(3) = 2
NDWLO(3) = 1
NDWLO(4) = 2
NDWLO(4) = 0

BLOW #1 STARTS AT T = 3639
BLOW #1 ENDS AT T = 4105
BLOW #2 STARTS AT T = 4180
BLOW #2 ENDS AT T = 4835

THE AMOUNT OF SLACK TIME IN THIS CYCLE IS 75 TENTHS OF A MINUTE
Table 6.1: The Transient Cycle

<table>
<thead>
<tr>
<th>Time Interval (Minutes)</th>
<th>Service Provided for Blow</th>
<th>Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:07-0:17</td>
<td>#2</td>
<td>C4</td>
</tr>
<tr>
<td>0:17-0:27</td>
<td>#3</td>
<td>C7</td>
</tr>
<tr>
<td>0:27-0:35</td>
<td>#2</td>
<td>C5</td>
</tr>
<tr>
<td>0:36-0:43</td>
<td>Copper</td>
<td>C6</td>
</tr>
<tr>
<td>1:15-1:24</td>
<td>High</td>
<td>C4</td>
</tr>
<tr>
<td>1:40-1:47</td>
<td>High</td>
<td>C7</td>
</tr>
<tr>
<td>2:26-2:48</td>
<td>ESER</td>
<td>C6</td>
</tr>
<tr>
<td>2:51-3:00</td>
<td>Copper</td>
<td>C5</td>
</tr>
<tr>
<td>3:24-3:32</td>
<td>Copper</td>
<td>C4</td>
</tr>
<tr>
<td>3:34-3:44</td>
<td>#2</td>
<td>C6</td>
</tr>
<tr>
<td>3:44-3:51</td>
<td>Copper</td>
<td>C7</td>
</tr>
<tr>
<td>4:20-4:36</td>
<td>ESER</td>
<td>C5</td>
</tr>
<tr>
<td>4:42-4:51</td>
<td>High</td>
<td>C6</td>
</tr>
<tr>
<td>4:51-5:07</td>
<td>ESER</td>
<td>C4</td>
</tr>
<tr>
<td>5:27-5:34</td>
<td>#2</td>
<td>C5</td>
</tr>
<tr>
<td>5:39-5:47</td>
<td>#2</td>
<td>C4</td>
</tr>
<tr>
<td>5:47-6:09</td>
<td>ESER</td>
<td>C7</td>
</tr>
<tr>
<td>6:24-6:31</td>
<td>#3</td>
<td>C4</td>
</tr>
<tr>
<td>6:36-6:44</td>
<td>#3</td>
<td>C5</td>
</tr>
<tr>
<td>6:45-6:54</td>
<td>Copper</td>
<td>C6</td>
</tr>
<tr>
<td>6:54-7:02</td>
<td>#2</td>
<td>C7</td>
</tr>
<tr>
<td>7:14-7:22</td>
<td>High</td>
<td>C4</td>
</tr>
</tbody>
</table>

*ESER represents service at the end of a copper blow, including preparation for blow #1 in the next charge cycle.
Clearly, the ability to generate a transient cycle is important to the task of reaching an optimal schedule. Five such transient schedules have been successfully calculated. That is to say, of five attempts, all have been successful. It is conceivable, however, that conditions could be so chaotic that some delay is inevitable. This would occur if several converters were initially down at the end of a copper blow. Then there would be an inevitable X minutes of slack time during which some of the converters may well have to stand idle.

6.3 Practical Implementation of this Scheduling Approach

In order to implement this scheduling approach in a copper smelter the following steps are necessary:

1. An accurate evaluation of the parameters of the system and acceptable modes of smelter operation agreed upon by both management and workers. Possibly an automatic entering of events as they occur.

2. Condensation of the computer programmes used in the scheduling into a single package so that given a change in operation, a transient schedule is immediately obtained.

3. On-line terminal facilities at the smelter in an isolated environment so that the computer package
may be instantaneously applied.

4. Radio communication (or teletype) to the crane operators outlining an updated version of the next five major tasks, say, which their crane will have to perform. This would still leave free time to the operators to perform miscellaneous tasks.
CHAPTER 7

CONCLUSIONS

A methodology has been established for generating converter schedules which show great promise of increased converting potential in a copper smelter. A decomposition of the original problem into a number of subproblems constitutes part of the analysis. Computer programmes have been coded to calculate processing time coefficients, to generate converter cycle times and to search for an acceptable 'optimal' value for a superposition of discontinuous (histogram shaped) functions.

A schedule has been generated for a four converter, two matte grade, two crane operation. Smelter production corresponding to this schedule can be interpreted as an upper limit and suggests that if one were able to eliminate all random effects, actual production could be increased by 20 to 25%. While the schedule so generated may not be absolutely 'optimal' in a mathematical sense, it has been shown to be optimal in a realistic sense. Linear programming techniques have shown that a higher matte processing rate is not possible for the given values of the parameters.
An important aspect of model building is the degree of approximation to real-life. Schedules generated were validated on the N.R.C. simulation not only by the author but by the builders of the model and senior smelter personnel. The net result was a 33% increase in the matte turnover rate as compared to any previous run on the model. Furthermore, because of the cyclical nature of the schedule, the end of a simulation period was characterized by conditions identical to the start.

At the request of Noranda Mines Ltd. a three converter schedule was generated for a six hour cycle using three grades of matte. The smelter was, at that time, (autumn, 1979) running a four converter operation. For the conditions simulated, no difficulty was experienced in implementing the schedule and achieving the same production level with three converters as with four. Simulation experiments conducted by the model builders in the presence of a senior converter aisle foreman resulted in the following conclusion: "With the guidelines based on the generated schedules using three converters, it appears possible to achieve the same production level achieved using four converters with 'regular' or current scheduling practice." [27]

A technique has been established for generating transient converter schedules to reach an ideal mode of
operation from an arbitrary operational converter status. Clearly this is needed, if one would choose to implement a schedule in the smelter. Even smooth smelter operation is frequently disrupted by unforeseen delays, equipment breakdowns, scheduled maintenance, etc. The technique is an offshoot of the schedule generating methodology which shows the versatility of this type of approach.

A practical extension of this research would be the amalgamation of the various computer programmes so that input of the parameter values would immediately result in the output of converter schedules.

In order to maximize the overall converter aisle production, interaction of converter and anode furnace cycle lengths as well as reverberatory cycle characteristics must be considered. The anode furnaces and casting wheels operate with a cycle time of fixed duration. Matte and slag tapping practices in the reverberatory furnaces tend to result in cyclic variations in the bath level. Therefore, it should be possible to find converter and anode cycle lengths and reverberatory slag tapping intervals which are compatible with each other and which permit maximum converter aisle production.

The problem treated so far is restricted to five specific converters, three matte grades and two cranes. To
be more useful, the method of solution could be generalized to handle an arbitrary number of different sized converters, several matte grades and any number of cranes.

Once the above extensions have been implemented and provisions made to compute crane service times based on arbitrary locations and crane speeds, the method of matte allocations and smelter scheduling could be used as a smelter design tool to help in the determination of good configurations and operating practices for new smelters during their design stages. Problems of component size, location and quantity, material grades and operating practices could be investigated.

Ideally, the scheduling methodology could be an on-line interactive computer package in a smelter continuously producing schedules for a horizon of several hours. Before such ambition can be attained one needs to be able to identify the values of the parameters. There is little, if any, agreement on this amongst researchers, smelter administration and smelter workers. The latter probably have the most accurate perception of the process, if they care to divulge it. The experience of the converter foremen might well be translated into parameter values using fuzzy algorithms, [37] an attempt to quantize heuristics. Fuzzy algorithms used in conjunction with simulation models could prove to be a most valuable tool in solving industrial scheduling problems.
REFERENCES


APPENDIX A

XNOR: A FORTRAN programme to calculate the GOMGEN coefficients in line 118 of the listing
83.000 END OF PROCESSING TIME

84.000 PIGE MEHN:UOKE /10 TONK OF COP  

85.000

86.000 END OF PROGRAM

87.000 TFO=-755.5/114.0 *FLOAT(IRC(A,1)+IRC(A,2)+IRC(A,3)+IRC(A,4))

88.000 TRCU=(10/19.0) *FLOAT(IRC(A,1)+IRC(A,2)+IRC(A,3)+IRC(A,4))/B.

89.000 THCU=(THCU+.76+CH)*FLOAT(IRC(A,1)+IRC(A,2)+IRC(A,3)+IRC(A,4))/B.

90.000 .B.

91.000 JMCU=(MCUS/JM)*FLOAT(IRC(A,1)+IRC(A,2)+IRC(A,3)+IRC(A,4))/B.

92.000 .B.

93.000 CODE TO SOME OF THESE CONSTANTS

94.000 .31 REPRESENTS THE TIME FOR PIG ADDITION (SEE NOTES)

95.000 .18 TONS PER LADLE OF REACTOR MATTE

96.000 .75 ASSUMED REACTOR MATTE IS PURE CUSZ

97.000 .05 TONS IS THE WEIGHT OF A PIG

98.000 .19 TONS IN A LADLE OF BLISTER COPPER

99.000 .23 FRACTION OF CU IN REACTOR MATTE

100.000

101.000 WM=INT(TPM+TRCU+.31*18)

102.000 =NPM=INT(DTIME+TPDM+MCUS+.31*TCU)

103.000 WM=INT(16.0+TRCU+.31+TCU)

104.000 END OF PROCESSES CONSIDERED

105.000

106.000 RESULTS ARE NOW STORED

107.000

108.000 BLOC(K)=N

109.000 VNPM(K)=NPM

110.000 VNPM(K)=NPM

111.000 VTDF(A)=INT(TF)

112.000 313 CONTINUE

113.000 WRITE(100,316)

114.000 FORMAT(10X:"THE RESULTS ARE THE FOLLOWING:"/)

115.000 DO 314 J=1,5

116.000 HE=J2

117.000 WRITE(100,315)/YPM(J),VMPM(J),VTPM(J),VTDF(J),BLOC(J)

118.000 315 FORMAT(15X:"FOR CONVERTER:"/X"NM="/X"NM="/X"NM="/X"NM="/X"NM="/X"

119.000 TPM='16" BLOW COEFFICIENT='16")

120.000 316 CONTINUE

121.000 STOP

122.000 END

3
APPENDIX B

Listings of the two compared matte distributions due to runs of programme GOMGEN. Note that the number of dry matte assigned to converter 4 is fixed by the production ratio and as such the corresponding variable is missing. The third listing is a run of a simplex algorithm programme to verify that the integer optimization is maximal.
PCL

COPY DE/RAFILE TO LPINCI

NUMBER OF VARIABLES IS 7

NUMBER OF CONSTRAINTS IS 12

**THE PROBLEM TABLEAU 10**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>3</th>
<th>3</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1075</td>
<td>-341</td>
<td>682</td>
<td>-341</td>
<td>682</td>
<td>-341</td>
<td>682</td>
<td>-341</td>
</tr>
<tr>
<td>-1075</td>
<td>341</td>
<td>-682</td>
<td>341</td>
<td>-682</td>
<td>341</td>
<td>-682</td>
<td>341</td>
</tr>
<tr>
<td>0</td>
<td>354</td>
<td>403</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>-354</td>
<td>-403</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**THE REARRANGED TABLEAU 10**

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>3</th>
<th>3</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>393</td>
<td>-1023</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>-393</td>
<td>1023</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>354</td>
<td>403</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>-354</td>
<td>-403</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**OPTIMUM IS**

-0.1

---

carleton university computing

**THE SOLUTION VECTOR IS**

<table>
<thead>
<tr>
<th>8</th>
<th>6</th>
<th>6</th>
<th>13</th>
<th>0</th>
<th>14</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>1075</td>
<td>341</td>
<td>120</td>
<td>-487</td>
<td>-487</td>
<td>982</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>254</td>
<td>403</td>
<td>0</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>-354</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>468</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>317</td>
<td>454</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>499</td>
<td></td>
</tr>
</tbody>
</table>

**THE REARRANGED TABLEAU 16**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>293</td>
<td>-1623</td>
<td>0</td>
<td>-1023</td>
<td>0</td>
<td>1023</td>
</tr>
<tr>
<td>0</td>
<td>293</td>
<td>1623</td>
<td>0</td>
<td>1023</td>
<td>688</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>349</td>
<td>0</td>
<td>0</td>
<td>490</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>480</td>
</tr>
<tr>
<td>366</td>
<td>366</td>
<td>366</td>
<td>366</td>
<td>366</td>
<td>366</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**OPTIMAL 16**

-31

carleton university comp.
**Linear Programming Problem with 8 Variables and 14 Constraints**

**Minimum u = Cx, where C is:**

| 0,000 | -1,000 | -1,000 | -1,000 | -1,000 | -1,000 | -1,000 | -1,000 |

**Subject to x > 0 and Ax > B, where A is:**

<table>
<thead>
<tr>
<th>201,0</th>
<th>333,0</th>
<th>0,000</th>
<th>0,000</th>
<th>0,000</th>
<th>0,000</th>
<th>0,000</th>
<th>0,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>333,0</td>
<td>201,0</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>334,0</td>
<td>409,0</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>338,0</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>341,0</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>312,0</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>361,0</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>364,0</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
<td>0,000</td>
</tr>
</tbody>
</table>

**Primal Solution: u = (0.1, 0.1, 0.1) with w = 1.531.**

**Dual Solution:**

### Dual Variables

- $x_1$: 0.025
- $x_2$: 0.469
- $x_3$: 0.300
- $x_4$: 0.000
- $x_5$: 0.000
- $x_6$: 0.000
- $x_7$: 0.000
- $x_8$: 0.000
APPENDIX C

A listing of the FORTRAN programme for the Rosenbrock Hill Climb Technique for the case of 44 in-blow task insertions. (ROSY4)
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>19</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>25</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td>28</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>31</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>34</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>37</td>
<td>38</td>
<td>39</td>
</tr>
<tr>
<td>40</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>43</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>46</td>
<td>47</td>
<td>48</td>
</tr>
<tr>
<td>49</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>52</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>55</td>
<td>56</td>
<td>57</td>
</tr>
<tr>
<td>58</td>
<td>59</td>
<td>60</td>
</tr>
<tr>
<td>61</td>
<td>62</td>
<td>63</td>
</tr>
<tr>
<td>64</td>
<td>65</td>
<td>66</td>
</tr>
<tr>
<td>67</td>
<td>68</td>
<td>69</td>
</tr>
<tr>
<td>70</td>
<td>71</td>
<td>72</td>
</tr>
<tr>
<td>73</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td>76</td>
<td>77</td>
<td>78</td>
</tr>
<tr>
<td>79</td>
<td>80</td>
<td>81</td>
</tr>
<tr>
<td>82</td>
<td>83</td>
<td>84</td>
</tr>
</tbody>
</table>

**Note:** The table is a representation of data entries, and the context is not entirely clear from the provided image. The entries seem to be numerical or code-related, typical of scientific or technical documents.
493.000  IF (K.EQ.29) FLOW=32.
494.000  IF (K.EQ.30) FLOW=601.
495.000  IF (K.EQ.31) FLOW=448.
496.000  IF (K.EQ.32) FLOW=906.
497.000  IF (K.EQ.33) FLOW=972.
498.000  IF (K.EQ.34) FLOW=1172.
499.000  IF (K.EQ.35) FLOW=981.
500.000  IF (K.EQ.36) FLOW=738.
501.000  IF (K.EQ.37) FLOW=904.
502.000  IF (K.EQ.38) FLOW=1345.
503.000  IF (K.EQ.39) FLOW=2703.
504.000  IF (K.EQ.40) FLOW=2703.
505.000  IF (K.EQ.41) FLOW=3957.
506.000  IF (K.EQ.42) FLOW=4061.
507.000  IF (K.EQ.43) FLOW=4389.
508.000  IF (K.EQ.44) FLOW=4389.
509.000  RETURN
510.000  END
511.000  FUNCTION FHIGH(X+X+X)
512.000  DIMENSION X(14)
513.000  IF (K.EQ.1) FHIGH=2801.
514.000  IF (K.EQ.2) FHIGH=3269.
515.000  IF (K.EQ.3) FHIGH=4427.
516.000  IF (K.EQ.4) FHIGH=154.
517.000  IF (K.EQ.5) FHIGH=498.
518.000  IF (K.EQ.6) FHIGH=792.
519.000  IF (K.EQ.7) FHIGH=1440.
520.000  IF (K.EQ.8) FHIGH=1440.
521.000  IF (K.EQ.9) FHIGH=1814.
522.000  IF (K.EQ.10) FHIGH=2001.
523.000  IF (K.EQ.11) FHIGH=2188.
524.000  IF (K.EQ.12) FHIGH=4144.
525.000  IF (K.EQ.13) FHIGH=4166.
526.000  IF (K.EQ.14) FHIGH=4618.
527.000  IF (K.EQ.15) FHIGH=4936.
528.000  IF (K.EQ.16) FHIGH=507.
529.000  IF (K.EQ.17) FHIGH=1879.
530.000  IF (K.EQ.18) FHIGH=2127.
531.000  IF (K.EQ.19) FHIGH=2904.
532.000  IF (K.EQ.20) FHIGH=3149.
533.000  IF (K.EQ.21) FHIGH=3225.
534.000  IF (K.EQ.22) FHIGH=3509.
535.000  IF (K.EQ.23) FHIGH=3547.
536.000  IF (K.EQ.24) FHIGH=1921.
537.000  IF (K.EQ.25) FHIGH=2002.
538.000  IF (K.EQ.26) FHIGH=3210.
539.000  IF (K.EQ.27) FHIGH=4564.
540.000  IF (K.EQ.28) FHIGH=4827.
541.000  IF (K.EQ.29) FHIGH=488.
542.000  IF (K.EQ.30) FHIGH=643.
543.000  IF (K.EQ.31) FHIGH=804.
544.000  IF (K.EQ.32) FHIGH=1007.
545.000  IF (K.EQ.33) FHIGH=1011.
546.000  IF (K.EQ.34) FHIGH=1259.
547.000  IF (K.EQ.35) FHIGH=167.
548.000  IF (K.EQ.36) FHIGH=799.
549.000  IF (K.EQ.37) FHIGH=1003.
550.000  IF (K.EQ.38) FHIGH=1431.
551.000  IF (K.EQ.39) FHIGH=2094.
552.000  IF (K.EQ.40) FHIGH=2989.
553.000  IF (K.EQ.41) FHIGH=4081.
554.000  IF (K.EQ.42) FHIGH=4177.
555.000  IF (K.EQ.43) FHIGH=4409.
556.000  IF (K.EQ.44) FHIGH=4453.
557.000  RETURN
558.000  END
APPENDIX D

Glossary of the N.R.C. simulation model commands p. 145.
A copy of the deterministic validation run pp. 146-160.
Strip flow chart of non-deterministic validation p. 161.
Listing of non-deterministic validation run pp. 162-190.
Glossary of P.E.C. Model Commands:

**COMMAND**

**POLATCHE, FNCH, # (for pigs)**
- **KRABIN**: pick up material HATC using crane number MCR from one location

**INLATCHE, TO, # (for pigs)**
- **KRABIN**: dump material HATC using crane number MCR into something

**PULLCH, LOC,**
- **KRABIN**: pull the collar of a converter specified by LOC using crane number MCR

**CYLCH,**
- **KRABIN**: shake up crane number MCR in case of malfunction

**WAITCH, LOC, WAITTIME, PRIORITY**
- crane number MCR to wait at position LOC for some time subject to certain priority

**REPANO##,**
- **KRABIN**: anode number #, to refine

**CASPANO##,**
- **KRABIN**: anode number #, to cast

**MANTIF, ES,**
- **KRABIN**: bump crane number MCR at the bumping block

**STOP##, TIME,**
- **KRABIN**: converter number # breaks down for a specified time

**CINCH,**
- **KRABIN**: for converters must use INPOC),

**INPOCH, PACE, TO**
- **KRABIN**: pick up and dump material HATC and return crane MCR to its original position

**LIT## LIGHT##, STATE,**
- **KRABIN**: turn on or off a malfunctioning light

**CHAN##,**
- **KRABIN**: changes value of an initialization parameter during simulation

**RECALL## (of ladles),**
- **KRABIN**: request for # ladles of reactor matte

**COORD##,**
- **KRABIN**: to change a gain-high request made by mistake

**MATERIAL CODES (HATC)**

- **SL**: slag
- **MT**: matte
- **TN**: transfer matte
- **CU**: copper
- **PG**: pig
- **BC**: scrap
- **HS**: reactor slag
- **PD**: flux dust
- **SK**: skull
- **LD**: ladle
- **AS**: anode slag
- **AC**: high copper content converter slag
- **RN**: reactor matte

**POSITION CODES (LOC)**

- **KI**: reverb #1
- **AI**: anode furnace #1
- **KI**: matte tunnel #1
- **CI**: converter #1
- **FI**: flux dust bin near CI
- **FP**: pig pile
- **PB**: pig bay
- **BB**: bumping block
- **CP**: collar puller location
- **NB**: north end (of converter aisle)
- **SR**: south end
- **GP**: GASP
- **AL**: entire smelter
TIME = 00 DATE 5.05.73

ENTER
INFOOP.
ENTER
TTY SAYS PERTURBED FES POLICY ONLY
ENTER
CLOSE
ENTER
GSP SAYS C4 COMING DOWN AT 0125 1 MIN. AHEAD OF SERVICE TIME
ENTER
CLOSE
ENTER
INFOOP.
ENTER
WAIT,PP.

MATT TUNNELS
M1 M2

MT ON FLOOR 1 1
MT ON CAR -1 -1
MT MT IS WAITING 00 00

ENTER
WAIT C4.
ENTER

EVENT 44
TIME 0125.
ENTER
PONT1,M1,M1.
ENTER
END C4 2,61 LAD SLAG 1,1 TONS FLUX

EVENT 45
TIME 0125 C4 COMES DOWN 1 MIN. EARLY AS PREDICTED
ENTER
PDSL1,C4,M3.
ENTER
PDSL1,C4.
ENTER
dpsl1,h2.
ENTER

EVENT 46
TIME 0126
ENTER
PONT1,M1.
ENTER
PDSL3,C4.
ENTER
WAIT1,C4.
ENTER

LAD AT M1 = 1

ENTER
PONT1,C4.
ENTER
C4 CONT 3 LD CU, YE TO GO HIGH
TIME 0144 PULL COLLAR ON C4 SERVICE CONCLUDED ON C4 2 MINS. EARLY

EVENT 91
ENTER
OPEN1,3,5.
ENTER
PONT1,M2,M2.
ENTER
PULL C4.
ENTER

ENTER

EVENT 44
TIME 0139.
ENTER
PONT1,M1,M1.
ENTER
C4 CONT 3 LD CU, YE TO GO HIGH
COLLAR PULL END AT 0129 AS PREDICTED
ENTER
PONT1,M1.
ENTER
PONT1,C4.
ENTER
PONT1,M1, M1.
ENTER
C 4 CONT 3 LD CU, YE TO GO HIGH

EVENT 2585
TIME C1837
END OF SLAG STAGE IN C 6

EVENT 2586
TIME C1837
C6 COMES DOWN 1 MIN, LATE

EVENT 2587
TIME C1839
HIGH Cu SLAG AT C 6

EVENT 2889
TIME C1851
C7 COMES DOWN 1 MINUTE LATE

C 5 CONT 2 LD CU, YE TO GO HIGH

C5 IS 1 MINUTE LATE

C6 IN 2 MINS, EARLY

C7 TO COME DOWN AT C152 DEAD ON TIME
C 7 CONT 1 LD CU, YE TO GO HIGH
TIME 1:10 C SERVICE FINISHED
C 7 IS 2 MINS. LATE
EVENT 1:10 1:13
ENTER

C 7 CONT 2 LD CU, YE TO GO HIGH
C 5 LTE IN C 5, FILLED FOR BLOW 3
EVENT 1:14 1:17
ENTER

C 7 CONT 2 LD CU, YE TO GO HIGH
EVENT 2:16
TIME 1:17
ENTER

EVENT 45
TIME 1:16
ENTER

C 4 CONT 4 LD CU, YE TO GO HIGH
EVENT 44
TIME 1:30
ENTER

C 4 CONT 4 LD CU, YE TO GO HIGH
EVENT 66
TIME 1:29
ENTER

C 7 CONT 2 LD CU, YE TO GO HIGH
EVENT 93
TIME 2:17
ENTER

C 7 CONT 2 LD CU, YE TO GO HIGH
END 58 C 4 2.23 LAD SLAD 9.6 TONS FLUX
EVENT 2:48
TIME 1:37
ENTER

C 4 COMES DOWN 7 MINS. EARLY
EVENT 1:37
ENTER

MATE TUNNELS
M1 M2
MT ON FLOOR 0 2
MT ON CAR -1 -1
MIN MT IS WAITING 20.92 19.15
EVENT 1:14
TIME 1:14
ENTER

C 4 COMES DOWN 7 MINS. EARLY
EVENT 1:14
ENTER

C 4 COMES DOWN 7 MINS. EARLY
EVENT 1:14
ENTER

C 4 COMES DOWN 7 MINS. EARLY
EVENT 1:14
ENTER

C 4 COMES DOWN 7 MINS. EARLY
EVENT 1:14
ENTER
C 7 CONT 3 LD CU, YE TO GO HIGH
4 MATE IN C 7, FILLED FOR BLOW 2
ENTER

ENTER
INFOS.
ENTER
WAIT, C 3
PAUSE: 00001
ENTER
INFOS.
ENTER
WAIT, C 3
ENTER

EVENT 45
TIME 11:45 GAPSP SAYS C 7 WILL COME DOWN AT 2:00 3 MINS. EARLY
END SB C 7 2.01 LAD SLAG 11.9 TONS, FLUX

EVENT #47
C 5 COMES DOWN AT 11:44
ENTER
P6SL 3
ENTER
C 5
ENTER
P6SL 5, C 5
ENTER
DP6L 3, R 3
ENTER
P6SL 1, C 5
ENTER
DP6L 1, R 2
ENTER

EVENT 44
TIME 1:45
ENTER
P01L 3, P 2, C 3
ENTER
P01L 1, C 3
ENTER

C 5 CONT 3 LD CU, YE TO GO HIGH
TIME 1:35 PULL COLLAR ON C 5

EVENT 92
C 5 CONT 3 LD CU, YE TO GO HIGH
2 MATE IN C 5, FILLED FOR BLOW 4
ENTER
FULL 5, C 5
ENTER

ENTER
COLLAR PULL BEGINS AT 1:53
ENTER
C 6
ENTER

EVENT 44
TIME 2:00
ENTER
P01L 1, P 1, M 1
ENTER

TIME = 2:00 DATE = 9-06-1973
C 5 CONT 3 LD CU, YE TO GO HIGH
END OF COLLAR PULL AT 2:15
2 MATE IN C 5, FILLED FOR BLOW 4
ENTER
INFOS.
ENTER
P603, P 6, C 6
ENTER
C 7 DUE DOWN IN 1 MINUTE 2 MINS. .... NO 3 MINS. EARLY
ENTER
C 7
ENTER

ENTER
END SB C 7 3.22 LAD SLAG 13.2 TONS, FLUX

EVENT 89
TIME 2:12
ENTER
GAPSP SAYS C 6 WILL COME DOWN AT 2:12 2 MINS. LATE
ENTER
C 6
ENTER

ENTER
P6SL 3, C 7
ENTER
P6SL 1, C 7
ENTER
P6SL 3, R 3
ENTER
INFOS.
ENTER
MATE TUNNELS
MT
MT2
MT ON FLOOR
1
MT ON CAN
-1
MIN MT IS WAITING 26.71 25.49
EVENT 44
TIME 212
ILLEGAL REMOVAL FROM CONVERTER 7
ENTER
PONI1,M1,C7,2,
ENTER
LAD, AT M2 = 1
C7 CONT 3 LD CU, YE TO Go HIGH
SERVICE COMPLETED ON C7 AT 2114
PULL COLLAR ON C7

EVENT 94
ENTER
C7 CONT 3 LD CU, YE TO Go HIGH
LAD, AT M1 = 1
C7 CONT 4 LD CU, YE TO Go HIGH
3 BLAST IN C7, FILLED FOR BLOW 3
ENTER
POLL1,C7,
ENTER
INFOPO,
ENTER
POSSL,C4,K3,
ENTER

EVENTIZER
COLLAR PULL STARTS AT 2119 ON C7
ENTER
POSSL,F8,C6,
ENTER

EVENT 45
TIME 212
3' 6" ON FLOOR

EVENT 247
SERVICE ON C6 WAS CONCLUDED AT 2148
ENTER
C6 COMES DOWN AT 2150
6 MINS, EARLY

EVENT 246
TIME 3:00 DATE 5-06-1973
ENTER
C5 COMES DOWN AT 2150
8 MINS, EARLY

EVENT 245
C6 IS 3 MINS, EARLY
ENTER
C5 DOWNS 8 MINS, EARLY

Event Notes
C6 CONT 1 LD CU, YE TO GO HIGH

EVENT 246 E
C6 COMES DOWN AT 2150
6 MINS, EARLY

EVENT 245
TIEP 2156 CA COMES DOWN
END W/F SLAG STAGE IN C4

C4 IS 10 MINS, EARLY

EVENT 44
ENTER
EVENT 2159
ENTER
C5 COMES DOWN AT 2150
8 MINS, EARLY

EVENT 43
C5 CONT 4 LD CU, YE TO GO HIGH

EVENT 42
C4 DOWNS 10 MINS, EARLY
EVENT 44
TIME 4:12
ENTER
PO1, M1, C1,
ENTER

PULL COLLAR ON 44

EVENT 37
TIME 4:21
A Mode Statistics

AT 49 40 TOTAL
A Mode Cast 896 0 0 896
Furnace Capacity 17.50 15.50 17.50
Copper in Furnace 4.00 4.50 13.70 19.2
Total LDS Added 2.20 1.50 2.00 4.7
Furnace Status 3 0 0 0
Time of Status Start 4:21 0 0 0
A Mode X-wheel Status
Time = 4.21 Date = 5.05.1973
C 6 Cont 2 LD CU, YE TO GO HIGH

3 WHTIE IN C 6, FILLED FOR BLOW 2
ENTER
FULL1, A7,
ENTER
INFOOP,
ENTER

EVENT 19
GASP SAYS C5 DUE TO COME DOWN AT END OF MI 4:133 10 MINS. EARLY

EVENT 44
PO1, M1, M1,

EVENT 266
TIME 4:16
ENTER
PO1, M1, M1,
ENTER
PO03, P3, C4,
ENTER

5 MT ON FLOOR
ENTER
DPLO3, BB,
ENTER
BUMP3, B3,
ENTER

EVENT 43
TIME 4:24
ENTER
PO1, M2, M2,
ENTER

ENTER
INFOOP,
ENTER
TIME NOW 4:135 TO CHECK WHEN C5 IS COMING DOWN
ENTER
C5
ENTER
DUE DOWN AT 2:33 SORRY 4:133 THUS MIGHT AS WELL SKIM IT
ENTER
C5
ENTER
PO1, M3, C3, R2,
ENTER
PO1, M7, R1,
ENTER

EVENT 44
TIME 4:30
ENTER
PO1, M1, M1,
ENTER

EVENT 97
C5 COMES DOWN AT 4:134
END OF SLAB STAGE IN C 5
ENTER
PO1, M3, C5, R3,
ENTER
PO1, M5, C5, R1,
ENTER

A MT ON FLOOR

EVENT 266
TIME 4:137
HIGH CU SLAG AT C 5
ENTER
PO03, F3, C5,
ENTER
PO03, P3, C4,
ENTER

ENTER
END OF SERVICE FOR C5 OCCURS AT 4:143
C5 IS 5 MINS EARLY
ENTER
C5
ENTER
INFOOP,
ENTER
DPLO1, C5,
ENTER

C5 DUE DOWN AT 4:135
C5
ENTER
C5
ENTER
EVENT 44
TIME 414R
ENTER
Pомните, что стимулировать пролонгируется, что стимулировать пролонгируется
ENTER
3 % ON FLOOR
ENTER
457, C6, C6, C6
ENTER
WRITE, C6, C6
ENTER

EVENT 45
TIME 4157
END 58 C 6 297 LAD SLAG 14.1 TONS FLUX

EVENT 46
TIME 4157
ENTER
PSL1, C6, C6, C6, C6
ENTER
PSL1, C6
ENTER
PFL1, R2, C6
ENTER

EVENT 46
C6 COMES DOWN AT THE END OF A CYCLE
END CU STAGE IN C 4 5.5 LADLES OF CU
TIME = 9.00 DATE = 9.26.1975

EVENT 46
C6 IS 10 MINS. LATE
C6 CONT 2 LD CU, YE TO GO HIGH
TIME 51C6
ENTER
PSL3, R3, C6
ENTER

EVENT 67
TIME 51C7
ENTER
PNTS, M1, C6
ENTER
PNTS, C6, C6, C6
ENTER
PNTS, C6
ENTER
POLL1, M1, C6
ENTER
POLL1, PB, C5
ENTER

C6 CONT 2 LD CU, YE TO GO HIGH
2 MATTE IN C 6, FILLED FOR BLOW 5
ENTER
PDCU5, C4, P8
ENTER
PDCU5, C4, P8
ENTER
PDCU5, C4, C6
ENTER
PDCU5, C4, C6
ENTER
PDCU5, C4, A6
ENTER
PDCU5, C4, A6
ENTER
PDCU5, C4, A6
ENTER
PDCU5, C4, A6
ENTER
PDCU5, C4, A6
ENTER
PDCU5, C4, A6
ENTER
PDCU5, A6
ENTER

EVENT 44
TIME 51C2
ENTER
PSL1, C6
ENTER
PNT1, M2, C6
ENTER
WRITE, C6, C6
ENTER
ENTER
PFL1, R2, C6
ENTER
EVENT 44
TIME 5142
COMV BLOW MATTE TRANSFER REACTOR START SLAC AIR
A CU SLAG C 0 0.0 C 0.0 22429
9 OM COPP 12 0 0.0 4.2 13.2 21159
5 3 0.0 326 6.0 22259
7 GO HIGH 14 0.0 344 11.2 2444
ENTER
PONTI,M2,C4,
ENTER
PONTI,M1,C4,
ENTER
C 4 NEEDS MORE MATTE TO BLOW
ENTER
TIME 5135
ENTER
PDEF1,C7,M2,
PAUSE 1 MINUTE
ENTER

EVENT 45
TIME 5134
ENTER
INFOCP,
ENTER
PDEF1,C7,M1,
ENTER
PDEF1,M1,C4,
ENTER
PDEF1,M2,C2,
ENTER
ENTER
LAD AT M1 = 4

EVENT 46
TIME 5129
ENTER
PDEF1,M1,C4,
ENTER
PONTI,M1,C4,
ENTER
ENTER
LAD AT M1 = 3
C 4 CONT 1 LD CU, YE TO GO HIGH
4 MATTE IN C 4,FILLED FOR BLOW 1
LAD AT M1 = 2

EVENT 47
TIME 5142
ILLEGAL ADDITION MESSAGE IS CONSEQUENCE OF NO CR MOVE-
ILLEGAL ADDITION TO CONVERTER 4

EVENT 48
TIME 5145
ENTER
INFOCP,
ENTER
PDEF1,P7,C7,
ENTER
PONTI,M1,C1
ENTER
PONTI,M1,M1
ENTER
INFOCP,
ENTER
JUST FOR INFO
ENTER
CC
ENTER
C6 DUE TO CORE DOWN AT 61C1
8 MINS. LATE
ENTER
CC
ENTER
WHITI,C6,
ENTER

EVENT 49
TIME 5146
END OF SLAG STAGE IN C
END SB C 7 2.63 LAD SLAG 23.4 TONS FLUX

EVENT 50
TIME 5146
C 7 IS 4 MINS. LATE
ENTER
PDEF1,C7,M1,
ENTER
PDEF1,C7,M3,
ENTER
ENTER
ENTER
PDEF1,C7,M1,
ENTER
PDEF1,C7,M1
ENTER
HIGH CU SLAG AT C
ENTER
63 LADLES SHOULD HAVE BEEN REGARDED AS A B FULL LADLE
ENTER
CC
ENTER
ILLEGAL REMOVAL FROM CONVERTER
ENTER
PDEF1,P7,C7,
ENTER

EVENT 51
TIME 5156
ENTER
LITEN,C7,
ENTER
PONTI,M1,M1,
ENTER
INFOCP,
ENTER
JUST FOR INFO
ENTER
CC
ENTER
C6 DUE TO CORE DOWN AT 61C1
8 MINS. LATE
ENTER
CC
ENTER
WHITI,C6,
ENTER
C4 COMES DOWN 7 MINS EARLY

4 MT ON FLOOR

ENTER

PC51.C7,
ENTER

NO C5 -1 0 0 0 0
ENTER

PC51.C7,
ENTER

EVENT 45
TIME 6:00
ILLEGAL REMOVAL FROM CONVERTER 7

ENTER

GARAGE 1 WAS JUST TRYING TO PUT OUT THAT CENSORED LITFLAT
ENTER

C6
ENTER

C66.C6,
ENTER

WAIT1.C6,
ENTER

EVENT 67
TIME 5:25
TIME = 6:00 DATE = 5.06.1973

ENTER

P050.1.1.PP.C5,
ENTER

END 59 C 6 2.13 LAD SLAG 11.7 TONS FLUX

EVENT 69
TIME 6:10

EVENT 44
TIME 6:19

EVENT 267
ENTER

PENT1.M1.C4,
ENTER

C6 CONT 4 LD CU, YO GO HIGH
END OF COLLAR PULL ON C6 AT 6:14
2 MATE IN C6,FILLED FOR BLOW 4
C 4 CONT 2 LD CU, YO GO HIGH
TIME 6:28
ENTER

P050.WP.C7,
ENTER

PC03.WP.CS,
ENTER

PC05.2.58,
PAnd 22321
ENTER

PC03.WP.CA,
ENTER

PC03.WP.CS,
ENTER

C6 COMES DOWN 8 MINS. LATE

C 4 IS 7 MINS. LATE

EVENT 44
TIME 4:01
ENTER

PENT1.1.1,
ENTER

ENTER

WAIT1.C6,
ENTER

END 58 C 4 3.06 LAD SLAG 9.1 TONS FLUX
EVENT 29
TIME 6:32
EVENT 27
TIME 6:33
EVENT 26
TIME 6:33
EVENT 25
TIME 6:35
EVENT 24
TIME 6:35
EVENT 45
TIME 6:35
EVENT 44
TIME 6:35
EVENT 43
TIME 6:32
EVENT 69
TIME = 7:00 DATE = 5.06.1973
END SB C 6 2.37 LAD SLAG 6.1 TONS FLUX
EVENT 289
C6 COMES DOWN AT 7:01
ENTER
PM01S, C6
ENTER

EVENT 303
C6 10.3 MIN. EARLY, PM01S, R2, C6
ENTER

C6 CONT 4 LD CU, YE TO GO HIGH
YE
1 MATE IN C 6, FILLED FOR BLOW 8
ENTER
TIME 7:13
ENTER
CC
ENTER

EVENT 689
ENTER
P003, P0, C7
ENTER

EVENT 45
TIME 7:17
ENTER
PM01S, R2, C5
ENTER

EVENT 44
TIME 7:17
ENTER
PM01S, R1, M1
ENTER

C5 CONT 1 LD CU, YE TO GO HIGH
1 MATE IN C 5, FILLED FOR BLOW 1
END SB C 4 2.31 LAD SLAG 11.7 TONS FLUX

EVENT 926
TIME 7:21
ENTER
PM01S, C4, R3
ENTER
PM01S, M1
ENTER

C4 IS 5 MINS. BEHIND SCHEDULE
ENTER
PDDL, C4, R3, ENTER

5 MT ON FLOOR
LAD. AT M 1 = 4
ENTER
ENTER
PDDL, C4, ENTER
PDDL, CA, ENTER
ENTER
ENTER
PDDL, C4, ENTER

C 4 CONT 3 LD CU, YE TO GO HIGH
TIME 7:27
ENTER
PDDL, R2, ENTER
PDDL, M1, CA, ENTER

LAD. AT M 1 = 3
C 4 CONT 3 LD CU, YE TO GO HIGH
2 MATTE IN C 4, FILLED FOR BLOW 3

EVENT 97
TIME 7:41
ENTER
PDDL, C5, R3, ENTER
PDDL, C5, ENTER
PDDL, R1, ENTER

EVENT 97
TIME 7:47
ENTER
PDDL, C5, R3, ENTER
ENTER
PDDL, M1, C5, ENTER
PDDL, M1, C5, ENTER
PDDL, M2, C5, ENTER

C 5 CONT 2 LD CU, YE TO GO HIGH
TIME 7:52
C 5 CONT 2 LD CU, YE TO GO HIGH
LAD. AT M 1 = 3
C 5 CONT 2 LD CU, YE TO GO HIGH

EVENT 289
TIME 7:13
END CU STAGE IN C 7 6.1 LADIES OF CU
ENTER
PDDL, ENTER
TO SEE WHEN C 5 IS EXPECTED DOWN
ENTER
C 7 COMES DOWN 13 MINS EARLY
3 MATTE IN C 5, FILLED FOR BLOW 2
ENTER
PDDL, C7, R8, ENTER
PDDL, C7, A7, ENTER
PDDL, C7, C5, ENTER
END OF SHIFT
EVENT 5K
TIME 000
CONV BLOW MATTE TRANSFER REACTOR START SLAG AIR
4 3 9 0 0 724 5.5 22429
5 2 7 0 0 732 3.0 21159
6 00 00 0 0 713 12.5 22259
7 ON COMP 1A 0 0 546 13.5 24414
TIME 0100 DATE 3-06-1973
CONV BLOW MATTE TRANSFER REACTOR START SLAG AIR
4 3 9 0 0 724 5.5 22429
5 2 7 0 0 732 3.0 21159
6 00 00 0 0 713 12.5 22259
7 ON COMP 1A 0 0 546 13.5 24414
ENTER POINT 1A, C7, 3.
ENTER

EVENT 45
TIME 000
ENTER POINT, A4, C7.
ENTER
LAD 4 AT M 1 = 2
C Y NEEDS MORE MATTE TO BLOW
ENTER POINT, A4, R2.
ENTER

EVENT 44
TIME 000
ENTER POINT, A1, C7.
ENTER
C Y NEEDS MORE MATTE TO BLOW
LAD 4 AT M 1 = 1
C Y CONT 1 LD CU, YE TO GO HIGH
BLOW C Y CONT 2 LD CU, YE TO GO HIGH
END OF CYCLE T1 SHOULDB BE EQUIVALENT TO T1-C100
5 MIN IN C 7, FILLED FOR BLOW 1
ENTER INFOCS.
ENTER INFOOP.
CONV BLOW MATTE TRANSFER REACTOR START SLAG AIR
4 3 9 0 0 724 5.5 22429
5 2 7 0 0 732 3.0 21159
6 00 00 0 0 713 12.5 22259
7 ON COMP 1A 0 0 827 13.5 24414
ENTER
TIME = 0.00  DATE = 5.26.1973

ENTER
WAIT2,PP,
ENTER
INFOGP,
ENTER
INFOM1,
ENTER

C4 SCHEDULED TO COME DOWN AT C:05 .....1 MEN. EARLY

MATTE TUNNELS
MT1        MT2
MT ON FLOOR  1      1
MT ON C4R    -1     -1
MT M1 IS WAITING .00  .00

ENTER
CC
ENTER
IWAIT3,C4,
ENTER

EVENT 44
TIME C:04
ENTER
PDST1,M1,M1,
ENTER

END SB C4  2.61 LAD SLAG 1.1 TONS FLUX

EVENT286
TIME C:05
ENTER
PDST3,C4,R3,
ENTER
PKSL1,C4,
ENTER
DSST1,R2,
ENTER

EVENT 45
TIME C:06
ENTER
PKSL3,C4,
ENTER
PDST1,M2,M2,
ENTER

ENTER
PKMT1,M1,
ENTER
WAIT1,C4,
ENTER

LAD AT M1 = 1

ENTER
DPST1,C4,
ENTER
C 4 CONT 3 LD CU, YE TO GO HIGH
TIME C:14 C 4 STARTS SCHEDULE BLOW 2 MINS. EARLY
PULL COLLAR ON C 4

EVENT 91
ENTER
WAIT1,M1,
ENTER
PULL3,C4,
ENTER
ENTER
ENTER
PSL3,R2,
ENTER
PULL3,C4,
ENTER

EVENT 44
TIME C:17
ENTER
PDPM1,M1,M1,
ENTER
ENTER
COLLAR PULL STARTS AT C:18 ON C4
ENTER
ENTER
ENTER
DPLD1,BB,
ENTER
BUMP1,BB,
ENTER

ENTER
INFOGR,
ENTER

ENTER
WAIT1,M2,
ENTER
C 4 CONT 3 LD CU, YE TO GO HIGH
TIME C:26 COLLAR PULL ENDS ON C4
ENTER
PMR3,M1,
ENTER
DPMR3,C4,
ENTER
LAD M = 1

EVENT 44
TIME C:30
ENTER
PDPM1,M1,M1,
ENTER
C 4 CONT  3 LD CU, YE TO GO HIGH
TIME C:32
  2 MATTE IN C 4, FILLED FOR BLOW 4
ENTER
INFO GP,
ENTER

ENTER
C6 DUE TO COME DOWN AT 0:36 DEAD ON TIME
ENTER
CC
ENTER
WAIT
ENTER
CC
ENTER
DPLD3,BB,
ENTER
BUMP3,BB,
ENTER
WAIT3,C6,
ENTER

EVENT 45
TIME C:33
ENTER
PDMT1,M2,M2,
ENTER

3 MT ON FLOOR
END SB C 6  1.38 LAD SLAG  7.7 TONS FLUX

EVENT288
TIME C:36
END OF SLAG STAGE IN C 6

ENTER
PKSL3,C6,
ENTER
PKFD1,F6,
ENTER
WAIT1,FC6,
ENTER
C5 COMES DOWN BY GASP AT 0:43
ENTER
CC
ENTER
IGNORE ABOVE COMMENT
ENTER
CC
ENTER
C5 DUE TO COME DOWN 5 MINS. EARLY AT 0:38
ENTER
CC
ENTER

END SB C 5  2.82 LAD SLAG  7.8 TONS FLUX

EVENT287
TIME C:38
- HIGH GH SLAG AT C  6
C5 COMES DOWN 5 MINS. EARLY
DFFDI,C6,
ENTER

ENTER C6 STARTS BLOW AT 0:38 C6 IS 5 MINS. EARLY
ENTER C6
ENTER DPSL3,R3,
ENTER PKSL3,C5,R1,
ENTER DPSL3,C5,
ENTER DPSL3,R3,
ENTER

ENTER PKSL1,C5,
ENTER DPSL1,R1,
ENTER

EVENT 44
TIME 0:43
ENTER PDMS3,M2,C5,
ENTER PDML1,M1,C5,
ENTER

LAD .AT M 2 = 2
C 5 CONT 2 LD CU, YE TO GO HIGH
TIME G:48
C 5 CONT 2 LD CU, YE TO GO HIGH

2 MATE IN C 5,FILLED FOR BLOW 3
END SB C 7 3.32 LAD SLAG 10:6 TONS FLUX

EVENT 289
TIME 0:50
ENTER PDLS3,C7,R3,
ENTER PKSL1,C7,
ENTER DPSL1,R1,
ENTER

ENTER PKSL3,C7,
ENTER DPSL3,R3,
ENTER

EVENT 45
TIME 0:53
ENTER PKMT1,M1,
Enter
LAD .AT M1 = 1

ENTER
DPMT1,C7,
ENTER
C 7 CONT 2 LD CU, YE TO GO HIGH
TIME 2:57
ENTER
INFO1,
ENTER
PDMT3,M2,C7,

MATTE TUNNELS
MT1     MT2
MT ON FLOOR   1     2
MT ON CAR     -1    1
MIN MT IS WAITING 7.2C  6.69

ENTER
PDMT1,M1,C7,
ENTER

TIME = 1.00 DATE = 5.06.1973

EVENT 44
TIME 1:00
ENTER
PDME1,M1,C7,
ENTER
INFO3,
ENTER
PKCS3,C6,
ENTER
C4 CUE TO COME DOWN AT 1:06 8MINS. EARLY
ENTER

PAUSE CCCC1

C 7 CONT 2 LD CU, YE TO GO HIGH
C 7 CONT 2 LD CU, YE TO GO HIGH
C 7 CONT 3 LD CU, YE TO GO HIGH
4 MATTE IN C7,FILLED FOR BLOW 2

EVENT 268
TIME 1:03
ENTER
DPNL3,R3,
ENTER
PDPL3,RB,C6,
ENTER
END SB C4 2.2C LAD SLAG 9.1 TONS FLUX

EVENT 286
TIME 1:05
ENTER
PDNL3,C4,R3,
ENTER
C5 I.E. C4 COMES DOWN 9 MINS. EARLY
EVENT 44
TIME 1:12
ENTER
PKMT1,M1,
ENTER
WAIT1,C4,
ENTER
ENTER
DPMT1,C4,
ENTER
C4 CONT 4 LD CU, YE TO GO HIGH
TIME 1:14
ENTER
DPSL3,R2,
ENTER
DPLD1,M1,
ENTER
INFOGP,
ENTER
ENTER
C5 DUE DOWN AT 1:32.....15 MINS. EARLY
ENTER
CC
ENTER
ENTER
INFOGP,
ENTER
ENTER
ENTER
EVENT 45
PDMT3,M2,M2,
ENTER
TIME 1:20
ENTER
CC
ENTER
PDMT3,M2,M2,
ENTER
3 MT ON FLOOR
EVENT 44
TIME 1:25
ENTER
PDMT3,M1,C4,
ENTER
EVENT 68
ENTER
TIME 1:27
ENTER
C
ENTER
PDPG3, PB, C6,
ENTER
C 4 CONT 4 LD CU, YE TO GO HIGH
YE
2 MATTE IN C 4, FILLED FOR BLOW 8
END SB C 5 1.86 LAD SLAG 9.0 TONS FLUX

EVENT 287
TIME 1:31 C5 COMES DOWN 16 MINS. EARLY DELAY OF BLOW NEEDED HERE
ENTER
PDSL3, C5, R2,
ENTER
PDSL1, C5, R1,
ENTER

EVENT 44
TIME 1:39
ENTER
PDMT3, M2, C5, 2,
ENTER
1 WET MATTE INSTEAD OF DRY ADDED TO C5 TO SLOW IT DOWN
ENTER
CC
ENTER
PDMT1, M1, M1,
ENTER
LAD \ AT M 2 = 2
C 5 CONT 3 LD CU, YE TO GO HIGH
TIME 1:40 C5 STARTS BLOW 14 MINS EARLY WITH 1 WET TO SLOW IT
PULL COLLAR ON C 5

EVENT 92
LAD \ AT M 2 = 1
C 5 CONT 3 LD CU, YE TO GO HIGH
2 MATTE IN C 5, FILLED FOR BLOW 4
ENTER
PULL3, C5,
ENTER
ENTER
ENTER
COLLAR PULL ON C5 STARTS AT 1:45
ENTER
C5
ENTER
EVENT 44
TIME 1:48
ENTER
PDMT1,M1,M1,
ENTER

EVENT 45
TIME 1:50
ENTER
PDMT1,M2,M2,
ENTER

EVENT 68
ENTER
TIME 1:52
ENTER
CC
ENTER

C 5 CONT 3 LD CU, YE TO GO HIGH

2 MATTE IN C 5, FILLED FOR BLOW 4
END SB C 7 3.23 LAD SLAG 12.3 TONS FLUX

EVENT 89
TIME 1:54
ENTER
PDPG3,P8,C6,
ENTER
PDSL1,C7,R1,
ENTER
PDSL3,C7,R3,
ENTER

TIME = 2:00  DATE = 5.06.1973
 ENTER
 PKSLI,C7,
 ENTER
 DPSL1,R1,
 ENTER

EVENT 44
TIME 2:03
ENTER
PDMT3,M2,C7,
ENTER
PDMT1,M1,C7,2,
ENTER

LAD AT M 2 = 1
C 7 CONT 3 LD CU, YE TO GO HIGH
TIME 2:27
PULL COLLAR ON C 7

EVENT 94

C 7 STARTS BLOW 7 MINS EARLY
ENTER
INFOOFP,
ENTER

ENTER
PDSL3,C4,R3,
ENTER

C 7 CONT 3 LD CU, YE TO GO HIGH
LAD AT M 1 = 1
C 7 CONT 4 LD CU, YE TO GO HIGH

3 MATTIE IN C 7, FILLED FOR BLOW 3
ENTER
PULL1,C7,
ENTER

ENTER
COLLAR PULL ON C7 STARTS AT 2:12
ENTER
CC
ENTER

EVENT 45
TIME 2:16
ENTER
PDMT3,M2,M2,
ENTER

EVENT268

ENTER
PDPG3,PB,C6,
ENTER

EVENT 44
TIME 2:17

EVENT288
END OF BLOW COINCIDES WITH PIG ADDITION HENCE WILL GERT ILLLEGAL REMOVAL
END CU STAGE IN C 6 5.0 LADLES OF CU

ENTER
TIME 2:20
ENTER
CC
ENTER
PDSK3,BB,C6,
ENTER

ILLEGAL ADDITION TO CONVERTER 6

C 7 CONT 4 LD CU, YE TO GO HIGH
TIME 2:21 END OF COLLAR PULL ON C7
3 MATTIE IN C 7, FILLED FOR BLOW 3
ENTER
PDMT1,M1,M1,
ENTER
ENTER
TIME 2:12A STARTS REMOVAL OF COPPER 5 LADLES FROM C6
ENTER
C:
ENTER
INFO5,
ENTER
PDCU3,C6,PIB,
PUSH CCCR01
ENTER
INFO5,
ENTER
PDCU1,C5,A5,

ANODE STATISTICS

<table>
<thead>
<tr>
<th></th>
<th>A7</th>
<th>A5</th>
<th>A6</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

FURNACE CAPACITY 17.50 15.50 17.00

COPPER IN FURNACE 14.00 3.50 10.75 28.2
TOTAL LDBS ADDED .00 .00 .00 .00
FURNACE STATUS 4 4 4 4
TIME OF STATUS START 0 0 0 0
ANODE WHEEL STATUS 1 1 0 0
ENTER
PDCU3,C5,A4,
ENTER
PKC1,C5,
ENTER
DPCU1,A4,
ENTER
PKC1,C6,
ENTER
DPCU1,A5,
ENTER

EVENT 44
TIME 2:134
ENTER
PDMT1,M1,M1,
ENTER

CONV BLOW MISMATCH TRANSFER REACTOR START SLAG AIR

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>GO</td>
<td>HIGH</td>
<td>0</td>
<td>.0</td>
<td>114</td>
<td>12.0</td>
<td>22429</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>11</td>
<td>0</td>
<td>.0</td>
<td>152</td>
<td>5.0</td>
<td>21159</td>
</tr>
<tr>
<td>6</td>
<td>CU</td>
<td>SLAG</td>
<td>0</td>
<td>.0</td>
<td>0</td>
<td>0</td>
<td>22259</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>12</td>
<td>0</td>
<td>.0</td>
<td>-221</td>
<td>6.0</td>
<td>24419</td>
</tr>
</tbody>
</table>

ENTER
ENTER
PDMT1,M2,C6,2,
ENTER
PDMT1,M1,C6,1,2,
ENTER
LAD AT M1 = 2
LAD AT M2 = 1
6 needs more matte to blow

ENTER
TIME 2:41
ENTER
C6 starts B#1 10 mins. early
ENTER
CC
ENTER

EVENT 45
TIME 2:42
LAD AT M1 = 1

C6 cont 1 LD CU, ye to go high

4 matte in C6, filled for blow 1
ENTER
INFO GP
ENTER

ENTER
C5 due to come down at 2:51 7 mins., early
ENTER
CC
ENTER
PSL3, C4, R3,
ENTER

EVENT 44
TIME 2:46
ENTER
PDMT1, M1, M1,
ENTER

End SB C5 2.60 LAD SLAG 11.7 TONS FLUX

EVENT 287
TIME 2:50
ENTER
PSL1, C5, R1,
ENTER
PKSL3, C5,
ENTER
PSL3, R3,
ENTER

ENTER
PKSL1, C5,
ENTER
PSL1, M1,
ENTER

End SB C4 2.03 LAD SLAG 21.3 TONS FLUX

EVENT 286
TIME 2:56
End of slag stage in C4
ENTER
PD13, M2, C5,
ENTER

C5 comes down 8 mins. early

C4 comes down 10 mins. early
TIME = 3:00  DATE = 5.06.1973

C 5 CON'T  3' LD CU, YE TO GO HIGH
YE
1 MATTE IN C 5, FILLED FOR BLOW B
ENTER
TIME 3:00
ENTER
CC
ENTER
PDLS3,C4,R3,
Enter
PSL1,C4,
Enter
PSL1,R3,
Enter
EVENT 44
TIME 3:01
ENTER
PDFT3,F4,C4,
Enter
PDFT1,M1,M1,
Enter
3 MT ON FLOOR

EVENT 45
TIME 3:06
ENTER
PDFT1,M2,M2,
Enter
HIGH CU SLAG AT C  4
ENTER
TIME 3:09
ENTER
CC
ENTER
INFOGF,
Enter
PKCS3,C4,
Enter
C7 TO GONE DOWN AT 3:23 ...... 6 MINS. EARLY
MO' CS -1  0  0  0  0
ENTER
CC
ENTER
LITE65,0
ENTER

EVENT 44
TIME 3:17
ENTER
PDFT1,M1,M1,
Enter
4 MT ON FLOOR
END SB 57 3.55 LAD SLAG 13.2 TONS FLUX
EVENT 289
TIME 3:22
ENTER
PDMT3,
ENTER
CC
ENTER
PDSL3,C7,R3,
ENTER
ENTER
PKMTSL1,C7,
ENTER
DPSL1,R1,
ENTER
PKSL3,C7,
ENTER
DPSL3,R3,
ENTER

EVENT 45
TIME 3:27
END SB C 6 3.44 LAD SLAG 10.3 TONS FLUX

EVENT 288
TIME 3:28

EVENT 44
TIME 3:29

EVENT 266
TIME 3:30
ENTER
PKSL1,C7,
ENTER
DPSL1,R2,
ENTER
PDMT1,M1
ENTER
CC
ENTER
PDMT3,M2,M2,
ENTER
PDPG3,PB,C4,
ENTER
ENTER
PDMT1,M1,C7,
ENTER
PDMT1,M1,C7,
ENTER
PDSL3,C6,R3.2,
ENTER

C 7 CONT 4 LD CU, YE TO G7 HIGH
TIME 3:35
LAD AT M 1 = 3

C 7 COMES DOWN 7 MINS. EARLY

C 6 COMES DOWN 9 MINS. EARLY

C 7 STARTS HI BLOW 2 MINS EARLY
C 7 CONT  5 LD CU, YE TO GO HIGH
YE
   2 MATTE IN C 7, FILLED FOR BLOW B
ENTER
PKSL3, C6,
ENTER
ENTER
PKMT1, M1,
ENTER
WAIT1, C6,
ENTER

LAD .AT M 1 = 2

ENTER
DPMT1, C6,
ENTER

C 6 CONT  2 LD CU, YE TO GO HIGH
TIME 3:45
ENTER
DPSL3, R3,
ENTER
PDMT1, M1, C6,
ENTER
PKMT3, M2,
ENTER
DPMT2, C6,
ENTER

LAD .AT M 1 = 1
LAD .AT M 2 = 1

EVENT 44
TIME 3:47
C 6 CONT  2 LD CU, YE TO GO HIGH

C 6 CONT  2 LD CU, YE TO GO HIGH

3 MATTE IN C 6, FILLED FOR BLOW B
ENTER
INFOGP,
ENTER

ENTER
PDMT1, M1, M1,
ENTER
PDML3, C5, R2,
ENTER
PDLD3, BB,
ENTER
BUMP3, BB,
ENTER
EVENT 266
TIME 3:52
ENTER
PDG3,P8,C4,
ENTER
INFOPB,
ENTER

PIG BAY

NO. OF PIGS 14
COOL PIGS 10
TOTAL PIGS POURED: 4
TIME = 4.00 DATE = 5.06.1973
PULL COLLAR ON A4

EVENT 37

AMODE STATISTICS

| AMODES CAST | 896 | 0 | 0 | 896 |
| FURNACE CAPACITY | 17.50 | 15.50 | 17.00 |
| COPPER IN FURNACE | 0.00 | 5.50 | 12.75 | 18.2 |
| TOTAL LOADS ADDED | 0.00 | 2.00 | 2.00 | 4.0 |
| FURNACE STATUS | 5 | 0 | 0 | 0 |
| TIME OF STATUS START | 400 | 0 | 0 | 0 |
| AMODE WHEEL STATUS | 0 | 0 | 0 | 0 |

PULL, A7,
ENTER

EVENT 45
TIME 4:02
ENTER
CCPDMT3,M2,M2,
ENTER

EVENT 44
TIME 4:05
ENTER
PDMT3,M1,M1,
ENTER

3 MT ON FLOOR
ENTER
INFOB,
ENTER

ENTER
PDLS1,C7,R2,
ENTER

EVENT 38
TIME 4:09 AMODE 7 READY TO RECEIVE COPPER

EVENT 266
BUMPING BLOCKS

COOLING LADLES: C C
SKULLS: 3 C
TOTAL SKULLS PROD.: 3 C

EVENT 44
TIME 4:14
ENTER
PDPG3,PB,C4,
ENTER
INFOAB,
ENTER

EVENT 44
TIME 4:14
ENTER
PLD3,BB,
ENTER
PDMT1,M1,M1,
ENTER

4 MT ON FLOOR

EVENT 44
TIME 4:25
ENTER
INFOGP,
ENTER
PDMT1,M1,M1,
ENTER

5 MT ON FLOOR
ENTER
PDSL1,C5,R2,
ENTER

EVENT 45
TIME 4:28
ENTER
PDMT3,M2,M2,
ENTER

3 MT ON FLOOR

EVENT 266
ENTER
TIME 4:36
ENTER
CC
ENTER
PDPG3,PB,C4,
ENTER
EVENT 44
TIME 4:38
ENTER
PDMI, M1, M1,
ENTER

END SB C 5 1.39 LAD SLAG 19.5 TONS FLUX

EVENT287
TIME 4:38
ENTER
PKSL3, C5,
ENTER
DPSSL3, R3,
ENTER

6 MT ON FLOOR
HIGH CU SLAG AT C 5

ENTER
PDFDI, F5, C5,
ENTER
INFOGP,
ENTER
ENTER

END SB C 6 3.54 LAD SLAG 12.2 TONS FLUX

EVENT288
TIME 4:41
ENTER
PDSSL3, C6, R3,
ENTER
ENTER
TIME 4:42
ENTER
PDSSL1, C7, R2,
PAUSE 200001
ENTER

ENTER
PKSL3, C6,
ENTER
PKSL1, C6,
ENTER
DPSSL3, R3,
ENTER
DPSSL1, R1,
ENTER

EVENT 45
TIME 4:49
EVENT 44
TIME 4:49
ENTER
CFIX3,
ENTER
ENTER
PDMT3,M2,C6,
ENTER
PDMT1,M1,C6,
ENTER

C 6 CONT 3 LD CU, YE TO GO HIGH
TIME 4:51 C6 IS 4 MINS. EARLY
C 6 CONT 3 LD CU, YE TO GO HIGH

2 MATTE IN C 6, FILLED FOR BLOW 3
ENTER
PKCS1,C5,
ENTER
DPSL1,R2,
ENTER

EVENT266
TIME 4:57
ENTER
CC
ENTER
INFOGP,
PAUSE COCC1
ENTER

ENTER
WAIT3,C4,
ENTER

TIME = 5:00 DATE = 5.06.1973

EVENT286
TIME 5:05 NO THAT7 THAT'S 5:01 C4 COMES DOWN 5 MINS EARLY
END CU STAGE IN C 4 5.8 LADLES OF CU
ENTER
PDCSK1,BB,C4,
ENTER

ENTER
INFDAG6,
ENTER
ANODE STATISTICS

<table>
<thead>
<tr>
<th></th>
<th>A7</th>
<th>A5</th>
<th>A6</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANODES CAST</td>
<td>896</td>
<td>0</td>
<td>0</td>
<td>896</td>
</tr>
<tr>
<td>FURNACE CAPACITY</td>
<td>17.50</td>
<td>15.50</td>
<td>17.50</td>
<td></td>
</tr>
<tr>
<td>COPPER IN FURNACE</td>
<td>.00</td>
<td>5.50</td>
<td>12.75</td>
<td>18.2</td>
</tr>
<tr>
<td>TOTAL LDLS ADDED</td>
<td>.00</td>
<td>2.25</td>
<td>2.00</td>
<td>4.0</td>
</tr>
<tr>
<td>FURNACE STATUS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>TIME OF STATUS START</td>
<td>416</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ANODE WHEEL STATUS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>PDCU3, C4, PB,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>PDCU1, C4, A6,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>PDCU3, C4, A6,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>PDCU1, C4, A5,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>PKCU1, C4,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>DPCU1, A7,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>PKDUCU3, A6,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTER</td>
<td>DPCU3, A5,</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EVENT 267
TIME 5:05
NOTE 5:08

EVENT 44
TIME 5:09

EVENT 45
TIME 5:12

CONV  BLOW  MATTE  TRANSFER  REACTOR  START  SLAG  AIR

<table>
<thead>
<tr>
<th></th>
<th>CU</th>
<th>SLAG</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td></td>
<td>C</td>
<td>C</td>
<td>.0</td>
<td>.0</td>
<td>.0</td>
<td>22429</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>OW</td>
<td>COPP</td>
<td>12</td>
<td>C</td>
<td>.0</td>
<td>443</td>
<td>13.0</td>
<td>21159</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>9</td>
<td>0</td>
<td>C</td>
<td>.0</td>
<td>455</td>
<td>6.0</td>
<td>22059</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>HIGH</td>
<td>14</td>
<td>0</td>
<td>.0</td>
<td>336</td>
<td>12.0</td>
<td>24419</td>
<td></td>
</tr>
</tbody>
</table>

ENTER

PDMT3, M2, C4,
ENTER
PDMT1, M1, C4,
ENTER

C 4 NEEDS MORE MATTE TO BLOW
ENTER
TIME 5:21
ENTER
CC
ENTER
INFOGP,
ENTER
PDPG3,P8,C5,
ENTER
PDSL1,C7,R2,
ENTER
ENTER
WAIT5,C6,
ENTER
PDMT1,M1,C4,2,
ENTER
LAD .AT M 1 = 5
LAD .AT M 1 = 4

EVENT 44
TIME 5:29
C 4 CONT 1 LD CU, YE TO GO HIGH
TIME 5:30
A MATTE IN C 4,FILLED FOR BLOW 1
ENTER
PDMT1,M1,M1,
ENTER

EVENT 267
ENTER
PDPG3,P8,C5,
ENTER

5 MT ON FLOOR
END SB C 7 1.64 LAD SLAG 24.2 TONS FLUX

EVENT 289
TIME 5:36
C7 COMES DOWN 6 MINS. EARLY
END OF SLAG STAGE IN C 7
ENTER
PDSL3,C7,R1,
ENTER
PDSL1,C7,CC
ENTER
PDSL3,C7,R3,
ENTER
PDSL1,C7,R1,
ENTER
HIGH CU SLAG AT C 7
LADLE AT C 7 DOES NOT CONTAIN MATERIAL TYPE 1
ENTER
PDPD3,F7,C7,
ENTER
EVENT 45
TIME 5:43
ENTER
INFOGP,
ENTER
PDMT3,M2,M2,
ENTER
PKSL1,C7,
ENTER

EVENT 44
TIME 5:43
4 MT ON FLOOR
ILLEGAL REMOVAL FROM CONVERTER 7
ENTER
LITE66,C
ENTER
PDMT1,M1,M1,
ENTER
WAITS,C6,
ENTER

END SB C 6 2.11 LAD SLAG 11.7 TONS FLUX

EVENT 288
TIME 5:46
ENTER
PKSL3,C6,
ENTER
PKSL1,C6,
ENTER
DPSL3,R2,
ENTER
DPSL1,R1,
ENTER

6 MT ON FLOOR
ENTER
PDMT3,M2,C6,
ENTER
PDMT1,M1,C6,
ENTER

LAD AT M 2 = 3
LAD AT M 1 = 5
C 6 CONT 3 LD CU, YE TO GO HIGH
PULL COLLAR ON C 6

EVENT 93
ENTER
PULL3,C6,
ENTER
EVENT 45
TIME 5:55
C 6 CONT 4 LD CU, YE TO GO HIGH
2 MATTE IN C 6 FILLED FOR BLOW 4

EVENT 44
TIME 5:56
ENTER

EVENT 44
TIME 5:58 COLLAR PULL STARTS ON C6
ENTER
PDPG1, PB, C5,
ENTER
PDMT1, M1, M1,
ENTER
PDMT1, M2, M2,
ENTER

TIME = 6:00  DATE = 5.06.1928
6 MT ON FLOOR
END SB C 4  3,04 LAD SLAG  9,8 TONS FLUX

EVENT 286
TIME 6:05
C4 COMES DOWN 6 MINS EARLY

EVENT 269
ENTER
PDSL1, C4, R1,
ENTER

4 MT ON FLOOR
C 6 CONT 4 LD CU, YE TO GO HIGH
TIME 6:06
2 MATTE IN C 6 FILLED FOR BLOW 4
ENTER
PKSL3, C4,
ENTER
PKSL1, C4,
ENTER
DPSL3, R2,
ENTER
DPSL1, R1,
ENTER

EVENT 44
TIME 6:13
ENTER
PKMT3, M2,
ENTER
DFMT3, C4,
ENTER
PDPG1, PB, C7,
ENTER
PDMT1, M1, C4, 2,
LAD AT M 2 = 3

C 4 CONT 2 LD CU, YE TO GO HIGH
TIME 6:18
C 4 CONT 2 LD CU, YE TO GO HIGH

C4 STARTS ITS BLOW 3 MINS. EARLY

EVENT 267
ENTER

LAD AT M 1 = 5

C 4 CONT 2 LD CU, YE TO GO HIGH

3 MATTE IN C 4, FILLED FOR BLOW 2
ENTER
PDPG3, PB, C5,
ENTER
INFO 005,
ENTER

ENTER
C 5 TO COME DOWN AT 6:28 .... 8 MINS. EARLY
ENTER
C 5
ENTER

EVENT 269
TIME 6:26
ENTER
PDPG3, PB, C7, 2,
ENTER

EVENT 287
TIME 6:27
C 5 COMES DOWN 9 MINS. EARLY AT CYCLE
END CU STAGE IN C 5 5.1 LADLES OF CU

ENTER
PDSK3, BB, C5,
ENTER

EVENT 45
TIME 6:32
ENTER
INFO 006,
ENTER
PDCUS, C 5, PB,
ANODE STATISTICS

<table>
<thead>
<tr>
<th>A7</th>
<th>A5</th>
<th>A6</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>896</td>
<td>C</td>
<td>C</td>
<td>896</td>
</tr>
</tbody>
</table>

FURNACE CAPACITY 17.50 15.50 17.00

COPPER IN FURNACE 1.00 7.50 14.75 23.20
TOTAL LDLS ADDED 1.00 4.00 4.00 9.00
FURNACE STATUS 0 0 0
TIME OF STATUS START 410 0 0
ANODE WHEEL STATUS 0 0 0

ENTER
PDCUS3,C5,A6,2,
ENTER
PDCUI1,C5,A7,
ENTER
PKCUI1,C5,
ENTER
DPCUI1,A5,
ENTER

EVENT 44
TIME 6:33

CONV BLOW MATTE TRANSFER REACTOR START SLAG AIR

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>7</td>
<td>0</td>
<td>.0</td>
<td>618 3.0 22429</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td></td>
<td>0</td>
<td>.0</td>
<td>698 9.0 22059</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>11</td>
<td>.0</td>
<td>543 13.0 24419</td>
<td></td>
</tr>
</tbody>
</table>

ENTER
PDMT3,M2,C5,2,
ENTER
PDMT1,M1,C5,2,
ENTER

EVENT 32

AMODE 6 READY TO CAST
ENTER
CAST6,
ENTER

AMODE 6 NOT READY TO CAST
ENTER
FEFNG6,
ENTER

PAUSE 00001

C 5 NEEDS MORE MATTE TO BLOW

LAD .AT M 1 = 4

ENTER
TIME 6:45
ENTER
C5 STARTS ITS BLOW 8 MINs EARLY
ENTER
C
ENTER

LAD .AT M 2 = 2

C 5 CONT 1 LD CU, YE TO GO HIGH
NAME OF AUTHOR/NOM DE L'AUTEUR: Marys Vilis Neimana\n
TITLE OF THESIS/TITRE DE LA THÈSE: Scheduling in the Copper Converter Aisle

UNIVERSITY/UNIVERSITÉ: Carleton

DEGREE FOR WHICH THESIS WAS PRESENTED/GRADUE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE: M. ENG.

YEAR THIS DEGREE CONFERO/ANNÉE D'OBTENTION DE CE DÉGÊRE: 1980

NAME OF SUPERVISOR/NOM DU DIRECTEUR DE THÈSE: C. M. Woodside

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

DATED/DATE: Nov 29/79

SIGNED/SIGNÉ: M. V. Neimana

PERMANENT ADDRESS/RÉSIDENCE FIXÉ: 2400 Carling Ave, Apt. 806, Ottawa, K2B-7H2
NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED

Ottawa, Canada
K1A 0N4

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formulaires d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RÉCU
SCHEDULING
IN
THE COPPER CONVERTER AISLE

by
Maris Vilis Neimanis, B.Sc., M.Sc.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfilment
of the requirements for the degree of
Master of Engineering

Carleton University
Ottawa, Ontario
November, 1979
The undersigned recommend to the Faculty of Graduate Studies acceptance of the thesis

SCHEDULING

IN

THE COPPER CONVERTER AISLE

Submitted by Maris V. Neimanis in partial fulfilment of the requirement for the degree of Master of Engineering.

[Signatures]

F. J. Gordon
CHAIRMAN, DEPARTMENT OF SYSTEMS ENGINEERING

M. L. [Signature]
THESIS SUPERVISOR
ABSTRACT

This thesis describes a technique for generating converter aisle schedules in a copper smelter to maximize the material processing rate. The first step in the procedure is the development of a mathematical model of the flow of materials in the aisle in the absence of process upsets or equipment failures. Then, based on this description, a problem of matte allocation to the converters to maximize overall matte consumption is formulated and solved. The resulting schedule is validated on an interactive computer model of the converter aisle. Finally, similar techniques are employed to develop transient schedules to reach this ideal mode of operation starting from any arbitrary converter aisle status which could arise due to disruptions.
ACKNOWLEDGEMENT

The help and direction of my supervisor, Professor C.M. Woodside, not only in this work, but throughout my graduate work at Carleton University is sincerely appreciated.

The assistance provided by Dr. U.P. Graefe and Mr. L.K. Nenonen of the National Research Council of Canada in this study is gratefully acknowledged.

The co-operation of Noranda Mines personnel in providing data for this study is appreciated. As well, financial assistance by Noranda Mines Ltd. in work related to this thesis is appreciated. This assistance was provided under an arrangement between Noranda Mines Ltd. and N.R.C.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Scheduling Literature</td>
<td>5</td>
</tr>
<tr>
<td>2.1</td>
<td>Introduction</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>A Scheduling Problem</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Industrial Scheduling</td>
<td>8</td>
</tr>
<tr>
<td>2.4</td>
<td>Basic References</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>A Description of the Scheduling Problem</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>The Flow of Materials in the Converter Aisle</td>
<td>16</td>
</tr>
<tr>
<td>3.2</td>
<td>Practical Scheduling of the Plant</td>
<td>26</td>
</tr>
<tr>
<td>3.3</td>
<td>The Noranda Smelter</td>
<td>31</td>
</tr>
<tr>
<td>3.4</td>
<td>Previous Optimization Research of the Copper Smelter</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>The Scheduling Technique</td>
<td>45</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>45</td>
</tr>
<tr>
<td>4.2</td>
<td>Determination of Model Parameters</td>
<td>46</td>
</tr>
<tr>
<td>4.3</td>
<td>An Overview of the Optimization Problem</td>
<td>58</td>
</tr>
<tr>
<td>4.4</td>
<td>Overall Matte Allocation for Maximum Production</td>
<td>60</td>
</tr>
<tr>
<td>4.5</td>
<td>Allocation of Matte Ladies to Blowing Period</td>
<td>69</td>
</tr>
<tr>
<td>4.6</td>
<td>Determination of Best Time Spacing Between Converter Cycles</td>
<td>70</td>
</tr>
<tr>
<td>4.7</td>
<td>The Determination of the Best Timing of In-Blow Converter Tasks</td>
<td>75</td>
</tr>
<tr>
<td>4.8</td>
<td>Summary</td>
<td>82</td>
</tr>
<tr>
<td>5</td>
<td>Validation on the Interactive Model</td>
<td>86</td>
</tr>
<tr>
<td>5.1</td>
<td>The N.R.C. Interactive Smelter Model</td>
<td>86</td>
</tr>
<tr>
<td>5.2</td>
<td>Description of a Validation Run</td>
<td>94</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>5.3 Summary of Results</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>Chapter 6 Reaching the Optimal Cycle</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>6.1 Introduction</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>6.2 Steps in Calculating the Transient Schedules</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>6.3 Practical Implementation of this Scheduling Approach</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>Chapter 7 Conclusions</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>References</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>Appendix A</td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>Appendix B</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>Appendix C</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td>Appendix D</td>
<td>143</td>
<td></td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 4.1: Matte Addition Limits per Blow 53
Table 4.2: Average Matte Processing and Handling Times for Each Converter 59
Table 4.3: Maximum Matte Capacities for Various Converter Charge Cycle Times 65
Table 4.4: Converter Matte Allocations for the 8 Hour Cycle 66
Table 4.5: Service at End of Blows in the Case Study Schedule 74
Table 4.6: Service at End of Blows for In-Blow Deterministic Study 79
Table 4.7: All my Schedules 85
Table 6.1: Meshed Transient Cycle 117
LIST OF ILLUSTRATIONS

Fig. 3.1 : The Pearce-Smith Copper Converter 18
Fig. 3.2 : General Flow of Materials 22
Fig. 3.3 : Sequence of Events in a Typical Converter Charge Cycle 25
Fig. 3.4 : Smelter Layout 32
Fig. 3.5 : Material Flow Chart 37
Fig. 4.1 : Flowchart for Calculating Material Results Due to the Addition of a Ladle of Matte 40
Fig. 4.2 : Gantt Chart for Sequence of Converter Operations 77
Fig. 4.3 : Gantt Chart for the very First Case 78
Fig. 4.4 : Demand for Crane Service 80
Fig. 4.5 : General Flow Chart for Determining Optimal Aisle Operation 83
Fig. 5.1 : Smelter Display Unit 90
Fig. 5.2 : Smelter Display Unit: Information Format 91
Fig. 6.1 : Times Associated with Transient Schedules 107
Figs. 6.2-6.5: Detailed Converter Charge Cycle Times for Optimal Cycle Prior to Time Shifts 112-113
Figs. 6.6-6.9: Transient Schedules for the Individual Converters 115-116
Plate 1 : Smelter Display Unit 89
CHAPTER 1

INTRODUCTION

Copper smelting using the reverberatory furnace and converter with material transfer by cranes has been a standard procedure since the early part of this century. The process chemistry has not changed essentially. A standard reference on the physical chemistry of copper smelting was written by R.W. Ruddle in 1953. [34] Recently, the Japanese have developed a technique of continuous material transfer by flow, thus eliminating the need for crane service. [35] Moreover, in such smelters the material inputs and metallurgical compositions are computer controlled. If existing smelters are to be competitive with such new ones, increased plant efficiency is highly desirable.

This thesis deals with scheduling in a copper smelter aisle at Noranda, Quebec and describes an approach for computing a cyclical schedule in which the operation of four converters is properly spaced in time to avoid conflicts in crane demand and to maximize production. Chapter 2 discusses the principal types of mathematical
techniques used in optimization with a view toward scheduling. The techniques used in this thesis are discussed in more detail. Other techniques are merely referenced since optimization is such an all-encompassing field. Chapter 3 describes the particular scheduling problem in the converter aisle. The physical and chemical environment of the converter aisle is discussed. Previous attempts at optimization in this reference frame are noted. Chapter 4 discusses the scheduling technique in detail. The actual mechanics of the procedure are illustrated by means of a completely calculated sample schedule. Various other schedules with different values for the parameters are also mentioned. Listings of the appropriate computer programmes can be found in the appendices. Chapter 5 deals with the validation of these schedules on the interactive smelter model at the National Research Council. Some practical problems in this verification are included as well as a brief description of the operation of the model. A sample model run with comments is included in the appendices. Chapter 6 describes a technique for attaining an optimal schedule from an arbitrary converter aisle status. A sample schedule is included to illustrate the mechanics of this procedure. Finally, a few pertinent remarks are made regarding the practicality of such scheduling. The concluding chapter summarizes the work done and suggests various extensions. Parts of this work have been published. [15], [24], [25]
The research described in this thesis was done over a period of some four years, mainly during the summers. The initial impetus was provided by the study of the National Research Council's (N.R.C.) hybrid computer model of a converter aisle as an example of applied simulation. A preliminary effort at scheduling was attempted by programming a module of the model to report the material contents of each converter versus the 'ideal' material contents whenever a major event occurred in the converter aisle. (Refer to Section 5.2) [15] During the summer of 1975, the analysis of the scheduling problem was detailed by decomposing the structure into the following steps:

(A) Calculation of process times per unit raw material

(B) Determination of an ideal cycle time

(C) Maximization of material flow for the converter system

(D) Calculation of end point times for individual converter cycles

(E) Staggering of converter cycles to avoid crane conflicts

(F) Investigation of in-blow task insertions

Computer codes were written for tasks (A), (D), (E), and (F) while an available code was used to solve problems (B) and (C). Results showed the material throughput to be relatively constant subject to the volume constraints of the converter. Thus the length of a working shift - 8 hours - was chosen for the cycle length. A visit to the Noranda smelter was also made during this time period to verify some parameter values with operating personnel and
to measure others. The schedules were validated on the N.R.C. interactive model during the summer of 1976. It was a laborious process because the model was not often used and had been originally designed to be run with different computers. Eventually, however, the schedule showed an increase in matte turnover rate of some 33% which implied an in-plant increase in converting potential of up to 25%. The schedules were shown to be feasible even when the model was run in non-deterministic mode with air-flow rate deviations and deviations in cuprous sulphide allocation policy. The smelter personnel reacted positively to these results. Subsequently several months were spent in generating schedules under new plant operating conditions which showed how the same workload might be handled by fewer number of converters. These schedules were verified by senior plant operations personnel. Unfortunately, the values of the parameters which were originally supplied by Noranda Mines Ltd. were questioned as well as certain operating practices of the N.R.C. model which had previously been judged to be impeccable for some five years. It is emphasized that a change in operating policy only amounts to a change in the value of the control parameters and the schedule generating methodology remains unchanged. Finally, during the summer of 1977, a technique was developed for generating transient schedules to reach the ideal mode of operation starting from any arbitrary converter aisle status.
CHAPTER 2

SCHEDULING LITERATURE

2.1 Introduction

Control over the detailed operations of large industrial processes has become a subject of basic research. An important aspect of industrial control is deciding upon the precise use of manufacturing facilities at each instant of time. Many factors have to be taken into account in making these decisions. It is this kind of decision making, the allocation of resources over specified time periods, that will be called 'scheduling' in this thesis.

The literature survey which follows was undertaken at the start of this research and is therefore somewhat dated. This survey is by no means exhaustive, but rather is merely an indication of the most widely used tools. It is included mainly for completeness, although with the approach taken in this thesis, the scheduling problem did not fit into any one established technique. Rather, the schedule generation methodology is a blending of process knowledge, common sense and a little mathematical programming.
The lack of success of scheduling theory in solving practical problems may be attributed to the gap between the theoretical developments in scheduling theory and the nature of the practical problems. Scheduling research suffers from an over-emphasis on the rigorous mathematical development of the problem and too little emphasis on the realism of the formulation of the problem. See for example [32], where the difficulty of modeling an industrial process is shown by detailed analyses of specific processes. Also, [5] indicates that theory deals with generic models which might be too much of a simplification of real life. The elegant formal machinery developed in scheduling is of no appreciable use to practising schedulers who are thus forced to use the old technique of trial and error.

2.2 A Scheduling Problem

The mathematical analysis of optimal operating conditions presumes the existence of a reliable mathematical model of the system. The techniques of optimization are therefore model-dependent.

That there is no uniquely satisfactory scheduling method will now be illustrated by reference to three similar problems in resource allocation. Time, space and manpower will be the resources considered subject to
availability constraints. The underlying structure of these three problems in basically the same.

In turn, we look at examination timetabling, classroom allocation and the assignment of workers to shifts.

The author of this thesis has modified the work of Broduer, [4] from a Monte Carlo technique to a heuristic rule for breaking ties in a student conflict matrix. Using this approach, a computer programme yields an examination timetable for one thousand seven hundred students taking ninety courses. Using fifteen available writing slots, the number of student conflicts is less than twenty. Subsequently I have discovered that my heuristic rule is called the FFDR (First-Fit Decreasing) algorithm in Bin packing. [5]

Appleton [1] describes an interactive computer simulation of room usage at the University of Newcastle Upon Tyne to allocate rooms efficiently to classes and to plan new buildings. Interaction between the computer and user frequently makes results more acceptable since it allows the use of personal experience and expertise, i.e. heuristic scheduling. The programme, written in ALGOL, has submodules to perform reallocations, print out timetables, update student numbers, add new rooms, change existing
rooms, update the timetables and gather statistics. A sample terminal session is included as part of the paper.

Linear programming has been used to generate garbage collection schedules in New York City in order to minimize weekly collections missed, subject to union regulations and man-power and truck constraints. [18]

Thus heuristics (or job-shop scheduling), simulation and linear programming have been used to solve three very similar timetabling problems.

2.3 Industrial Scheduling

Three basic approaches to scheduling include networks, the construction of schedules with the aid of linear programming and simulation. Reference will now be made to some of the most commonplace techniques used in scheduling and allied problems in industry.

The two major methods of attack in network approaches are the critical path method (C.P.M.) and program evaluation and review technique (P.E.R.T.). They differ in that P.E.R.T. is used for projects for which there is job time uncertainty whereas the critical path technique is used on relatively well-known job times, as might occur in
building a house. In a pair of papers, Kelley [19], [20] laid the mathematical foundations of the critical path method and suggested some uses for P.E.R.T. Widely diverse kinds of projects lend themselves to analysis using these methods, such as:

1. The assembly line
2. Mobilization, strategic, and tactical planning
3. Budget planning
4. The construction of a building, highway, new plant, ...
5. Maintenance projects such as the operation of an oil refinery
6. Installation of a computer system

Each of these projects has several characteristics that are essential for analysis by these methods:

1. The project consists of a well-defined collection of jobs which, when completed, mark the end of the project.
2. The jobs may be started and stopped independently of each other, within a given sequence.
3. The jobs are ordered—that is, they must be performed in a given sequence.

In the field of project scheduling, P.E.R.T. and its descendants have established themselves as excellent, feasible, money and time-saving methods. This is shown by the vast number of diverse projects where the technique has been used with considerable success.
Schedules may be constructed using linear programming and integer programming. A few examples will suffice to indicate the wide variety of uses. These techniques are limited only by the ability of the analyst to translate the problem into this framework.

A linear programming model is used by Bennett, Curr and Haywood [3] to develop schedules to optimize the commercial parameters for transfer of fish between trawlers in a fleeting system. This was forced due to the fact that the fish were far from home base and freshness of the catch is a factor in market price. The conclusion is that the transfer at sea system has been satisfactory and has contributed significantly to the profits.

The practical solution of large mixed integer programming problems is reported by Forrest et al. [11]. The algorithm employed, coded as UMPIRE, uses linear programming as the main fathoming device. UMPIRE has solved many problems of the generally combinatorial type. These have included the generation of schedules in the field of construction and production and distribution of resources. Some of these models involve less than five hundred constraints or have only a few dozen integer or special ordered set of variables. However, UMPIRE has solved a number of very large problems with up to eight thousand constraints and several thousand integer variables. The
paper includes two tables of computational efficiency of the algorithm corresponding to the two types of problems. It is concluded that large scale integer programming is a viable economic proposition.

Simulation is intrinsically valuable since it allows non-experts to visualize the results. A paper by Ashour and Bindingnavle [2] analyzes the flow of hot ingots from the steel works through to the rolling mill. Even though soaking pits are nonproductive units in the process, they could create serious bottlenecks in production if their capacities were not properly determined before installation. The paper represents the pit-mill complex as a queueing system and develops a simulation model to predict the improvement in the capacity of the system attainable through the addition of more pits and to predict the effects of breakdowns and maintenance and the shutdown of a pit. The simulation was written in GASP-IIA. Two sets of runs were done varying the service queueing discipline (FIFO and LIFO) for the arriving ingots. The critical factor economically is the idling of the mill. The simulation experiments suggest that even a small reduction in mill idle time will offset substantial costs for pits and increased capacity until the optimum is closely approached.
Freeman, Hoover and Satia [12] discuss the elimination of machine interference by simulation. The parameters of the problem include task characteristics, machine characteristics and scheduling rules. The scheduling rules include an assignment of interruptability characteristics in terms of task priorities. They discuss the three traditional techniques of assigning operators to machines: namely, interference tables, queueing analysis and expected work load analysis. The shortcoming of interference tables is that this technique suffers from the necessity of oversimplification of the problem. Rather severe assumptions and semi-empirical approximations are required to apply queueing theory analysis. Work load analysis fails to recognize the impact of high variability in arrival or performance times in causing interference. The paper describes input and output for their machine interference simulator. Included is a sample run for a family of three and six machines. The simulator has been used in both batch and time shared modes. It was found easier to input the data and perform sensitivity analysis in the time shared mode.

2.4 Basic References

A good introduction to scheduling methods is via one of the following books.
The 'Scheduling Handbook' by O'Brien [30] is a useful reference for a person who wishes to apply a particular method to a real-life problem. The level of mathematics is quite unsophisticated and the book abounds with a plethora of practical examples. The book is reviewed as containing every known method of scheduling except the rhythm method.

Ray and Szekely [32] have published a textbook which illustrates various techniques of scheduling and optimization with detailed real-life applications. The text is suitable for a graduate level course while techniques of optimization are drawn from chemical and metallurgical industries.

'Industrial Scheduling' by Muth and Thompson [23], although somewhat dated, gives an excellent insight into various types of scheduling methods. The general emphasis is on the illustration of theory by means of simple examples. The book is recommended as a light introduction to someone unfamiliar with the ideas behind some of the basic theory.

'Computer and Job-Shop Scheduling Theory' by Coffman et al. [5] expounds on the theory of one important type of scheduling which is practically applied, namely, the job shop. Job shops deal with the manufacture of discrete units processed either as single entities or in small batches.
Scheduling is generally controlled by a shop order process rather than by an assembly-line system. In the past, routing sheets controlled manufacturing through a series of operations, each group consisting of a job. This resulted in the term 'job shop'. Examples of the use of job-shop techniques include mail-sorting, textile machine works, manufacture of machinery and shipbuilding. The intent of this book is to provide students and researchers in specific areas with a means of staying moderately up to date in scheduling theory as a whole, without having to peruse extensive literature. From a mathematical point of view, the book is not light reading. The focus is on generic models of simple structure whose combinatorial complexity and analysis resembles that of various structures encountered in a wide variety of disciplines. The treatment is wholly mathematical, with very little recourse to discussions of pragmatics.
A DESCRIPTION OF THE SCHEDULING PROBLEM

In order to have a clear understanding of the operation, a brief description of the processes involved in copper smelting is given.

The copper smelting process description and model parameter values are based on discussions with and reports from Noranda Mines Ltd. personnel. During the summer of 1975 a two day visit was made to the smelter during which operations were observed and discussions took place with all relevant operating personnel. Much valuable insight was also provided by Mr. L.K. Nenonen and Dr. U.P. Graefe, who have modelled and simulated copper-smelting operations for more than a decade. An eighteen page survey of the values of operating parameters was provided by a Noranda Mines' conventional converter technician in February, 1975. This included pickup and dumping times of materials, weights, distances and assay values of materials. In cases where values were not available, the opinions of people in these departments were collected. These estimated values were considered to be representative. In addition, data was also
provided in the following ways. Discussion of operating practices and parameter values was carried on when a smelter metallurgist in charge of converting and a senior converter aisle foreman visited the National Research Council's simulation model in September, 1975 and October, 1976. A visit by the director of the Noranda Research Center in August, 1976 provided further insight. During the summers of 1975 and 1976, there were numerous communications with the smelter technical superintendent.

3.1 The Flow of Materials in the Converter Aisle

The Physical Components

In this thesis, the operation is viewed in terms of material handling by the cranes and matte processing by the converters. The equipment in the converter aisle consists of reverberatory furnaces, converters, anode (or holding) furnaces and gantry cranes.

The reverberatory furnaces supply the raw material and accept the converter waste. The converters operate on an oxidation/flotation principle so that waste products float on the surface and may be poured off. Anode furnaces accept the finished product from the converters for further refining.
In order to facilitate the description, the following is a glossary of commonly used terms. Sizes and capacities refer to the Noranda Smelter. British units of measure are used instead of the SI system because at the time of the case study schedule (1974), the smelter was using this system of measure. It is hoped that such a system might be of more benefit should this material be referenced by Noranda Mines Ltd.

Anode Furnace: holding furnace for pyrometallurgical refining of blister copper. Typical capacity of 150 tons.

Blister Copper: almost pure liquid copper. The end product of the converting process.

Blow: a period of time during which air is blown into the mass of molten metal and slag in the converter.

Converter: a cylindrical brick-lined container capable of holding some 125 tons of molten matte and fluxing ore at temperatures of 1200 degrees Celsius. As can be seen in Fig.3.1, the converter lies on a roller support which is motor driven to rotate the converter so that it may pour out slag.
Cranes:—Overhead cranes run on a common track with no siding or bypass to avoid interference. Forty tons is a typical crane carrying capacity. Cranes achieve speeds of 200 ft./min.

Fluxing ores:—some seventy per cent silicon oxides .. the remainder assumed to be inert materials which enter the slag

Ladies:—containers of some 150 cubic feet capacity capable of holding twenty tons of molten material .. transported by the cranes

Matte:—liquid ore in the reverberatory furnaces (eutectic mixture of iron and cuprous sulphides)

Reverberatory Furnace:—large (100 ft. x 50 ft.) boxlike brick structure holding matte and slag at 1300 degrees Celsius

Slag:—liquid mixture of fayalite and gangue (earthy particles in ore)

Tuyeres:—pipes through which air enters the converter .. must be repeatedly opened with a puncher (Fig.3.1)
White Metal: almost pure cuprous sulphide. The contents of the converter at the start of the copper blow

**The Process Chemistry**

Reverberatory matte is poured into the mouth of a converter from a ladle which is manipulated by an overhead crane. The converter then rolls into the stack, i.e. the blowing position with its mouth under the hood, submerging the tuyeres below the surface of the molten bath, and air is blown into the bath.

There are basically two parts to the converting process, the slag phase and the copper phase. Although the chemistry is quite complex, I will follow Nenonen and Pagurek [29] in assuming that essentially the process can be summarized by the following two exothermic reactions.

### Slag Phase

$$2\text{FeS} + 3\text{O} \rightarrow 2\text{FeO}.\text{SiO} + 2\text{SO}_2$$

Fluxing ore is continuously added to the converter by a belt system and slag floats to the surface. During converting, flue gases are exhausted by an overhead hood fan.

### Copper Phase

$$\text{Cu}_2\text{S} + 2\text{O} \rightarrow 2\text{Cu} + 2\text{SO}_2$$
During this stage more white metal may be added by crane service from other sources. For cooling purposes, cranes transport chunks of solid copper called 'pigs'. At the end of this stage, the blister copper is either transported to the anode furnaces by the cranes for further refining or, if need be, poured into sand moulds to cool into pigs.

A general overall flow of materials is indicated in Fig. 3.2.

Operational Sequence

The operations which define the length of a converter charge cycle are:

1. Transportation of matte from reverb to converter, including cycle interruption times when matte is added during a blow

Molten matte pours out into a ladle which is on a handcar on a track beside the reverb. This location is referred to as the matte tunnel. The hole is then closed with a clay plug. The car is pushed to the converter aisle where a crane is waiting. The ladle has jutting arms on either side and the crane connectors are oval-shaped. The time to pick up a ladle of matte takes less than one minute but is dependent on the experience of the crane operator. Travel
Fig. 3.2 General Flow of Materials
times can range from ten seconds to a minute depending on the relative location of the converter and the reverberatory. The pouring of matte takes about one half a minute. Then the ladle must be deposited somewhere, preferably back at the matte tunnel where it came from.

2. Oxidation of ferrous sulphide to slag during the matte blow phase

3. Removal of slag and its transportation to a reverberatory furnace

The procedure is essentially the same as procedure 1. but reversed. Slag is 'skimmed' when a converter rotates out of its stack and pours the top layer of its contents into a ladle.

4. Addition of pigs for cooling purposes during the copper blow

'Pigs' are five ton lumps of copper crusted with sand from the mold they are cooled in. There is a hook imbedded in each copper pig so that the crane may pick it up, and an auto-release crane hook which releases when the pig enters the converter bath.
5. Oxidization of cuprous sulphide during the copper blow.

6. Removal of blister copper from the converter and transportation to an anode furnace or pig bay.

Tapping of copper takes about half an hour. The charge is generally allowed to settle in the converter and a skull is added to form a crust on the surface. (A skull is the cooled residue of crust from a ladle and is formed when the ladle is bumped and its contents are dumped on the floor to cool.) Copper is tapped for twenty minutes and five to ten minutes are required to add reverberatory matte in preparation for a new cycle. The blister copper is dispatched in the same manner as was the slag. If it is dumped in the pig bay about four pigs can be formed from a ladle of copper which then take about three hours to cool.

The converter cycle is illustrated by the (ferrous sulphide:cuprous sulphide) vs. time profile in Fig.3.3. The cycle is divided into blows because of the physical volume capacity of the individual converters as well as limitations to effective oxidation depending on the depth of the bath. See, for example, [9]. Therefore, more matte may be added as slag is removed.

With the exception of blow #1, service prior to a matte blow consists of skimming slag and addition of matte.
In the profile, the horizontal segments followed by sawtooth peaks, during matte blows, indicate times of matte addition. Skimming is allowed during the last slag blow (called the going high blow) in order to distribute the demand for crane service. These slag skimming periods are represented by the horizontal segments in that particular blow's profile. The longer horizontal segment represents the task of collar pulling i.e. removing the crust deposit around the mouth of the converter due to spillage and dumping it into the converter. Crane service prior to the copper blow consists of skimming of all residual slag followed by the addition of flue dust. During the copper blow, the short horizontal segments indicate the addition of copper pigs for cooling purposes.

The purpose of this study is to design a converter schedule for optimal crane deployment with minimal crane interference.

3.2 Practical Scheduling of the Plant

Based on this description of the process, let us examine in more detail the problems of production scheduling.
The converter aisle foreman tries to achieve a maximal constant rate of matte flow from the reverberatory furnaces. In order to do this, he must continuously maintain a material demand-supply function on a macroscopic scale. Each unit in the converter aisle may be assigned such a function. To maintain a balance, the demands of one unit must be met by the supplies of another. At any instant, therefore, the foreman must be aware of the state of these functions for all units. Then the demands must be sequenced in order of time priority in conjunction with the total production of the whole system. Finally a non-conflicting crane assignment must be made to perform the operations in descending order of priority. Where choices are possible, he tries to determine the best feasible procedure maximizing productivity. To do this he generally tries to schedule the converter cycles so that their end-points are evenly spaced in time. Such an even spacing requires a detailed knowledge of blowing rates and efficiencies, matte grades, converter capacities, matte availability, traffic conflicts, etc. Such current data can only be collected accurately by some form of automatic data acquisition system and, to provide predictions, some form of computer system may be required. At any time three levels of information must be available:

1. The status
2. The priorities
3. A crane schedule to satisfy the priorities
The converter cycles must mesh with the reverberatory furnace cycles and the anode furnace cycles, otherwise, the material balance can not exist since there would be a shortage/surplus of reverberatory matte and/or blister copper.

Clearly, decision-making by the converter aisle foreman is a difficult process which may be satisfactorily approximated only after a lifetime of experience. Even then, the decisions can only be intuitive not quantitative. Under present circumstances, a bottleneck in material demand, and thus crane demand, invariably occurs.

In practice, each converter foreman attempts to take a certain number of ladles of matte from the reverberatory furnaces during his shift. Striving to meet this goal on one shift can cause difficulties on the following shift. The most serious schedule disruption occurs when two converters come down simultaneously at the end of a blow. If two converters come down simultaneously at the end of a copper blow, the situation is compounded. Not only is there an impossible crane demand, but subsequently there will be a matte shortage. In effect, one can safely say that one of the converters has lost about an hour.

Physical obstruction by a crane can also delay a schedule. An example of this is a crane performing a
collar pulling task. Collar pulling is the task of cleaning the mouth of a converter. The actual time required for this operation depends very much on the experience of the craneman and also the state of the mouth. In the meantime, some converter on the other side of this working crane from the free crane may require service at the end of a blow or in-blow service such as pig addition during a copper blow. Invariably time will be lost. Either the collar pulling will be interrupted which is not desirable, or else the other task may be delayed until the collar pulling is completed.

The synchronization of the converter and anode cycles is of prime importance. The anode furnace cycle is of approximately a twenty-two hour duration. Should all the anode furnaces be busy casting, there would be no place (other than the limited demand of the pig bay) to transfer the blister copper.

Prior to passing any judgment on the performance of the converter aisle foreman, we must consider his environment. He works in temperatures often in excess of 100 degrees Fahrenheit, with noise level around the pain threshold (he wears ear plugs) in clouds of noxious gases (all workmen wear gas masks). Under these circumstances, it is not surprising that there is an occasional error in communication between the foreman, crane-operator and the
swamper. (A swamper is a workman on the floor of the converter aisle who directs crane movements by hand signals.)

Every shift has its share of unexpected disturbances. A converter is temporarily held up due to mechanical trouble caused by material from the hood falling between the shell and rotating mechanism. A converter comes down due to an empty silica chute. A malfunction in the air flow system occurs, such as: punchers needing repairs, valves or punching bars sticking in the tuyeres.

The cranes must be serviced periodically. Overhead tracks must be inspected, causing a stoppage or at least a diminution of crane service. The tuyeres become periodically clogged with matte which causes a great deal of fluctuation in the air flow rate. The converter lining tends to be thinned with wear with the result that near the end of its life a converter can not be used on a copper blow. Instead the white metal must be transferred to some other converter which is in the copper blow.

The times of end points of blows in a smelter may be very non-deterministic because of reasons such as the following. Scrap material added to the converter includes items such as television chassis, telephones, cables, oily motors etc. Moreover, the building is open and thus the outside temperature affects the rate of chemical reactions.
3.3 The Noranda Smelter

Physical characteristics

The smelter includes the following equipment arranged as shown in Fig. 3.4, the overhead schematic diagram of the converter aisle:

1. Three reverberatory furnaces
2. Five Peirce-Smith copper converters
3. One fixed and two rotary anode furnaces
4. Three gantry cranes operating on the same track above the converter aisle

Reverberatory Furnaces

In the mode of operation illustrated in Fig. 3.4, there were two dry (or hot) charge furnaces and one wet-charge furnace, each of dimensions 110 ft. by 35 ft. Whereas a hot-charge furnace is fed with calcine from roasters, the wet-charged furnace accepts concentrates with a certain moisture content. Concentrate is charged to the furnaces from storage bins by a shuttle conveyor on each side of the furnace.

Typical metallurgical and production features of such furnace operations are:


CHARGE COMPOSITION

<table>
<thead>
<tr>
<th>Matte Type</th>
<th>Cu</th>
<th>Fe</th>
<th>S</th>
<th>Rate (dry tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet Charge</td>
<td>32%</td>
<td>33%</td>
<td>28%</td>
<td>600</td>
</tr>
<tr>
<td>Dry Charge</td>
<td>40%</td>
<td>28%</td>
<td>25%</td>
<td>1200</td>
</tr>
</tbody>
</table>

Converters

There are four 13 ft. x 30 ft. Peirce Smith converters. Converter #7 is larger being of dimensions 14 ft. by 32 ft. It is equipped with Kennecott 4B punchers with automatic sequential firing. The punchers are arranged in two banks of 25 each and are fired once a minute, taking four to five seconds to fire a 25 puncher bank. The machines are removed once every twenty-four hours to ream the tuyeres manually. An average converter life is 180 days with a production rate of one hundred tons per day. Theoretical upper limits for the charge sizes are 17 ladles of matte for the four converters of equal size and 20 ladles of matte for converter #7. In practice, 12 ladles of matte is a typical charge size.
Anode Furnaces

There are two rotary anode furnaces of dimensions 13 ft. by 35 ft. and 13 ft. by 30 ft. and one stationary anode furnace, similar in design to the Gaspe anode furnace reported in [22]. The stationary furnace capacity is 145 tons, copper being tapped at 40 tons per hour into a casting wheel with a capacity of twenty 625 pound anodes.

Other Converter Aisle Details

Matte and slag ladles are 180 cubic feet in volume. Copper ladles are limited to 130 cubic feet due to crane capacity. Approximate weights of matte and slag transferred are eighteen and twelve tons per ladle respectively. Slag and matte ladles can be used interchangeably, depending on their condition. Although matte ladles could be larger, slag ladles are limited to the present size by space restrictions when dumping slag into the reverb furnaces.

Collar pullers are stored on a rack near reverb #2.

Matte skulls are kept by the bumping block. These skulls are cooled residuals of ladle crust which forms so that every once in a while the ladle has to be bumped. The skulls are used to form a surface crust on a converter's contents at the end of a copper blow.
Pigs are poured in sand molds on the floor at the pig way and require some three hours to cool. The pig pile is an emergency storage place in case of pig shortage which would be disasterous to say the least.

Workmen collect flue dust in wheelbarrows and dump it into ladles located near each of the converters.

**Operating Mode for the Case Study**

During the summer of 1974, four of the five converters were in operation while the other one was down for rebricking. Although there are three cranes designated, only two were used for operation at any one time. The third crane is a smaller crane (CR#2) and is located at the north end of the smelter where it performs housekeeping chores such as unloading trucks. It is only used in production when one of the other cranes is out for repairs or servicing.

In this mode of operation no one kept track of what type of matte was added to a converter. Hence there was uncertainty about the exact content of a converter at any fixed time and added unpredictability of blow end point times, especially the definitive high blow and copper blow end points.
The material flow chart for these operating conditions is illustrated in Figure 3.5 (ignore the continuous smelter input).

3.4 Previous Optimization Research of the Copper Smelter

Research to date of optimization in the copper smelter has been largely in the control of metallurgical variables in the individual processes to minimize heat and material losses and to maximize production rates. There has been little in the way of scheduling of the operation of the individual processes and of the flow of material between them to maximize smelter production.

Research on Copper Converter Process Optimization

Foreman [9] developed a computer model that would yield a dynamic record of reaction rates and predict endpoints. He specifies in detail the model development which consisted of a Fortran program. The company was to proceed with a pilot installation of an on-line computer for the development of control criteria applicable to converter features. Foreman mentions that converter aisle throughput is directly related to the optimum operation of individual converters and scheduling of converter crane moves. He concludes that the present goal is to develop an integrated smelter process control system. In the later paper [10],
Fig. 3.5
MATERIAL FLOW CHART

RAW MATERIAL

REVERB FURNACE

REVERB SLAG

MATTE SULL

SLAG

FLUX

MATTE TRANSFER

LADLES

SLAG SULL

CONVERTER MATTE BLOW

CONVERTER CU BLOW

SCRAP INPUT

LOW CU SCRAP

CU SCRAP STORAGE

HIGH CU SCRAP

SCRAP INPUT

FLUE DUST STORAGE

FLUE DUST INPUT

REQUIRE CRANE SERVICE

CU SULL

CU SKULL

CU SKULL

SKULL LADLE COOLING

MATTE

PIGS

CONTINUOUS SMELTER

INPUT

PIG BAY

PIG PILE

ANODE FURNACE

CU OUTPUT
some results are reported. The importance of depth of blowing was confirmed as a process control variable and a method for blister copper end-point control was developed. Results indicated the value of computer process control and the need for a full scale development program. Predicted information has been used as a guide for overall operations scheduling; for example, matte grade fluctuations have been minimized. He proposes a simulation program to provide improved charge calculation and operations scheduling information based on all available material on hand and current reverberatory conditions.

Nenonen and Pagurek [29] employed a conjugate gradient method to determine the optimal rate of flux addition to a calibrated mathematical model of the converter for various levels of enriched oxygen.

Simulation of Effect of Plant Changes

Eastwood et al. [8] describe changes in the smelting practice of the Nchanga Consolidated Copper Mines' Rokana Smelter, due to a GPSS model. The model simulated many weeks of smelter operation in a short computer run and evaluated the effects of any change. The model endorsed a number of earlier decisions taken regarding plant additions and was able to simulate operations over a range of production levels to show the effect on plant capacity of
changes in operating technique, and positive contributions to revision in the converter aisle. Included in the additions to the plant during this period were an anode casting furnace, a converter, an overhead gantry crane and increased reverberatory furnace slag handling equipment. Continuation of this work has lead to increased aisle mechanisation to reduce overhead crane involvement with the more arduous of the aisle operations.

In a subsequent paper, Davies and Thixton [6] report on further equipment changes due to this simulation. Larger ladles were purchased since the simulation indicated that an increase of the order of 6% in smelter throughput could be expected. The provision of extra bumping blocks was shown to have but a marginal effect on production under the prevailing conditions. The investigation did, however, stimulate thought on the question of crust breaking and a device was designed and installed which breaks a hole in the crust of a ladle without the need for bumping. Other additional changes due to the simulation include the purchase of housekeeping equipment so that there would be reduced crane interference, and a choice of location for the installation of a slag settling furnace to receive all the slag from the converters.

DeMaire [7] describes a simulation of a copper casting alloy plant using GPSS in order to evaluate the
effect of plant expansion on the workload of a large single crane. Each crane task was detailed by sub-dividing it by breakpoints into sub-tasks. Through cooperation with operating personnel, a matrix was developed that fixed which events could not happen simultaneously. Since many of the crane tasks were relatively long in duration and consisted of several distinct steps, it was decided to allow the crane to be pre-empted at any breakpoint in a major task if a higher priority task was waiting. The major conclusion drawn showed that there was negligible loss in capacity due to increased crane interference. Further sections of this paper discuss simulation in quality control and standards for patrolling operators. The simulation resulted in a 20% reduction in the standard labour requirements with corresponding salary savings to the company.

Marchant et al. [21] report on a General Purpose Smelter Simulation System (GPSSS). This simulation system was designed to evaluate the effect that various smelting processes, gas capture methods and dispersion systems have on environment, production and operation of a copper smelter. New environmental laws forced The Kennecott Copper Corporation to do this research. One significant conclusion was that low level emissions have a disproportionately large effect on ambient concentrations in the area immediately surrounding a smelter.
Scheduling in the Converter Aisle

Aside from the National Research Council model, which this thesis considers in detail, there have been only two papers published dealing with this type of scheduling; one, [36], is theoretical and incomplete, the second, [6], is the GPSS simulation of Davies.

The difficulty lies in the setting up of an adequate mathematical model of the plant which is acceptable to non-mathematician management, so that they would put their trust in any conclusions drawn and implement changes in the plant.

The simulation approach is to develop a mathematical model of the plant which accurately imitates the behaviour of the real-life operation. The GPSS simulation is a set of rules which describes the behaviour of the plant, together with statistical information concerning plant variables. The Rokana Smelter simulated by Davies [24] consists of five reverberatory furnaces, six converters and four anode furnaces. Material handling is almost exclusively by the five gantry cranes. The model was used to estimate that a production increase of about 3% could be achieved if there was an alternate way of delivering cold copper pigs to the converters during the copper blow. Unfortunately that problem remains unsolved. The
simulation also investigated the possibility of staggering the cycles so that one converter would always be down for crane service. A second less-detailed simulation was run to account for the effects of converter overhauls. Many years of smelter operation were simulated in this manner and long term average production rates could thus be established for the various converter operating strategies.

The only other actual effort at scheduling in the converter aisle is reported by Nenonen and Graefe [27]. A planning pegboard arrangement was used by Noranda Mines Ltd. which worked reasonably well for routine operation but was of no help to the foreman when he wished to adjust plans following an unexpected disturbance. The planning horizon for the pegboard was to be three hours.

Templeton and Hankley [36] provide a theoretical analysis of the converter aisle. The paper indicates how the system may be formalized into a state variable model. However, the system they consider consists of a single crane, one reverberatory furnace, one anode furnace and three converters. Furthermore, their model describes the system only during the slag blow phase and only while the converters are actually blowing.

The authors then compare direct optimization vs. partitioning of the problem.
For direct total system optimization, continuous variables are quantized in time and combined with discrete decision variables to form one large discrete time model. They comment on three techniques of optimization. First, they considered dynamic programming. The number of calculations required varies exponentially as a function of the number of state variables. In the case investigated, the number of variables is so large that the authors decline to present a model. In a realistic case, this approach becomes unmanageable. Second, gradient search may not be used because it requires that the system performance function vary continuously with each control variable and that the control vector be independent of its value at any other time. Third, random search is unlikely to be useful because of the number of variables involved.

For the partitioned version, the paper considers the following hierarchy of control subproblems:

1. Given material requirements of the converters, find an optimum crane routing which will minimize the service time for each converter service.

2. Given fixed services and fixed service times for each converter, find an optimum converter schedule which will minimize the charge cycle time for each converter.
3. Given a schedule of converter services, find optimum inputs to each converter furnace which will achieve that schedule and satisfy the physical constraints of the converting process.

The first problem is solved by dynamic programming. The converter furnace control is solved by a gradient search in the space of control functions as by Nenonen and Pagurek [29]. A method is described to compose these solutions into a solution to the original problem.

This work was surveyed subsequent to the structure arrived at in this thesis. The concept of partitioning the main problem into a series of subproblems is the same. However, this thesis examines a more complex situation in greater detail. (Refer to Section 4.3) Templeton and Hankley perform a more theoretical analysis of a generic model, avoiding such details as crane interference, different grades of matte and service at the end of blows.
CHAPTER 4

THE SCHEDULING TECHNIQUE

4.1 Introduction

We now examine how the scheduling approach is applied to the process described in Chapter 3. Each converter goes through a cycle beginning with the addition of several ladles of matte (this cycle has been described in Section 3.1). The establishment of a steady state cyclical schedule for the entire converter aisle is logical for the following reasons. A cyclical schedule ensures that at any time the status of all machines is specified. Furthermore, it is a natural way to ensure a constant material flow and to avoid an extreme out of kilter status whereby the whole of production is delayed. It will also be shown that there is an easy way to return to a given cyclical schedule from an arbitrary state.

A work load analysis of the converter aisle is performed. The scale of modelling is macroscopic; i.e. batch times are allocated to events which need not be considered in detail. It is hoped that a level of detail has been established that is sufficiently gross to keep the
model simple yet specific enough to produce accurate results.

The following sequence of decisions is made in the construction of the schedule. A time is calculated to complete a stage in the refining process using the parameters of the machine as well as transportation times. The maximum total production turnover is calculated for the plant for a given fixed time under the constraints of machine capacity and raw material availability. A detailed schedule is then mapped out for each machine (converter) using this maximum turnover as data. Then, these machine schedules are staggered in time to avoid conflicts in crane service demand.

The approach involves four general steps which are now discussed in detail using the particular schedule which involved four converters serviced by two cranes and operating with two dry and one wet matte reverberatory furnaces; the operating conditions at the Noranda smelter in 1974. This example is being used because it is realistic and it explains the scheduling technique.

4.2 Determination of Model Parameters

The purpose of this section is to define the mathematical model for scheduling. The model will
represent the length of a converter cycle as a function of the type and quantity of matte added.

It is possible to estimate the total time to process and handle the matte, slag, blister copper and copper pigs during a typical converter cycle on a "per ladle basis" i.e. minutes per ladle of matte in the absence of crane or other conflicts. Furthermore, separate values can be determined for the hot charge matte, wet charge matte and reactor matte due to the separate locations from which they are picked up by the cranes (matte tunnels 1 and 2 and the north end of the plant) and due to their differing grades and consequently different processing times in the converter. Finally, these times will differ for each converter due to the differing blowing rates of each converter and due to the differing distances from the matte tunnels, reverb furnaces, anode furnaces and pig storage areas.

Material Content in a Converter Due to and Resulting From the Addition of a Ladle of Matte

The weights of ferrous sulphide, cuprous sulphide, free iron, free copper and slag formed as a result of the addition of one ladle of matte ore are calculated. For a detailed definition of the symbols representing these quantities, refer to Fig. 4.1.
Flow Chart for calculating quantities of ferrous sulphide, cuprous sulphide, slag, free iron, free copper (tuns) in a ladle of matte of weight W tons and proportions of iron, copper, sulphur of F, C, S respectively.
During the slag phase, the principal chemical reaction is given by:

\[2\text{FeS} + 3\text{O}_2 + \text{SiO}_2 \rightarrow 2\text{FeO} \cdot \text{SiO}_2 + 2\text{SO}_2\]  \hspace{1cm} (1)

Any free copper entering with input materials oxidizes instantaneously according to equation (2) and any free iron according to (3), then the resulting FeO combines with the silica to form slag according to (4).

\[4\text{Cu} + 2\text{FeS} + \text{O}_2 \rightarrow 2\text{Cu}_2\text{S} + 2\text{FeO}\]  \hspace{1cm} (2)

\[2\text{Fe} + \text{O}_2 \rightarrow 2\text{FeO}\]  \hspace{1cm} (3)

\[2\text{FeO} + \text{SiO}_2 \rightarrow 2\text{FeO} \cdot \text{SiO}_2\]  \hspace{1cm} (4)

During the copper phase, incoming oxygen reacts with cuprous sulphide according to equation (5).

\[\text{Cu}_2\text{S} + \text{O}_2 \rightarrow 2\text{Cu} \cdot \text{SO}_2\]  \hspace{1cm} (5)

Given the proportion by weight of iron, sulphur, and copper, \((\text{Fe}, \text{S}, \text{Cu})\) in a ladle of matte, we can calculate the resultant products formed during the converting process. The atomic weights of the elements are:

\[\text{O}-16.0 \quad \text{Si}-28.1 \quad \text{S}-32.1 \quad \text{Fe}-55.8 \quad \text{Cu}-63.5\]
Case (i)  If all the iron enters as ferrous sulphide, we have the condition that there is excess sulphur, the ratio being in excess of that found in the formula FeS i.e. 
\[ (S : F) > (32.1 : 55.8) = 0.575, \] or \[ S > 0.575F. \] So the proportion of ferrous sulphide present can be expressed in terms of the proportion of iron present by 
\[ FS = (32.1 + 55.8) : 55.8 \times F \text{ or } F = 1.57F. \]

Case (ii)  Otherwise, there is no cuprous sulphide as sulphur shows a greater affinity for iron than for copper. All the copper entering is then free copper. The proportion of free iron, FF, is given by the total proportion present minus the amount in the ferrous sulphide, i.e. 
\[ FF = F - 55.8 / (55.8 + 32.1) \times FS = F - 0.64FS. \] Now the free copper reacts according to equation (2), consuming the ferrous sulphide in the ratio of 
\[ (32.1 + 55.8) / (2 \times 63.5) \times FC. \] Therefore, 
\[ FS = FS - 0.691FC. \] In addition to the original proportion of slag (or waste material) present, fayalite is produced when ferrous oxide combines with the silica flux according to equation (4). The ferrous oxide is partly a result of chemical reaction of free copper and free iron according to equations (2) and (3). So the total proportion of slag present, SL, equals the original slag plus these by-products;
\[ \text{i.e. } SL = SL + \frac{(2 \times 71.8 + 0.1)}{(2 \times 55.8)} \times FF + \frac{(2 \times 71.8 + 60.1)}{(4 \times 63.5)} \times FC \]
\[ = SL + 1.825 \times FF + 0.801 \times FC \]

If Case (i) is true, \( S > 0.575F \); \( FS = 1.57F \) and two cases ensue depending on whether all the copper enters as cuprous sulphide or not. The condition that it enters solely as cuprous sulphide is given by \( S > 0.575F + \frac{32.1}{127}C = 0.575F + 0.252C \). If this is true, there is no free copper or free iron and the proportion of cuprous sulphide present is given by \( CS = \frac{(127 + 32.1)}{127} \times C = 1.25C \). If it is not true, then some of the copper enters as free copper and all the sulphur has combined to form cuprous sulphide and ferrous sulphide. Hence, the amount of free iron present is nil. The proportion of cuprous sulphide present is given by \( CS = (S - 0.575F) \times \frac{(127 + 32.1)}{32.1} = 4.96 \times (S - 0.575F) \) and that of free copper present by \( FC = C - (S - 0.575) \times 4.96 \times 127 / 159.1 \)
\[ = C - (S - 0.575) \times 3.96. \]

The calculations are summarized in an accompanying flowchart (Fig. 4.1). A similar flowchart was provided by L.K. Nenonen, but the above calculations have been derived independently.
Travel Times of Cranes

Crane travel times are of utmost importance in the model as these times lengthen the converter cycle time when the converter is down at the end of a blow and waiting for the conclusion of service.

Crane travel times were obtained by measuring respective distances on a scaled floor-plan (Fig. 3.4) and dividing by the average crane speed. These crane speeds were verified by observation in the plant itself.

At the start of each converter cycle, reverb matte is added to the converter. The addition limits are specified in Table 4.1. Two ladles of matte (three for converter 7) are required to start blow 1 whereas all other blows require only one ladle of matte to start. The operation of adding reverb matte consists of the following crane tasks: picking up matte, travelling to the converter, pouring matte, travelling to the matte tunnel, depositing ladle. Assuming that each converter receives quantities of hot and wet matte in the same ratio as their respective production rates, the average matte transport addition time for each converter is calculated. Note that the "optimal" ratios of not to wet charge matte for an individual converter will not necessarily correspond to the matte production ratio. Their calculation is based on best a priori estimates of
<table>
<thead>
<tr>
<th>NCV</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>TOTAL MATTE ALLOWED</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4.1 Matte Addition Limits per Blow
matte transport time. In this particular case the difference in travel times was insignificant. Generally, this calculation procedure would have to be iterative.

The following is an important model approximation. Since the initial positions of the cranes at an individual time cannot be found deterministically, allowance is made for increase in cycle time due to crane interference by assigning a full task time when only a partial time would suffice. As an example, suppose converter 4 requires two ladles of matte to start blow #1. The time for adding reverb matte and returning the ladle is 112 seconds plus travel time. If the ratio of the production rate (in ladles) of hot charge matte to that of wet charge matte is c, the time for the operation to take place is: time to add matte + (c x time to travel from converter 4 to matte tunnel 1 and return to converter 4 + time to travel to converter 4 to matte tunnel 2 and return to converter 4) + (c + 1). Assuming c=2, the expression is equal to 112 + (2x78 + 54)/3 = 182 seconds. A likely sequence of events could now be the following. Crane #3 picks up a ladle of wet matte at matte tunnel 2 which takes an estimated 45 seconds, travels to converter 4 in 27 seconds, dumps in the ladle of matte in 37 seconds, and takes 10 seconds to move out of the way of crane #1 (see Fig. 3.4). In the meantime, crane #1 has picked up a ladle of dry matte at tunnel #1 and moves in to pour it into converter 4.
in 37 seconds. The converter then rotates into the stack to start blow #1, using 5 seconds. Thus, converter 4 would be down for 161 seconds and crane service time allowed is 182 seconds, i.e. the two cranes are busy for 182 seconds.

Assuming that slag is returned in equal proportions to each reverberatory furnace, and using operating statistics on the occasions in the converter cycle when it is skimmed, the average times to skim and transport the slag produced per ladle of hot and wet charge matte added to each converter is determined.

The time to tap and transport the blister copper produced per ladle of hot charge and wet charge matte is calculated. Again there is assumption that the blister copper is evenly distributed amongst its possible receivers, namely, the anode furnaces and the pig bay.

**Calculation of In-Blow Processing Times**

The processing time of materials is now considered. The timing of the chemical reactions, expressed in tons/min., can be summarized by the following three rate equations found in Nenonen, Graefe, Stroble (28):

- Consumption of ferrous sulphide = \(0.000016 \times \text{AIR} \times \text{EFF}\)
- Production of slag = \(0.00013 \times \text{AIR} \times \text{EFF} \times (1 + 0.419 \times \text{FRAT})\)
- Oxidation of cuprous sulphide = \(0.000434 \times \text{AIR} \times \text{EFF}\)
where AIR and EFF measure the air flow entering a converter in standard cubic feet per minute and the proportion of oxygen which actually reacts on its way through the converter. A coefficient FRAT is introduced to approximate the actual rate of silica addition as a factor of the stoichiometric rate. For a complete discussion of this, one may consult Appendix C of the previously mentioned reference.

The number of ladles of slag produced per ladle of matte

\[(\text{Amt slag pres}) + (\text{Rate slag prod})(\text{Amt FeS})(\text{Wt ladle matte})\]

\[\text{Rate FeS consumed} \quad \text{Wt ladle slag}\]

\[=(\text{SLG} + 0.81 \times (1 + 0.419 \times \text{FRAT}) \times \text{FeS}) \times 19/11.9\]

From plant statistics for the month of December, 1974, it was determined that 14% of the slag is skimmed during the going high (or final slag) blow and the rest during end points.

**Miscellaneous Cycle Interruptions**

Other than equipment breakdown and servicing, there are some interruptions which are independent of the quantity of matte added to a converter. Notably there is the process of collar pulling which takes about 12 minutes and is dependent on the location of the converter with respect to the collar pulling location. The time taken to
add a skull is similarly dependent. The flue dust addition also lengthens the cycle and adds to the amount of blister copper produced at the end of the cycle.

Operations which increase the cycle time and are dependent on the amount of matte added include skimming of slag during the going high blow (see comment in section 5.1) and the addition of pigs for cooling during the copper blow. Copper pigs are added at the rate of approximately one pig per twenty tons of cuprous sulphide present. There is also, of course, interruption of blow for the addition of matte during the slag phase. In other schedules, there is interruption of the copper blow for the addition of reactor matte which is almost pure white metal.

The Total Time

The processing rate for each converter I, can be expressed in terms of $TH(I)$ and $TW(I)$, the average times in minutes to process and handle materials contained in one ladle of hot charge matte and wet charge matte respectively. Summing the operations described in this section one can approximate the cycle time as follows:

$$T(I) = TW(I) NW(I) + TH(I) NH(I) \quad (6)$$

where $NW(I) =$ no. ladles of wet charge matte in converter I

$NH(I) =$ no. ladles of hot charge matte in converter I
A computer programme which calculates the coefficients TW(I) and TH(I) is included in Appendix A. Refer to variables VNWM(J) and VNDM(J) in the output statement. For the case study presented in detail, the results of these calculations are shown in Table 4.2.

4.3 An Overview of the Optimization Problem

Since it was found that the matte processing rate was independent of the charge cycle length (see Section 4.4), a cyclical schedule was adopted as ideal for the converter aisle as a whole. In conjunction with an on-line computer this could lead to practical implementation involving a short range planning horizon.

The optimization problem is heuristically decomposed into the following layers:

1. The converter aisle matte turnover rate is maximized for a fixed converter charge cycle time, treating the converters as separate non-interfering entities.
2. Wet and hot charge matte are allocated to each converter on a per blow basis.
3. Converter charge cycles are sequenced in time so that the peak demand for crane service due to end of blow operations is kept at or below the availability level.
4. In-blow crane tasks are scheduled so that the other demands for crane service are dispersed.
## Average Processing Times

**Minutes/Ladle**

<table>
<thead>
<tr>
<th>Converter I Size (ft)</th>
<th>T HI</th>
<th>Dry Charge Matte 41% Cu</th>
<th>T WI</th>
<th>Wet Charge Matte 32% Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>4  13x30</td>
<td>34.1</td>
<td>39.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5  13x30</td>
<td>35.4</td>
<td>40.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6  13x30</td>
<td>34.8</td>
<td>40.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7  14x32</td>
<td>31.7</td>
<td>36.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.2: Average Matte Processing and Handling Times for Each Converter*
The non-applicability of the work-shop approach to the particular scheduling problem discussed in this thesis stems from the difference in the factors determining the length of a job. In the job-shop, job duration is a fixed time, though jobs may be pre-empted. In the model derived here, job times are functions of the present and previous contents of the machines. Additionally, job duration may depend on interference with other machines. This branch of theory is thus non-applicable to the model as derived in this thesis.

4.4 Overall Matte Allocation for Maximum Production

The first stage is to determine the number of ladles of hot charge matte $NH(I)$ and wet charge matte $NW(I)$ to be added to converter $I$ such that the overall matte processing rate is maximized, subject to various constraints imposed by smelter operation. In mathematical terms, the maximization problem can be stated as follows:

$$\text{Max } Z = \sum_{I=4}^{7} (NW(I) + NH(I))$$

for fixed cycle times, reverberatory matte production rates and converter volume capacity constraints. Note that the index $I$ has been assigned values corresponding to the converter numbers used in the actual smelter (Fig. 3.4).

To maintain steady-state smelter operation, the charge cycle times $T(I)$ for all converters must be equal.
By nature of converter operation, all cycle times can be made to equal some value $T$ minutes only by the addition of slack or converter down time $\Delta T$ as required. $\Delta T$ is the maximum allowable difference between the longest and shortest cycle generated by this optimization. It is undesirable, for example, to have one converter stand idle for half an hour while another is continuously in operation. This situation would result in numerous conflicts at stage (3) of the optimization (Section 4.3) where the individual converter cycles are to be sequenced into a single production cycle. Therefore, if the common cycle time is to be $T$ minutes and the maximum permissible slack time is $\Delta T$ minutes, the corresponding mathematical constraints are:

\[ TW(I)NW(I) + TH(I)NH(I) \leq T \]  \hspace{1cm} (8) \hspace{1cm} I=4,5,6,7

\[ TW(I)NW(I) + TH(I)NH(I) \geq T - \Delta T \]  \hspace{1cm} (9) \hspace{1cm} I=4,5,6,7

Matte must be drawn from the hot charge and wet charge reverberatory furnaces in the same ratio as their respective production rates. If $c$ is the ratio of the production rate of hot matte to that of wet charge matte, this constraint can be expressed mathematically as follows:
\[ \left| \sum_{I=4}^{7} c \times \sum_{I=4}^{7} NW(I) \right| \leq k \]  

where \( k \) could be a small positive integer such as 1.

Since \( \sum_{I=4}^{7} NH(I) = c \times \sum_{I=4}^{7} NW(I) \), inequality (10) is simply a statement of the fact that the consumption rate of reverb matte might vary from the production rate by a small integral number of ladles over the duration of the cycle. Translated into smelter operation, this means that the rate of matte production could be altered slightly, which is substantiated by plant operating data.

Converter capacity constraints are expressed as follows:

\[ NW(I) + NH(I) \leq N(I) \quad (11) \quad I=4,5,6,7 \]

where \( N(I) \) is the capacity in ladles of converter \#I.

Gomory's all integer programming algorithm [13], coded as GOMGEN, was employed to obtain the numerical solutions to this problem. GOMGEN was supplied courtesy of the Carleton University Computing Centre.

Analyzing the Numerical Results with \( T = 8 \) hours

The problem has been formulated as:

\[ \text{Max } Z = \sum_{I=4}^{7} NH(I) \]

subject to the following constraints:
\[341NH(4) + 393NW(4) \leq 4544\]
\[341NH(4) + 393NW(4) \geq 4444\]

\[354NH(5) + 409NW(5) \leq 4580\]
\[354NH(5) + 409NW(5) \geq 4480\]

\[348NH(6) + 401NW(6) \leq 4617\]
\[348NH(6) + 401NW(6) \geq 4417\]

\[317NH(7) + 366NW(7) \leq 4598\]
\[317NH(7) + 366NW(7) \geq 4498\]

\[NH(4) + NW(4) \leq 17\]

\[NH(5) + NW(5) \leq 17\]

\[NH(6) + NW(6) \leq 17\]

\[NH(7) + NW(7) \leq 20\]

\[\sum_{i=4}^{7} NH(i) = 2 \times \sum_{i=4}^{7} NW(i)\]

Note that the time coefficients and constants here are expressed in tenths of a minute, for convenience in a simulation with an integral time variable. A reasonable value for \(\Delta T\) was considered to be 10 minutes. The time coefficients are the results of a computer programme of the
process described in Section 4.2 (See Table 4.2). The limits on the converter capacity constraints can be found in Table 4.1. In actual practice, the variable NH(4) was eliminated using as the production constraint the last equation listed above. This corresponds to the choice of c = 2 and k = 0 in equation (10).

The time of certain operations such as collar pulling and skull addition are independent of the ladles of matte added to a converter. However, these differ amongst the converters because of each converter's physical location in the aisle. Thus, the time constraint bounds are different for each converter.

Also, the number of blows per cycle must be originally assumed because these time bounds are functions of the number of slag blows. Thus the process of optimization, here, was an iterative one. Because of these factors, several solutions were obtained in the nominal time region.

Two such solutions are listed in Table 4.4 and will be analyzed. The computer printouts are in Appendix B. It is to be noted, however, that the total matte turnover in the cycle was found to be 51 ladles of matte in every case. A linear programming approach using the same data gave a maximum of 51.2 ladles (Appendix B). Therefore, an
<table>
<thead>
<tr>
<th>Cycle Time</th>
<th>Total Ladies of Matte</th>
<th>Turnover Rate (Ladies/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hrs. Min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 00</td>
<td>51</td>
<td>6.38</td>
</tr>
<tr>
<td>8 30</td>
<td>54</td>
<td>6.35</td>
</tr>
<tr>
<td>9 00</td>
<td>57</td>
<td>6.33</td>
</tr>
<tr>
<td>9 30</td>
<td>60</td>
<td>6.32</td>
</tr>
<tr>
<td>9 55</td>
<td>63</td>
<td>6.35</td>
</tr>
<tr>
<td>10 25</td>
<td>66</td>
<td>6.33</td>
</tr>
<tr>
<td>11 00</td>
<td>69</td>
<td>6.37</td>
</tr>
</tbody>
</table>

Table 4.3: Maximum smelter capacities for various converter cycle times as determined using a maximization algorithm.
<table>
<thead>
<tr>
<th>CONVERTER</th>
<th>LADLES OF MATTE</th>
<th>BLOWS (ASSUMED)</th>
<th>SLACK TIMES (MINUTES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY</td>
<td>WET</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>C5</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>C6</td>
<td>13</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>C7</td>
<td>11</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CONVERTER</th>
<th>LADLES OF MATTE</th>
<th>BLOWS (ASSUMED)</th>
<th>SLACK TIMES (MINUTES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY</td>
<td>WET</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>11</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>C5</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>C6</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>C7</td>
<td>11</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4.4: CONVERTER MATTE ALLOCATIONS AND SLACK TIMES GIVING MAXIMUM MATTE THROUGHPUT FOR A NOMINAL CONVERTER CHARGE CYCLE OF 8 HOURS
absolute maximum was realized under the prevailing constraints.

Results for a cycle time of 8 hours are given in Table 4.4. Note that two sets of results are given, the first table allowing for a total of four slag blowing periods for converter 4, the second table allowing for five slag blowing periods for converter 4. The solution with five slag blowing periods was chosen as a basis for further work for the following reasons:

1. During the GOMGEN runs it was frequently found that the number of blows initially assumed for each converter was not compatible with the total numbers of ladles of matte handled by the converter. This problem can only be resolved through an iterative scheme. For example, referring to the first solution in Table 4.4, converter 4 handles 12 ladles of matte during four blows, whereas in practice at most 11 ladles are handled in four blows (see Table 4.1).

2. A comparison of slack times indicates a maximum difference in the cycle length of 2.1 minutes for solution #2 as compared with 6.1 minutes for solution #1.

3. It was considered desirable to assign some matte of each kind to each converter. Intuitively, such a scheme should smooth out the demand for each grade of matte.
Although the resultant matte distributions shown in Table 4.4 are by no means obvious, they do reflect the coefficients of the processing constraints. Converter 7 should be assigned as much dry matte as possible because this is by far the smallest coefficient, i.e. 317 tenths of a minute per ladle of dry matte. This is due to the fact that it has the highest blowing rate and is closest to the reverberatory and anode furnaces. The maximum ladles of dry matte it can process is \((\frac{4590}{317})\) or 14. However, due to the additional constraint that the ratio of total dry matte to total wet matte must be 2, (i.e. \(c=2\)) the solution is eleven dry matte and three wet matte, which is still the maximum total ladles which converter 7 can process in the specified time. Converter 5 is the least efficient mainly because it has the lowest blowing rate. The blowing rates and the locations in the converter aisle for converters 4 and 6 are not significantly different. For this reason, while the distributions of matte for converters 5 and 7 remain the same for solutions 1 and 2 for the reasons given previously, those for converter 4 and converter 6 vary considerably, reflecting the relative insensitivity of the smelter performance to the matte allocations to these two converters.
4.5 Allocation of Matte Ladles to Blowing Period

Having calculated the number of ladles of wet and hot charge matte, \( NW(I) \), \( NH(I) \), respectively, to be processed by converter \( I \), and using much of the process knowledge from the first stage (Section 4.2), it is possible to determine the number of blowing periods in the converter cycle and their start and end times relative to the starting time for the converter cycle. Understandably, the matte delivery times are now exactly specified which results in modifications to the slack times of Table 4.4. A uniform wet matte turnover rate was ensured using the following heuristic rule. If the total number of ladles of wet matte allocated to a converter is less than or equal to the number of blows, one ladle of wet matte is added at each blow until all wet matte is consumed. If the number of ladles of wet matte is greater than the number of blows (and less than twice the number of blows) two ladles are added to each blow until the number of remaining blows equals the number of remaining ladles of wet matte to be allocated. Then one ladle of wet matte is added per remaining blow. The output of the computer programme CYCLE is a sequence of times indicating the start and end times of each blow for each converter (see Figs. 6.2 - 6.5).
4.6 Determination of the Best Time Spacing Between Converter Cycles

Production delays can arise when crane interference or excessive demands for crane service occur. Effects of crane interference were included in an approximate way in the analysis and computation. This was done by allowing full crane task times where only partial ones were needed to start a blowing period. The problem of limiting the maximum demand for crane service is considered in this section.

Since demands for crane service are highest at end points of converter blowing periods, the maximum demands for crane service can be minimized by proper choice of the time spacing between starting times for each converter charge cycle. Let $t_4$, $t_5$, $t_6$ be the lengths of time between the start of the cycle for converter 7 and those of converters 4, 5 and 6 respectively. For any given value of $t_4$, $t_5$, and $t_6$, crane demand $n(t)$ as a function of time can be determined by the summation

$$ n(t) = \sum_{i=4}^{7} n(i, t) $$

In mathematical terms, the problem is to find the values of $t_4$, $t_5$ and $t_6$ which will minimize the maximum demand for crane service:

$$ \min FN = \max_{t_4, t_5, t_6} n(t) \quad (12) $$

$$ 0 \leq t \leq T $$
where $T$ is the common cycle length. The value of $\max n(t)$ was found by scanning a superposition of the four crane demand functions. To accelerate convergence, it was found useful to modify the criterion function of (12) by adding a counter of $.01$ every time a crane demand of 4 is encountered. Thus the number of such demands was reduced.

The Optimization Algorithm

Of the variety of methods available, the sequential technique called the Constrained Rosenbrock Hillclimbing Technique was used, coded as ROSY, because the objective function and the constraints were of the exact form so that no transformation of variables was required. The technique is discussed in detail, including flow charts, in Chapter 4 of Rosenbrock [33].

Here is a brief description following the reference. The technique assumes a global maximum; hence, for a general unfamiliar function such as FN several computer runs of ROSY have to be made. Starting values and step sizes must initially be specified by the user for each of the variables. Each variable in turn is increased and if the value of FN improves the move is termed to be successful and the step size is increased by a factor larger than 1. On the other hand, if the value of FN is increased, the step size is decreased by a factor between 0
and 1 and the direction of the step is reversed. If the current point lies outside the feasible region, the objective function FN is modified according to equations (38) and (39) of the reference. The function value is replaced by the best current value in the feasible region. After the search encounters a success and a failure for each variable, the axes are rotated to align them in the direction of the largest optimal change according to equations (24) and (25) of the reference. These steps constitute one stage in the search. The purpose of the rotation is to rapidly align the first axis with a 'ridge' of the performance function. The direction of the second axis tends to align itself in the best direction normal to the first, and so on. The last direction is mutually orthogonal to the others. The search is now continued in each of the new directions. The procedure terminates either when the problem has converged (i.e. the difference in FN from one stage to the next is less than some specified value) or when the maximum number of function evaluations has been exceeded.

Application of the Algorithm and Results

The number of interference points was recorded by a counter which adds .01 to the value of FN every time a value of 4 is encountered. In this way the number of interferences is reduced. Only crane demands at end points.
of converter blows were included, the crane demand being calculated at two minute time intervals over the cycle time \( T \). At time intervals where the minimized crane demand function exceeded two, additional slack time was introduced into the converter charge cycle, the overall cycle time \( T \) extended and the minimization repeated. An alternative procedure to this would be the reallocation of matte types in a blow to use these as decision variables in order to extend or contract a blow time. However, subsequent implementation of schedules under non-deterministic conditions on the interactive model has convinced the author of this thesis that these could be used as decision variables to return to the ideal schedule in case of slight disruptions.

The initial time spacing was assumed to be such that the copper blow end points were uniformly distributed in the cycle. An iterative scheme was employed whereby the end point of a solution was used as the initial point in the next computer run. The convergence to a good solution was fairly rapid, typically requiring some ten iterations. Referring to Figure 4.2 for maximum matte turnover, under the previously specified conditions, the charge cycles for converters 4, 5 and 6 should start 328, 413, and 170 minutes respectively after that of converter 7. The schedule is outlined in terms of times of service at the start and end blows in Table 4.5. Converter 7 was chosen as the basis...
for the fixed cycle for two reasons. First, it had the least amount of slack time available in its cycle. Second, it differed from the other converters in its physical size and also its number of blows per cycle.

4.7 The Determination of Best Timing of In-Blow Converter Tasks

Various additions and removals are made during converter blowing periods where the converter is rotated out of stack only long enough to make the addition or removal. In most cases, these operations can be performed at any time within a limited time interval, permitting their execution while cranes are available. Particular in-blow tasks included in this analysis were: the addition of copper pigs for cooling during the copper stage, addition of matte during slag blows and the removal of converter slag during the going-high (final slag) blow. The same Rosenbrock algorithm was used to determine the best times for executing these in-blow tasks and to minimize the time during which both cranes were in use. For the particular operation considered, the timing of forty-four in-blow tasks was determined. In cases where in-blow tasks could not be inserted without exceeding the demand for crane service, either slack time was inserted into the converter charge cycle, or, in the case of matte additions, the addition was rescheduled for the beginning
of the blow. As a result, for the example used in this thesis, the period of time during which in-blow tasks were executed and both cranes were in use was reduced from 126 minutes to 78 minutes.

This analysis was only performed on the very first model for reasons which will be subsequently discussed. The first model differed from the case study discussed to date in the time and duration of the collar pull. Subsequent changes were performed to agree with smelter operation as in the case study. The Gantt chart for this in-blow study case is found in Fig. 4.3 and the corresponding schedule is found in Table 4.6. Figure 4.4 shows the levels of crane service demanded during the time interval 250-350 minutes for this schedule. The corresponding ROSY listing is appended (Appendix C). Given that these results concern steady-state or undisturbed smelter operation, a number of desirable performance characteristics are noted:

1. Demand for only one crane during the execution of in-blow slag removals and matte additions during the time interval 270 to 290 minutes.

2. No crane demands during the interval 320 to 355 minutes, leaving both cranes free for a 15 minute interval to carry out other miscellaneous duties such as bumping ladles, moving pigs from the pig bay to the pig pile, etc.
Fig. 4.3 Gantt Chart for the Very First Case
<table>
<thead>
<tr>
<th>TIME (min./hr)</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>start of service for Bal1</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td>start of Bal1</td>
</tr>
<tr>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td>start of service for Bal3</td>
</tr>
<tr>
<td>251</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal3</td>
</tr>
<tr>
<td>324</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal3</td>
</tr>
<tr>
<td>404</td>
<td></td>
<td></td>
<td>end of high blow</td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>486</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal3</td>
</tr>
<tr>
<td>568</td>
<td></td>
<td></td>
<td></td>
<td>start of service for copper blow</td>
</tr>
<tr>
<td>640</td>
<td></td>
<td></td>
<td></td>
<td>start of copper blow</td>
</tr>
<tr>
<td>712</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>784</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>856</td>
<td></td>
<td></td>
<td></td>
<td>service ends, going Bal1</td>
</tr>
<tr>
<td>928</td>
<td></td>
<td></td>
<td></td>
<td>start of service for new cycle</td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td>start of Bal1</td>
</tr>
<tr>
<td>1182</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start of Bal1</td>
</tr>
<tr>
<td>1254</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal3</td>
</tr>
<tr>
<td>1326</td>
<td></td>
<td></td>
<td></td>
<td>service ends, go Bal</td>
</tr>
<tr>
<td>1408</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal3</td>
</tr>
<tr>
<td>1428</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal3</td>
</tr>
<tr>
<td>1500</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal3</td>
</tr>
<tr>
<td>1536</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal3</td>
</tr>
<tr>
<td>1712</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal3</td>
</tr>
<tr>
<td>2128</td>
<td></td>
<td></td>
<td></td>
<td>service ends, go Bal</td>
</tr>
<tr>
<td>2200</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>2232</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>2304</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>2336</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>2408</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>2428</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>2500</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>2528</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>2600</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>2632</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>2704</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>2808</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>2928</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>3036</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3112</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>3248</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3308</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>3384</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3468</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>3528</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3576</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>3648</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3720</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>3784</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>3888</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>4032</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>4096</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>4152</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>4224</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>4288</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>4352</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>4428</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>4504</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>4568</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>4632</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
<tr>
<td>4704</td>
<td></td>
<td></td>
<td></td>
<td>service ends, start Bal4</td>
</tr>
<tr>
<td>4772</td>
<td></td>
<td></td>
<td></td>
<td>end of Bal4</td>
</tr>
</tbody>
</table>

**TABLE 4.6** TIMING OF CONVERTER OPERATIONS FOR MAXIMUM CONVERTER PRODUCTION WITH NO CRANE INTERFERENCE

**NOTE:** Charge cycle time for all converters = 407 minutes.
A: Service to start new cycle on C4
B: Service for copper blow on C5
C: Skim during high blow on C7
D: Addition of matte to C4 during B1
E: Pig addition to C5
F: Skim during high blow on C7
G: Service to start B3 on C6
H: Service to start B2 on C4
I: Addition of 2 pigs to C5 and matte to C4 and C6
J: Service for copper blow on C7

Fig. 4.4 DEMAND FOR CRANE SERVICE
3. Total delay or slack times of 6% involving converters 4 and 5.

The slack times of converters 4 and 5 could be eliminated by adding wet charge matte rather than dry charge matte to those converters, thus extending their respective blowing periods by about five minutes, hence delaying the demands B and H for crane service (Fig. 4.4). However, if such set matte additions were made, subsequent demands for crane service would be affected in the following undesirable ways:

1. Crane service for the copper blow of converter C5 (segment B, Fig. 4.4) would be delayed by five minutes and no cranes would then be available for the previously scheduled skimming of converter C7, during the going high blow period (segment C, Fig. 4.4).

2. Crane service needed to start blow B2 in converter 4 (segment H, Fig. 4.4) would be delayed by five minutes and no cranes would then be available to add pigs to converter 5 and matte to converter 6.

The schedule implied by this analysis is much more rigid than that employed in practice. For example, while the analysis is based on a fixed policy regarding the accumulation of ferrous sulphide in the converter during the slag blowing periods, in practice, converter operators
effectively vary this policy to cope with problems such as momentary unavailability of cranes, etc. This type of analysis would only be relevant in a purely deterministic system. Since the determination of in-blow tasks is expensive from a computing viewpoint because of the large number of variables and since such a finely detailed schedule would be impossible to implement on a non-deterministic model, this aspect of the analysis was judged to be only useful as an academic exercise and abandoned in the calculations of future schedules.

4.8 Summary

A flow chart of the scheduling technique can be found in Fig. 4.5.

Comparing the results of Table 4.4 with corresponding figures from actual smelter operation, the actual production could, in the limit, be increased somewhat in excess of 25%. It is realized that this is a theoretical deterministic figure and that breakdowns and random variation would reduce the amount of matte produced. Nevertheless, it is felt that a considerable production increase could be realized.

As the smelter operation changed to reverb matte and reactor matte, a schedule was worked out for these
FIGURE 4.5 GENERAL FLOW CHART FOR DETERMINING OPTIMAL AISEL OPERATION
operating conditions. A schedule was formulated and validated which would allow the four converter operation in the smelter to be replaced by a three converter operation.

A summary of all the different modes of operation which have been scheduled is listed in Table 4.7.
<table>
<thead>
<tr>
<th># of converters</th>
<th># of cranes</th>
<th>Nominal Cycle Time (hrs.)</th>
<th>Wet Matte</th>
<th>Hot Matte</th>
<th>Reactor Matte</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>8</td>
<td>Yes</td>
<td>Yes</td>
<td>No*</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>7</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>8</td>
<td>Yes</td>
<td>No</td>
<td>Yes*</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>5</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes*</td>
</tr>
</tbody>
</table>

Table 4.7: Classes of Schedules Generated

* Indicates that the schedule was fully validated on the N.R.C. model.
CHAPTER 5

VALIDATION ON THE INTERACTIVE MODEL

Validation is the process of establishing the accuracy with which the optimization model resembles the system under study. Inferences made in establishing the model are checked by observing if the model behaves as expected. Since a simulation model of this system was available, it was an effective way of showing smelter personnel that the schedules generated were more than a mere academic exercise.

5.1 The N.R.C. Interactive Smelter Model

The copper conversion process is partly discrete, as typified by batch material additions and removals, and partly continuous, as indicated by the chemical conversion process. Therefore, a hybrid computer approach has been used by Graefe, Nenonen, and Stroble [28] to set up an interactive hybrid computer simulation model of the Noranda smelter. Analog computers are used for solving all differential equations associated with the continuous part of the model, while the digital computer handles the discrete event part of the model as well as controlling the analog portion of the model.
Considerable time was spent by the author in running the model to test his optimization and in assisting in the debugging of the model since the original digital computer had been replaced and the analog computer model had been changed from a single analog to two analog computers in slave-master mode. Thus some insight was gained into the operation of the model. In the on-line interaction and display situation, programming oversights could be immediately detected visually and unforseen model behaviour could be recognized.

The simulation of the smelter comprises the following components:

1. Executive program adapted from GASP
2. Analog-digital and purely digital submodels of the various processes, and material handling facilities.
3. Smelter display unit
4. Operator command entry system

GASP was modified to make it possible for the analog portions of the models to run in continuous time between successive discrete events. During the simulation, time advances twenty times as fast as real time. Each discrete event is assigned an event number which acts as a pointer to the corresponding subsection of a model where actions appropriate to that event are executed. If an end point of a continuous process occurs or if a discrete event occurs which effects the process, the simulation is frozen while