# A SCHEDULING MODEL FOR PRODUCTION IN A HOT STRIP MILL

by

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## ABSTRACT

This research dissertation highlights the important role of scheduling in a production environment. The functioning of an integrated iron and steel works is discussed. The importance of production scheduling in this environment is shown, followed by a literature survey of strip mill production scheduling models. Thereafter a model is introduced that aids in the production scheduling of plate via coil in a hot strip mill. Finally the benefits of the scheduling model are shown.

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# CHAPTER 1

## *HIGHVELD STEEL INTEGRATED IRON AND STEEL WORKS*

## 1.1 INTRODUCTION

This research dissertation presents a scheduling model for the production of plate, cut to length, via coil in a hot reversing strip mill. The aim is to improve overall plant efficiency by producing plates from hot rolled coils that are de-coiled and cut to length on a plate finishing end processing line. The primary goal of this study is to develop a scheduling model that will assist the schedulers in scheduling plate via coil orders at the Highveld Steel and Vanadium Corporation (Highveld abbreviated).

## 1.2 INTEGRATED IRON AND STEEL WORKS

Before presenting a plate via coil scheduling model, it is necessary to describe the basic functioning of the Highveld integrated iron and steelworks and highlight the need for production scheduling in a steel-making environment.

A brief overview of the history and functioning of the integrated iron and steel works of Highveld is also presented in this section. It highlights the complexity of the steel making process, from mining the ore to dispatching the finished products, thereby calling for production scheduling to enhance operational efficiency.



### 1.2.1 HIGHVELD STEEL AND VANADIUM CORPORATION: A BRIEF HISTORICAL BACKGROUND

During November 1964 it was decided by the Anglo American Board to build an integrated iron, steel and vanadium complex near Witbank [13]. That decision was based on positive results from a pilot-plant, launched in April 1961 that demonstrated that titaniferous magnetite ore from the region's bushveld igneous complex could be processed to produce liquid pig iron and vanadium-bearing slag. Four years later Highveld was in operation, producing rolled sections and vanadium pentoxide as a co-product. The total cost of the project came to R127 million [14].

The works consisted of an iron plant, a steel plant and a universal structural mill. Highveld listed on the Johannesburg Stock Exchange in March 1969 a month before the official opening of the steelworks. In February 1971 Highveld posted its first profit, followed by the declaration of a maiden dividend of 5 cents in August 1973. In 1977 the works was extended to include a plate mill and in May 1983 a hot reversing strip mill (steckel mill) was commissioned. By 1981 the first iron plant was operating to capacity and in June 1985 a second iron plant was commissioned, increasing pig iron production by 30% to 960 000 ton per year [14].

### 1.2.2 GENERAL INFORMATION ON THE HIGHVELD INTEGRATED STEELWORKS

This section provides an overview of the products and functioning of the Highveld integrated steelworks [13, 14]. In presenting the process flow, the need for production scheduling in an integrated steelworks is underlined.

Highveld's iron and steel works annually produces approximately one million ton of commercial grade steel [13]:

- 40% of the steel produced is used to manufacture structural sections, engineering rounds, etc. at the structural mill;
- 45% is used to manufacture plates and coils at the flat products complex;
- 15% is used to cast billets.

Other co-products of the iron and steel works are vanadium pentoxide and trioxide. Vanadium pentoxide and trioxide are intermediate products for the production of ferro-vanadium which is used to strengthen steel. Ferro-vanadium is used to produce high-strength, low-alloy steel gas pipelines for regions with extreme climates, such as northern China, Russia and Alaska. Vanadium pentoxide is a constituent in the production of light vanadium/aluminium/titanium alloys for the aerospace industry. Vanadium chemicals have a wide range of applications, from catalysts for sulphuric acid to colouring in the pigment industry [1].



The steel works consists of two iron plants, a steel plant equipped with shaking ladles for vanadium extraction, basic oxygen furnaces and five continuous casting machines, a universal structural mill, a plate mill and a hot steckel mill. Refer to figure 1.1 for the Highveld integrated steel works process flow sheet, which illustrates the process flow for the production of the above-mentioned products.

Iron plant 1 has ten pre-reduction kilns and six electric arc smelting furnaces in contrast to the more automated Iron plant 2 that has three pre-reduction kilns and one electric arc smelting furnace.

The molten iron is transported from the iron plant to the steel plant for charging into a series of shaking ladles that are used for the extraction of vanadium as a solid spinel.

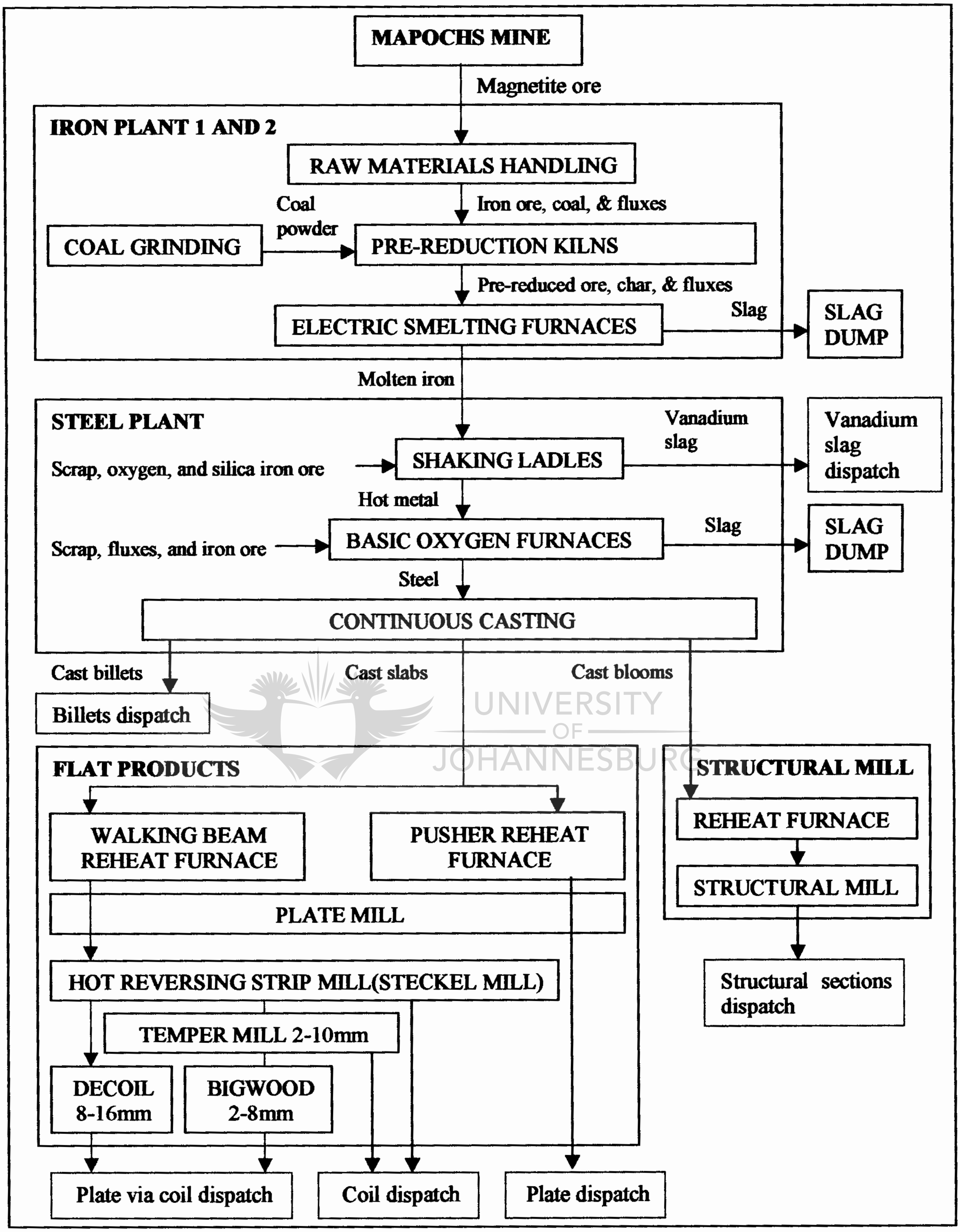



**Figure 1.1 Highveld integrated steel works process flow sheet [13].**

Once the vanadium is extracted, the metal is charged into one of three basic oxygen furnaces. The steel is then transferred to the continuous casting plant via the ladle refining stations, where temperature adjustment, de-sulphurisation and final composition adjustments are carried out. At the continuous casting plant the steel can be cast through any of five machines: one casts billets, three larger machines cast blooms for the structural mill, and one casts slabs for the strip and plate mill at the flat products complex.

Highveld's flat products complex illustrated in figure 1.3 comprises a plate and hot reversing strip mill (steckel mill). Slabs for both mills are transported from the continuous caster to the flat products slab yard by rail where they are inspected and prepared for furnace charging. Those slabs destined for the plate mill are cut on flame cutting beds to the required size and heated in the gas-fired pusher-type reheat furnace to the required processing temperature. On discharge from the furnace, the slabs are subjected to high-pressure de-scaling sprays, after which they are processed into plates of required dimensions by a four-high reversing mill stand, shown in figure 1.2.

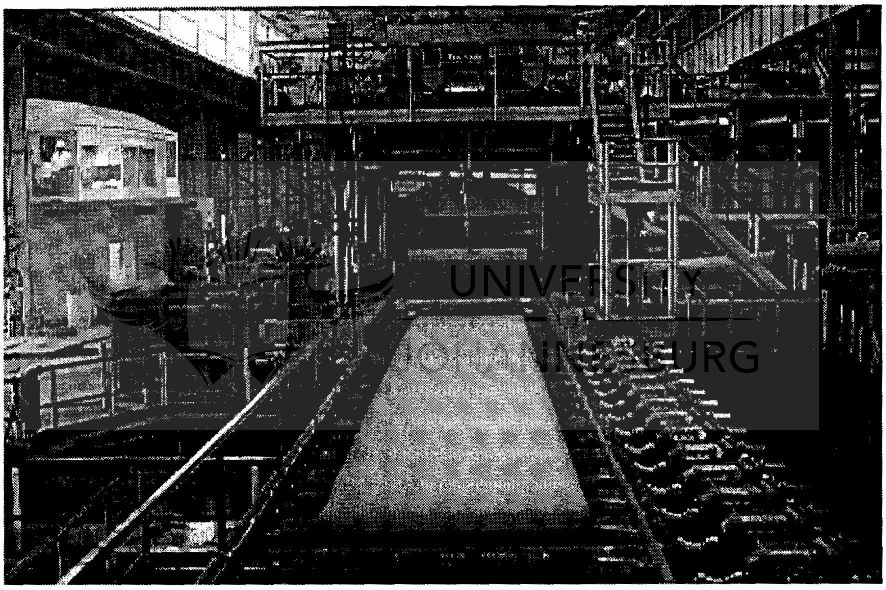


**Figure 1.2 Plate production at Highveld's plate mill [14].**

The hot plate passes from the mill though a four-high roller leveller to the hot banks. After the plates have cooled down sufficiently, they are inspected and cut to final size on the plate finishing end line. Those thicker than 16 mm are flame cut and the thinner plates are cut by shears. Finally the plates can be cold flattened or normalised if required.

Coils of plate and strip are produced in the steckel mill section of the flat products complex. Slabs, which will be processed into strip, are charged into a walking beam gas-fired reheat furnace and processed to the required transfer thickness and width by the plate

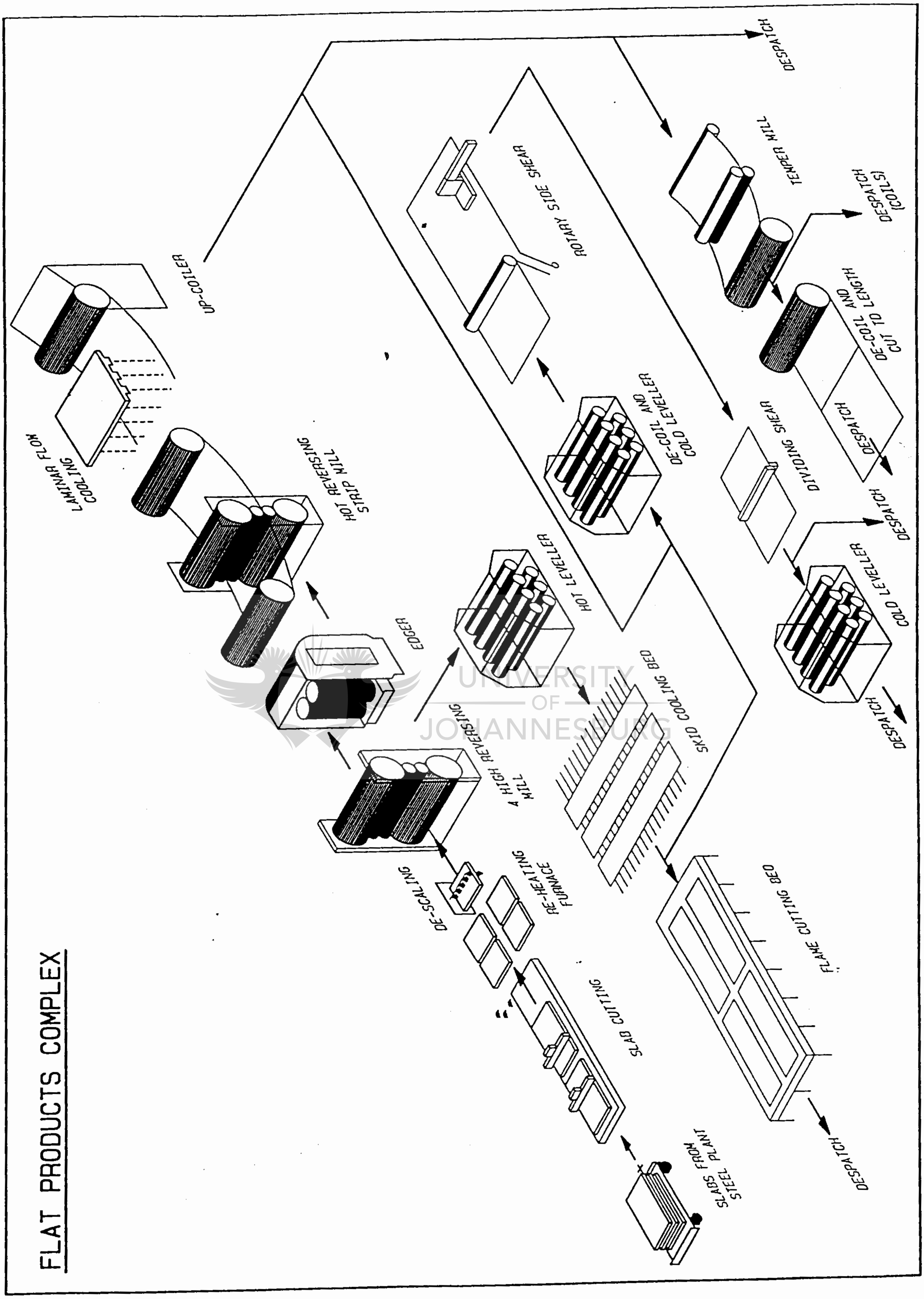



**Figure 1.3 Highveld's flat products complex process flow sheet [13].**

mill and edger before being transferred to the steckel mill by roller tables. The slab is de-scaled and the front and back ends are cropped by a flying shear during transfer.

A steckel mill, is generally a single stand, four-high reversing mill as presented in figure 1.4. Refer to [18] for an overview of the technology and performance of modern steckel mills. On the in-going and out-going sides of the mill stand there are two gas-fired hot coiling steckel furnaces with heated coiler drums onto which the strip is coiled during each successive pass. When the required strip gauge is achieved, after either five or seven passes, the strip runs out of the mill stand on roller tables to an up-coiler where it is coiled into the final coil form. Throughout this text, 'gauge' refers to the thickness of the steel sheet being produced. The strip is cooled from a last pass temperature of approximately 950°C to the required up-coiler temperature, ranging between 580°C – 720°C, by the laminar flow water spray system situated between the mill stand and the up-coiler [13].


**Figure 1.4 Hot reversing strip mill (steckel mill) at Columbus Stainless, Columbus Joint Venture [13].**

From the up-coiler coils are either dispatched directly to the customer or sent to the coil finishing end line for reprocessing. Refer to figure 1.5 for the process of manually strapping a hot rolled coil after processing on the coil finishing end line. The coil finishing end consists of a single stand, two-high temper mill, used for visual inspection and rectifying of coils, as well as the Bigwood, used for recoiling or cutting coils into plate lengths.

At the temper mill coils of gauge up to 12 mm thick are cold rolled. Coils of gauge 4,5 mm and smaller are inspected and rectified to improve product shape by removing centre and edge buckle, while coils of gauge 5 – 12 mm are inspected and samples are taken to verify product quality [13]. Coils may also be sent to the de-coiler, for uncoiling and levelling before being processed into plate lengths on the plate finishing end shear line.

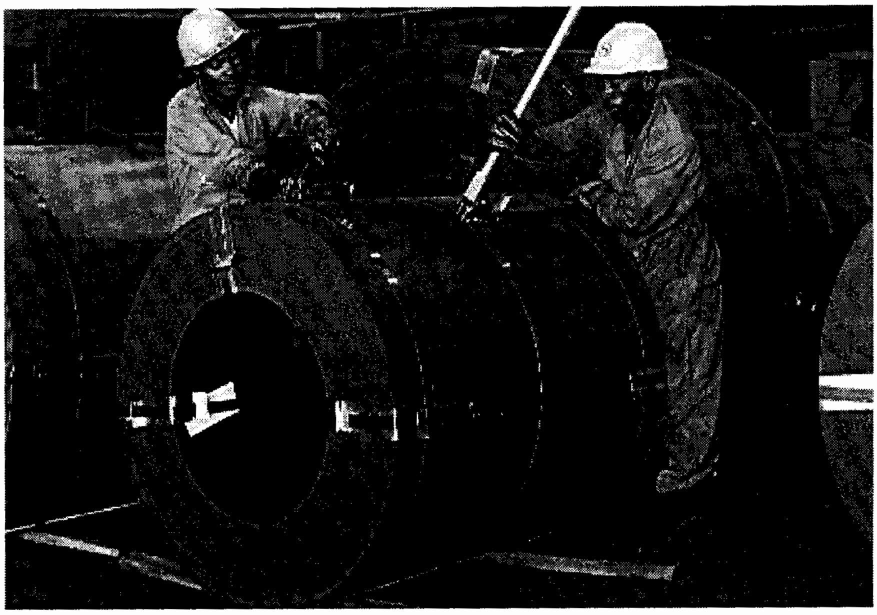


**Figure 1.5 Strapping a hot rolled coil for export at Highveld's flat products complex coil finishing end [14].**

Increasing production of plate via coil through the Bigwood and de-coiler lines has recently become the focus of management attention. This could result in improved levels of plant utilisation and production throughput through plate via coil production instead of standard plate production.



### 1.2.3 TANDEM MILL VERSUS STECKEL MILL COIL PRODUCTION

There are two common versions of a hot strip mill:

- A hot multi-stand strip mill (tandem mill)
- A hot reversing strip mill (steckel mill)

A tandem mill, illustrated in figure 1.6, is a straight through unidirectional continuous process which consists of a series of one directional four-high mill stands. The reversing roughing mill reduces the thickness of the slab to the required transfer gauge before it is transferred on roller tables to the tandem mill. At the tandem mill each four-high mill stand reduces the slab to a predetermined thickness, until it reaches the final gauge in the last four-high mill stand, after which it is cooled on the laminar flow water cooling tables and finally coiled on the up-coiler. Most steel mills reach production economy through economy of scale that is based on tandem mill processing technology.

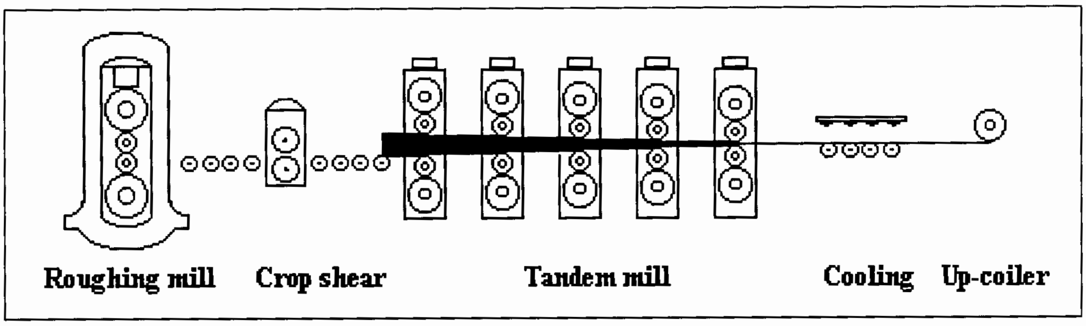



**Figure 1.6 Tandem mill processing illustration [adapted from fig. 1 Lopez *et al.* [21]].**

Highveld's ore deposits are titaniferous magnetite ore containing a mixture of iron and vanadium. Therefore production economy is reached through separation and beneficiation of the different metals instead of economy of scale. A steckel mill with a lower capital cost is more suitable for lower volume production than the high capital cost tandem mill suitable for high volume production. As illustrated in figure 1.7, the steckel mill consist of a single four-high reversing mill stand with two gas-fired coiling steckel furnaces with coiler drums onto which the strip is coiled during each successive pass.

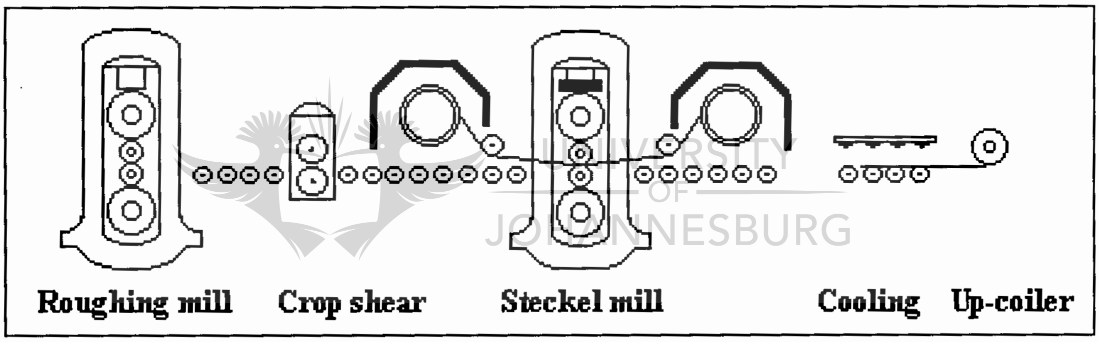



**Figure 1.7 Steckel mill processing illustration [adapted from fig. 1 Lopez *et al.* [21]].**

## 1.3 PROBLEM DEFINITION

In this era of intense global competition there is strong emphasis on achieving improved levels of production efficiency and throughput [6, 17]. Nyström *et al.* [24] highlight the importance of an integrated production and management system in a hot strip mill, in achieving integrated control that will lead to reduced inputs and increased output at high product quality levels.

The literature is rich with tandem mill studies, but singularly silent on steckel mill research. This is not surprising, as worldwide tandem mills are far outstripping steckel mills. Various studies of scheduling and sequencing in existing literature [2, 3, 6, 16, 17, 21, 24, 26, 30] demonstrate the importance of computerised scheduling and sequencing in achieving improved production efficiency in a tandem mill. This study thus contributes towards steckel mill research, based on the Highveld steckel mill.

Due to the flexible design of the plate and steckel mill, various opportunities exist for improving production efficiency at the Highveld flat products complex. One of these is the production of plate via coil orders; these would first be produced as coiled plate during the coil campaign and then be processed into plate lengths on the coil or plate finishing end lines. This process is referred to as plate via coil production.

The production of plate and coil occurs during separate plate and coil campaigns. During a coil campaign the plate mill functions as a roughing mill for the steckel mill. Usually a coil campaign lasts for about twenty days followed by a planned steckel mill shutdown maintenance period of around ten days. All coil and plate are produced to order since history has shown that at Highveld producing for stock was undesirable.

During a coil campaign the plate mill also produces heavy gauge plates but the plate mill's finishing end cut to length shear line is not fully utilised. This excess capacity can be exploited by initially scheduling plate orders into coil, de-coiling the coils and subsequently processing it into plates through the side trimmer and cross cut line. There exist various possibilities and combinations of scheduling plate orders into coils for processing on the strip and plate finishing end lines. Improved production efficiency could therefore be achieved, thereby reducing lead times and improving timely delivery.



This study aims to develop a scheduling model that will aid the schedulers in utilising the excess processing capacity of the plate finishing end cut to length shear line, through plate via coil production. Cooper and Schindler [7] define a model as a representation of a system that is constructed to study some aspect of that system or the system as a whole. It is this definition of a model that will be used throughout this dissertation.

## 1.4 APPROACH AND SCOPE OF THIS STUDY

The study is approached as follows:

- An investigation of scheduling models developed for the steel coil production environment.
- An investigation of scheduling of steel orders at the Highveld flat products complex.
- The development of a scheduling model to schedule plate orders via coil.
- Conclusions and recommendations.

## 1.5 CONCLUSION

The historical background and the functioning of the Highveld integrated steel works have been presented in this chapter. The need for production scheduling in this complex operating environment has been shown to be essential in order to achieve improved production efficiency and throughput.

Before presenting an overview of the current production scheduling practice at the Highveld flat products complex, the following chapter present some useful findings of a literature study into scheduling and especially production scheduling in a hot strip mill.

# CHAPTER 2

## *HOT STRIP MILL PRODUCTION SCHEDULING*

## 2.1 INTRODUCTION

The need for production scheduling in achieving improved production efficiency and throughput in an integrated iron and steel works has been highlighted in the previous chapter. An overview of scheduling in a production environment that focuses on scheduling models developed for a hot strip mill is presented in this chapter.

## 2.2 SCHEDULING

Scheduling has been defined as a field of study concerned with the optimal allocation or assignment of limited resources, over time, to a set of competing tasks or activities [25]. The challenge in production scheduling is to sequence the processing of jobs by machines so that a measure of performance achieves an optimal value [10].

Production scheduling attempts to balance various related but conflicting production objectives. It is therefore difficult to identify a single scheduling objective [17]. Scheduling objectives are numerous, complex, and often conflicting, thus the criteria by which success is judged must be chosen with care [10]. The criteria that are used to evaluate production schedules are based on various performance measures.



French [10] suggests that the following performance measures can be applied to the production scheduling environment:

- Adherence to delivery dates and accompanying penalties.
- Minimising overall length of the production scheduling period.
- Minimising idle time.
- Minimising inventory costs of raw materials and finished goods.
- Achieving a uniform production rate throughout the scheduling period so that labour and power demands remain stable.

The total cost of a production schedule is a complex combination of processing costs, inventory costs, machine idle time costs, and lateness penalty costs [10]. Consequently, a production schedule which minimises the cost component of a single performance measure may be very poor in terms of the total cost. Production scheduling in an integrated iron and steel works which attempts to balance production efficiency and throughput is discussed in the following section.

## 2.3 HOT STRIP MILL PRODUCTION SCHEDULING

Production scheduling within a modern steel works has been receiving increased attention in recent years. According to Kosiba *et al.* [17] steel production is a complex process involving several intricate and interrelated yet separate processes. Profitability in this high volume industry has historically been tied to overall production efficiency. However, in recent years the focus has shifted towards individual operations with increased attention to quality control. In order to increase overall production efficiency, the individual process that is most critical to the overall process and which generally constrains production levels receives priority attention.

The hot strip mill, considered the "bottleneck" to overall production [16,17], has been the focus of various studies aimed at improving the production efficiency of steel making facilities [2, 3, 6, 16, 17, 21, 24, 26, 30]. These studies utilise various different analytical methodologies aimed at increasing overall hot strip mill process efficiency through improved production scheduling without sacrificing product quality.

Before presenting an overview of some of these hot strip mill production scheduling models, the following section highlights some important yet conflicting hot strip mill production scheduling objectives. The hot strip mill production scheduling objectives form the basis from which production scheduling models are developed.



### 2.3.1 HOT STRIP MILL PRODUCTION SCHEDULING OBJECTIVES

This section presents some important hot strip mill production scheduling objectives that have to be adhered to throughout a production campaign.

Production campaign planning consists of selecting, sequencing and scheduling slabs into several rolling cycles for processing during a hot strip mill production campaign. A hot strip mill production campaign consists of a large number of slabs that are processed sequentially on a single set of backup rolls. Since the work rolls and backup rolls suffer from wear and tear, they have to be replaced periodically. Backup rolls are only changed before and after a production campaign that consists of numerous work roll changes. The set of slabs processed between two consecutive work roll changes is referred to as a rolling cycle. This definition of a rolling cycle is used throughout the text.

The goals of steel scheduling through the hot strip mill are to minimise production delays while maintaining product quality and consistency [17]. According to Lopez *et al.* [21] production efficiency can be improved by finding the optimum balance between product quality and productivity. Improving product quality requires changing rolls as frequently as possible, whereas increasing production rate requires minimising the number of roll changes. The overall hot strip mill scheduling problem can be described as a multi-objective optimisation problem [6].

Various authors have identified the following as the primary hot strip mill production scheduling objectives [17, 21]:

- Maximising production rate or productivity.
- Maximising product quality.
- Maximising process efficiency.
- Maximising on-time delivery.

These conflicting hot strip mill production scheduling objectives are examined in the following paragraphs.

#### 2.3.1.1 Maximising production rate

Most production delays result from the need to change rolls that have become damaged or worn during the production process [17]. Refer to figure 2.1 for a view of a work roll change. Unplanned work roll changes have to be performed if the production process damages the work rolls; this is because the surface quality of the coil is adversely affected if the marks on the damaged rolls are transferred to the coil.

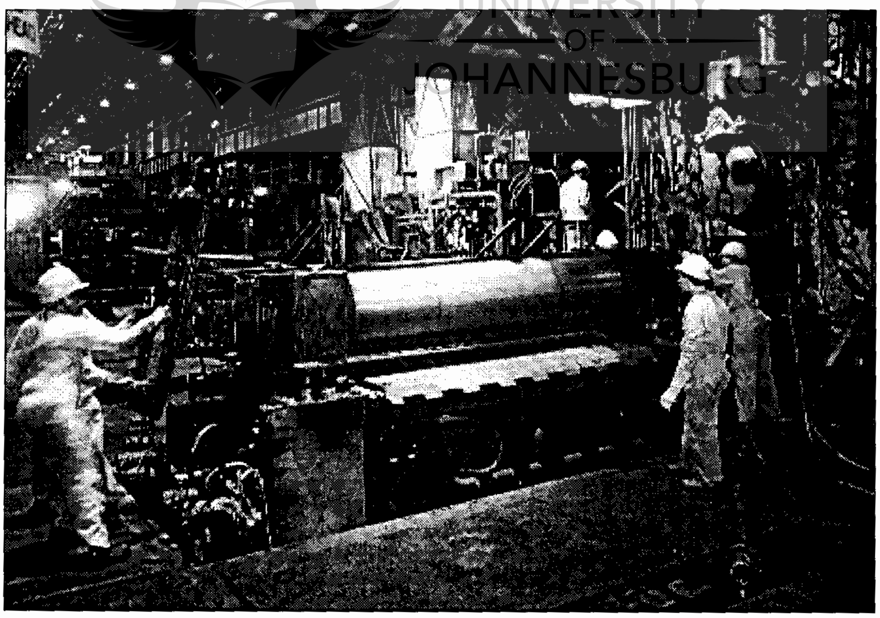


**Figure 2.1 A roll change at the hot reversing strip mill (steckel mill) in Highveld's flat products complex [14].**

Work roll changes to replace worn rolls are performed frequently and result in relatively short down time. In contrast backup roll changes result in significantly longer down time. The duration of a work roll change at Highveld's steckel mill is between half and one hour and a backup roll change is about four hours [13]. Work rolls are therefore periodically changed in an effort to prolong backup roll life and thus reduce down time.

Work rolls can be damaged in various ways during the production process. Generally, roll damage is in the form of surface cracks or bruise marks. Insufficient roll cooling, caused by blocked roll cooling water nozzles, results in circumferential work roll surface cracks. Longitudinal work roll surface cracks due to thermal shock are induced by prolonged production delays during which the work rolls are stationary and in contact with the hot strip. Bruise marks are caused when debris or a double folded strip end is pulled through the work rolls, bringing about excessive shock loads in the mill. If a work roll becomes heavily damaged during the production process, these marks can be transferred to the corresponding backup roll.

In general, work roll wear depends on the magnitude of the forces exerted on the mill by the products that are being processed. The length of a rolling cycle is determined by roll wear, which is a function of the hardness and gauge of the slabs scheduled to be processed in the rolling cycle. If a rolling cycle schedule is too short, the work rolls will be changed before it is necessary, resulting in lost production time and higher cost of roll maintenance.

Kosiba *et al.* [17] state that the major considerations in minimising work roll wear are:

- The hardness of the steel product being produced. The harder the steel, the more force is exerted on each mill stand.
- The magnitude of change in product gauge through the production process. More force is required to produce a lighter gauge product, and large changes in gauge from one stand to the next require proportionally more force exerted at a given stand.

These considerations can be translated into a scheduling model which selects a sequence of slabs through the mill in order to minimise changes in hardness and gauge from one slab to the next. The process time between roll changes can therefore be increased and the production rate can be improved.

#### 2.3.1.2 Maximising product quality for tandem mill production

In order to maintain product quality throughout a tandem mill production campaign, product sequencing during each rolling cycle must be based on a coffin shape width profile as illustrated in figure 2.2 [17, 21].

Product quality is affected by work roll wear. As each slab is processed, stress concentrations occur on the work rolls at the edges of the slab/work roll contact area. If too many slabs of equal width are processed, the work rolls will be severely marked at that location. During the processing of subsequent wider slabs these marks will cause defects on the surface of the coils. In extreme cases these marks could also be transferred to the backup rolls, enforcing costly unplanned backup roll changes. In order to avoid these problems, coffin shape width profiles, as illustrated in figure 2.2, have been developed for tandem mill production scheduling.

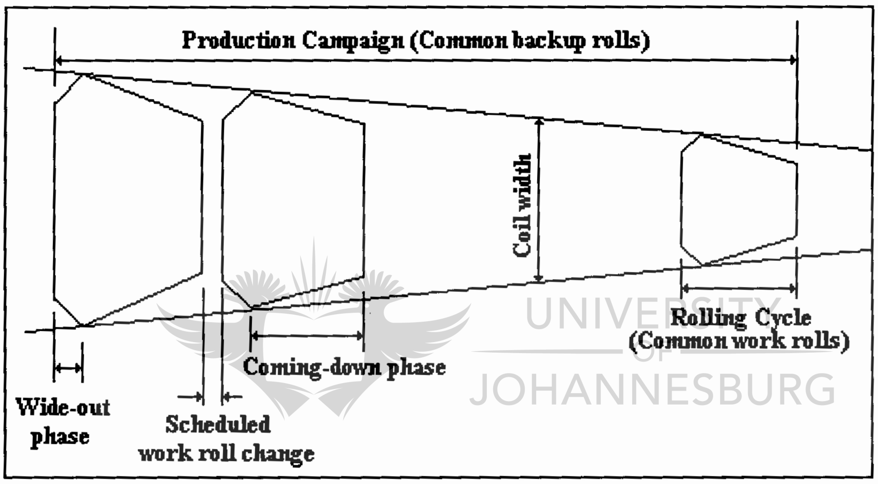



**Figure 2.2 Coffin shape width profile for tandem mill production scheduling [adapted from fig. 2, Kosiba *et al.* [17] and fig. 2, Lopez *et al.* [21]].**

Backup rolls are not changed during a tandem mill production campaign which consists of several homogeneous rolling cycles. These homogeneous rolling cycles should ideally contain slabs of similar reheat furnace retention time, hardness, gauge, grade, and the sequencing of slabs throughout each rolling cycle should allow for gradual coffin shaped width changes [21]. Throughout this text, 'grade' refers to the metallurgical composition or property of the steel sheet being produced.

The coffin shape rolling cycle scheduling sequence consist of the following two parts:

- wide-out phase
- coming-down phase

The rolling cycle wide-out phase starts with a work roll warming-up phase that generally consists of two to six slabs, referred to as warmers, that are narrow and easy to process [21]. The work roll warming-up phase ensures that the work roll transits from the state of thermo-imbalance to that of thermo-balance by processing a few slabs. This heats up the mill in a systematic manner [6]. After the warm up phase, the wide-out phase enters the ascent zone with five to fifteen progressively wider slabs that are not of a hard grade [21]. If during the wide-out phase slabs of a hard grade are processed this could mark the work rolls at the edges of the slab/work roll contact area and be detrimental to product quality during the coming-down phase.

Smooth changes in hardness and gauge during a rolling cycle allow the mill operators to make initial adjustments to the loads at the start of the rolling cycle followed by gradual changes throughout the rest of the rolling cycle. The position of some critical products within a rolling cycle is restricted. For instance, orders that demand high quality surface coils have to be processed within the first 50 slabs of a production schedule [21]. If these slabs are not processed within this production window, the rolls at the finishing stands are likely to be worn and their surface may not produce high quality surface coils.

Throughout a complete tandem mill backup roll production campaign, the number of slabs that can be processed sequentially at a given width is restricted, especially if wider slabs have to be processed within consecutive rolling cycles of the production campaign [17]. An overall width profile for all tandem mill processing being done between backup roll changes is presented in figure 2.2.

#### 2.3.1.3 Maximising product quality for steckel mill production

A steckel mill production campaign, as illustrated in figure 2.3, uses a single set of backup rolls and consists of several rolling cycles. The sequencing of rolling cycles throughout a steckel mill production campaign should be based on a coffin shape width profile. This will prolong backup roll life and assist in maintaining product quality.

The difference in tandem mill and steckel mill design, as illustrated in figure 1.6 and 1.7, results in up to seven times more work roll wear per coil during steckel mill production. Consequently the number of slabs processed per rolling cycle in a steckel mill is about seven times less than that processed during a tandem mill rolling cycle. A steckel mill rolling cycle could consist of between 2 to 40 slabs [13], whereas a tandem mill rolling cycle ideally consists of between 180 and 220 slabs [21]. Table 2.1 presents a comparison between tandem mill and steckel mill production scheduling guidelines.

**Table 2.1 Tandem mill vs. steckel mill production scheduling guidelines [13, 15].**

| **Tandem mill rolling cycle scheduling** | **Steckel mill rolling cycle scheduling** |
|---|---|
| Rolling cycle length is restricted to 180 km<br>i.e. (180 – 220 slabs) or (3000 – 6000 ton) | Rolling cycle length is restricted to 35 km<br>i.e. (15 – 50 slabs) or (350 – 950 ton) |
| A coffin shape width profile is used to sequence slabs within a single rolling cycle between work roll changes.<br><br>Wide-out phase<br>• 2 – 5 km warmers.<br>• 10 – 20 km ascent zone (ascent zone: gradual increasing width, decreasing gauge and increasing hardness).<br>Coming-down phase<br>• Gauges less than 2 mm are produced after the ascent zone in batches of less than 50 km. The maximum hardness of products with gauges less than 2 mm is restricted.<br>• Then 70 km gauges larger than 2.2 mm are produced.<br>• Sequential processing of equal width slabs during a rolling cycle is limited to 60 km. Then gradual decreasing of width is required due to work roll wear on the final 3 mill stands. | Generally, rolling cycles consists of equal width slabs. If necessary, a range of widths can be processed starting with the widest directly after the warmers, followed by gradual decreasing widths.<br><br>• Up to 2 warmers of gauge ± 6 mm could be produced at the start of a rolling cycle but generally no warmers are used.<br>• The thinnest gauges are produced early in a rolling cycle.<br>• Gauges less than 3 mm must be processed within the first 20 km.<br>• The rolling cycle ends with increasing gauges. |
| Slabs are grouped together in equal gauge groups to achieve the best quality, and gauge jumps are limited to 0.5 – 0.8 of the previous gauge. | |
| Width jumps of less than 100 mm are preferred but up to 250 mm are allowed. | |
| Maximum product width/gauge ratios are subject to the hardness range. | Maximum product width/gauge ratios apply (figure 3.3). |
| The duration of a work roll change in all seven stands is 10 – 12 minutes. | The duration of a work roll change is 30 – 45 minutes. |
| | |
| **Tandem mill backup roll changes** | **Steckel mill backup roll changes** |
| Backup rolls of all seven stands are changed every 2 weeks (120 000 – 180 000 ton). | Backup rolls are changed weekly<br>(8 000 – 15 000 ton). |
| Widths of less than 1250 mm are allowed during the first 6 000 ton and the last 6 000 ton of a backup rolling cycle.<br><br>80 000 ton into a backup roll production campaign, product width/gauge limits are applied. | A coffin shape width profile is used to sequence rolling cycles between backup roll changes.<br><br>Wide-out phase<br>• Incrementally wider homogeneous rolling cycles of widths between 1200 mm to 2050 mm<br>• Maximum 3000 ton.<br>Coming-down phase<br>• Incrementally narrower homogeneous rolling cycles of decreasing widths from 2050 mm to 1000 mm. |

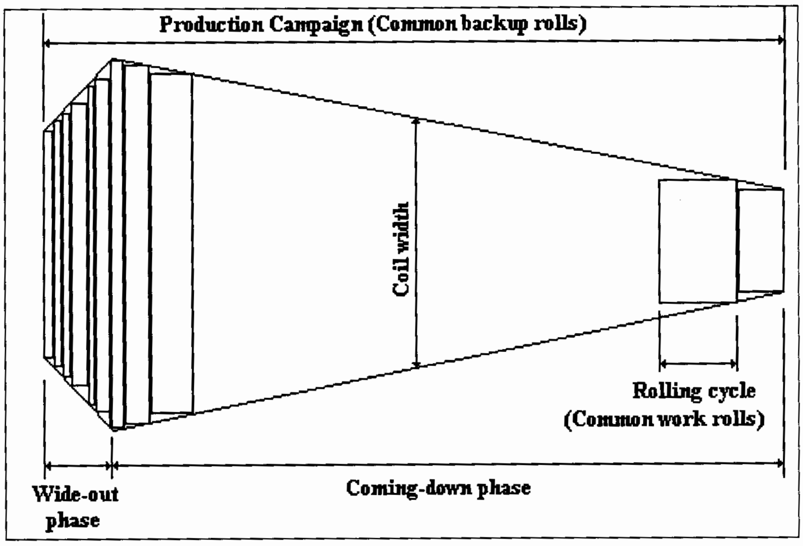



**Figure 2.3 Coffin shape width profile for steckel mill production scheduling [adapted from fig. 2, Kosiba *et al.* [17] and fig. 2, Lopez *et al.* [21]].**

Due to the small number of slabs processed during a steckel mill rolling cycle, it is relatively easy to achieve a high degree of homogeneity within rolling cycles. These rolling cycles should ideally contain slabs of similar retention time, hardness, gauge, grade and width.

The sequencing of rolling cycles throughout a steckel mill production campaign that uses a single set of backup rolls is based on a coffin shape width profile, as illustrated in figure 2.3. In contrast to the tandem mill production scheduling guidelines, which stipulate that the slabs within each rolling cycle must follow a coffin shape width profile, all the rolling cycles within a steckel mill production campaign form a coffin shape width profile over the duration of the production campaign. Therefore, as with a tandem mill rolling cycle schedule, a steckel mill production campaign consists of a wide-out and coming-down phase.

#### 2.3.1.4 Maximising process efficiency

Lopez *et al.* [21] have identified reheat furnaces as the main factor in maximisation of process efficiency. In order to maximise process efficiency, slab retention time as well as furnace discharge delays should be kept to a minimum.

The retention time of a slab in a reheat furnace is a function of the slab size, furnace charging temperature and the required processing temperature. Slabs are cycled through the furnace at the speed of the slab that requires the longest retention time. Generally, the wider the slab the longer the retention time. Therefore some slabs could remain in the furnace longer than required, resulting in a waste of energy and lower efficiency. Consequently, changes in retention time from slab to slab should be gradual.

The current capacity of the walking beam furnace at Highveld's flat products complex is about 100 ton/hour. There may be between 15 to 24 slabs (approximately 600 ton) in the walking beam furnace at one time. It takes four to six hours for a slab to reach the required processing temperature, from cold charging.

Furnace discharge delays are caused by having to wait for a slab to reach the required processing temperature before being extracted from the furnace for processing. These delays due to heat give rise to a decrease in mill utilisation and adversely effect process efficiency. Smooth changes in retention time, however, reduce these furnace discharge delays.

#### 2.3.1.5 Maximising on-time delivery

In order to maximise productivity, schedulers prefer to create homogeneous rolling cycles with similar retention time, hardness, gauge, grade and smooth width changes [21]. Therefore, orders for less common slabs are frequently delayed until sufficient quantities can be scheduled into an efficient rolling cycle. However, on-time delivery is negatively impacted by this scheduling practice. The conflict between on-time delivery and homogeneous rolling cycles could be resolved by producing less common slabs in batches and keeping them in stock. High inventories are, however, yet another source of inefficiency.

### 2.3.2 CONCLUSION



In this section it has been shown that roll performance plays a significant role in determining product quality, operating costs, and productive capacity. It is therefore not surprising that the majority of rolling cycle scheduling models presented in the next section reconciles throughput and quality maximisation objectives by combining these goals into the single objective of minimising equipment wear.

## 2.4 LITERATURE SURVEY

This section presents some analytical procedures that have been developed for tandem mill production scheduling. All these methodologies aim at reconciling various conflicting hot strip mill production scheduling objectives presented in the preceding section.

Firstly, the travelling salesman problem formulated by Kosiba *et al.* [17] as a model for tandem mill production scheduling is presented. This is followed by the vehicle routing problem with time windows model formulated by Chen *et. al* [6]. Then the prize collecting travelling salesman problem model formulated by Lopez *et al.* [21] is presented. Finally a goal programming model formulated by Jacobs *et al.* [16] as a model for tandem mill production scheduling is presented.

### 2.4.1 THE TRAVELLING SALESMAN PROBLEM AS A MODEL FOR TANDEM MILL PRODUCTION SCHEDULING

Kosiba *et al.* [17] formulate the tandem mill scheduling problem as a travelling salesman problem (TSP). The TSP is a widely studied combinatorial optimisation problem in the field of operational research [19]. Consequently, once the tandem mill scheduling problem has been formulated as a TSP, many algorithms previously proposed to solve the TSP [19] may be used to find a solution to the tandem mill scheduling problem. Furthermore Kosiba *et al.* [17] introduce "order-blocks", significantly reducing the size of the problem. By reducing the size of the problem Kosiba *et al.* [17] could employ the Miller and Pekney [19] branch-and-bound, integer linear programming, algorithm to find an exact and optimal solution to the problem.

#### 2.4.1.1 The classic travelling salesman problem

The travelling salesman problem is commonly interpreted as a salesman seeking the shortest route through a number of cities. Several permutation problems not directly associated with routing, such as computer wiring, wallpaper cutting, hole punching, job sequencing and dartboard design [19], can be described by the travelling salesman problem. It is therefore not surprising that researchers have been able to describe tandem mill rolling cycle scheduling as a travelling salesman problem.

Kosiba *et al.* [17] formulate the classic travelling salesman problem as follows:

- Given a graph with a number of nodes {cities} with edges possessing real valued weights {inter-city distance or costs}, determine the minimum total weight circuit/cycle in the graph that visits each of the nodes exactly once, except for the initial and final vertices which are the same.



Kosiba *et al.* [17] formulate a mathematical model for tandem mill rolling cycle scheduling based on the classic travelling salesman problem. The rolling cycle scheduling objectives considered by Kosiba *et al.* [17] in the formulation of the mathematical model are presented in the following paragraph.

#### 2.4.1.2 Rolling cycle scheduling objectives

Kosiba *et al.* [17] focus their research on the development of an analytical procedure for the optimisation of production through a tandem mill with consideration of the following conflicting primary production scheduling objectives:

- Maximising production rate
- Maximising product quality
- Maximising intra-order product consistency

Kosiba *et al.* [17] propose that the throughput and quality maximisation objectives may be reconciled by combining these goals into the single objective of minimising roll wear. They evaluate roll wear using a penalty structure that reflects penalties for big jumps in the following three product characteristics:

- Width (slab width)
- Gauge (final coil thickness)
- Hardness (a function of the grade or metallurgical composition of the slab)

Refer to table 2.2 to 2.4 for typical penalty structures used by Kosiba *et al.* [17] to evaluate changes in width, gauge or hardness of sequential slabs. These penalties are allocated from slab to slab.

Kosiba *et al.* [17] simplify the problem by not assigning penalties when slabs of identical width, gauge and hardness are scheduled sequentially. Furthermore, they add an artificially large outgoing penalty to the penalty structure to ensure a coffin shape rolling cycle width profile because the width penalty structure given in table 2.2 does not explicitly assign penalties to increases in width.

**Table 2.2 Tandem mill rolling cycle scheduling width penalty structure Table 1 Kosiba *et al.* [17]]**

| Inward width jump (inches) | Penalty (points) |
|---|---|
| 0-1 | 1 |
| 1-2 | 2 |
| 2-3 | 3 |
| 3-4 | 5 |
| 4-5 | 10 |
| 5-6 | 20 |
| 6-7 | 30 |
| 7-8 | 50 |
| 8-9 | 70 |
| 9-10 | 90 |
| 11-12 | 150 |
| 12-18 | 220 |
| 18-30 | 500 |
| 30-50 | 1000 |

**Table 2.3 Tandem mill rolling cycle scheduling gauge penalty structure [Table 3 Kosiba *et al.* [17]]**

| Excess jump (inches) | Penalty | |
|---|---|---|
| | Gauge jump up | Gauge jump down |
| 0.0001-0.0100 | 3 | 6 |
| 0.1010-0.0200 | 7 | 14 |
| 0.0201-0.0300 | 12 | 24 |
| 0.0301-0.0400 | 18 | 36 |
| 0.0401-0.0500 | 25 | 50 |
| 0.0501-0.0600 | 33 | 66 |
| 0.0601-0.0700 | 42 | 84 |
| 0.0701-0.0800 | 52 | 104 |
| 0.0801-0.1000 | 66 | 132 |
| 0.1001-0.1500 | 99 | 198 |
| 0.1501-0.9999 | 199 | 398 |

**Table 2.4 Tandem mill rolling cycle scheduling hardness penalty structure [Table 2 Kosiba *et al.* [17]**

| Factor change (units) | Penalty (points) |
|---|---|
| 0-9 | 1 |
| 10-19 | 2 |
| 20-29 | 20 |
| 30-39 | 30 |
| 40-49 | 120 |
| 50-99 | 150 |



Roll wear is considered to be cumulative, therefore the total penalty of a rolling cycle schedule is determined by summation of the width, gauge, and hardness penalties. The schedule with the lowest penalty will result in the least work roll wear, leading to higher product quality, improved production rate and thus increased profits. The objective of the scheduling model proposed by Kosiba *et al.* [17] is to evaluate and minimise the total rolling cycle schedule penalty.

In addition to the objective of minimising roll wear, Kosiba *et al.* [17] also consider the following system constraints in their tandem mill production scheduling model:

- The overall width profile through a rolling cycle must reflect the coffin shape.
- No more than the maximum total length of product can be produced during a rolling cycle.
- Any rolling cycle schedule may only consist of a singe grade (metallurgical composition) product.
- All products that make up a single customer order must be processed within a single rolling cycle.

The rolling cycle scheduling objectives presented in this paragraph were considered by Kosiba *et al.* [17] in formulation of the mathematical model for tandem mill rolling cycle scheduling shown in the following paragraph.

#### 2.4.1.3 Mathematical model for tandem mill rolling cycle scheduling

The travelling salesman problem as applied by Kosiba *et al.* [17] to represent the rolling cycle scheduling problem is presented in this paragraph. The objective of the scheduling model proposed by Kosiba *et al.* [17] is to evaluate and minimise the total rolling cycle schedule penalty. Initially all symbols are defined; this is followed by the mathematical model.

- Consider a directed graph $G=N(V, A)$ that represents a series of tandem mill orders where:
    - $N$ is a set of nodes that represents all the orders;
    - $A$ is a set of arcs that represents the links between orders (or paths between cities in the classical travelling salesman problem). A link originates from a source node and terminates in a sink node.
    - $n$ is the number of orders that have to be scheduled;
    - $V=\{v_1, v_2, \ldots, v_n\}$ is a set of orders that have to be scheduled;
    - $S$ is an arbitrary subset of $V$.
- $c_{ij}$ is the total penalty to produce slab $i$ immediately ahead of slab $j$ as given by the penalty structure: $c_{ij}= P_{ij}^{w} + P_{ij}^{g} + P_{ij}^{h}$ where:
    - $w$ is the ordered coil width;
    - $g$ is the ordered coil gauge;
    - $h$ is the ordered coil hardness;
    - $P_{ij}^{w}$ represents the width penalty (refer to table 2.2 for typical values);
    - $P_{ij}^{g}$ represents the gauge penalty (refer to table 2.3 for typical values);
    - $P_{ij}^{h}$ represents the hardness penalty (refer to table 2.4 for typical values);
    - Non-negative lengths representing $c_{ij}$ are associated with each arc $a_{ij} \in A$;
    - $Z$ is the value of the total penalty of all the slabs included in the optimal rolling cycle solution.
- $x_{ij}$ is the sequencing decision variable:
    - $x_{ij} = 1$ if link $ij$ is included in the optimal rolling cycle solution;
    - $x_{ij} = 0$ if link $ij$ is not included in the optimal rolling cycle solution.
- $\phi$ represents the "dummy" nodes at the beginning and end of each rolling cycle. $x_{\phi j}$ and $x_{i\phi}$ are the links, which are associated with the two "dummy" nodes and carry a penalty of 0. The first node can only be a source node and

the final node can only be a sink node, since a link originates from a source node and terminates in a sink node.

- $O=\{o_1, o_2,\ldots,o_m\}$ represents the set of order-blocks, which consist of slabs of identical width, gauge, and hardness that have to be produced for the same customer. If $v_i \in o_k$ and $v_j \in o_k$ then $w_i=w_j$, $g_i=g_j$ and $h_i=h_j$.

Kosiba *et al.* [17] introduce the concept of order-blocks in order to assure product consistency and to reduce the size of the problem. Processing identical slabs sequentially assures product consistency and carries no penalty. Since processing identical slabs sequentially carries no penalty, an order-block may be represented by a single node on the graph, thereby reducing the size of the rolling cycle scheduling problem significantly. A complete network that represents the rolling cycle scheduling problem can therefore be drawn with the order-blocks identified by the nodes and the sum of the penalties associated from order-block to order-block as the arcs.

The mathematical model proposed by Kosiba *et al.* [17] to evaluate and minimise the total rolling cycle schedule penalty is represented by the following objective function:

$$\text{Minimise } Z = \sum_{i \in O} \sum_{j \in O} \left(P_{ij}^{w} + P_{ij}^{g} + P_{ij}^{h}\right) x_{ij} \tag{2.1}$$



subject to the following constraints

$$\sum_{i \in O} x_{ij} = 1, \quad \forall j \in O, \tag{2.2}$$

$$\sum_{j \in O} x_{ij} = 1, \quad \forall i \in O, \tag{2.3}$$

$$\sum_{j \in O} x_{\phi j} = 1, \tag{2.4}$$

$$\sum_{i \in O} x_{i\phi} = 1, \tag{2.5}$$

$$\sum_{i \in S} \sum_{j \in S} x_{ij} \le |S| - 1, \quad \forall S \subset O,\ S \ne 0,\ S \ne O, \tag{2.6}$$

$$x_{ij} = \{0,1\}, \quad \forall i \in O,\ \forall j \in O \tag{2.7}$$

- The objective function (2.1) evaluates a series of tandem mill orders in order to minimise the total penalty associated with each rolling cycle. Kosiba *et al.* [17] maintain that the tandem mill rolling cycle scheduling objectives presented in section 2.4.1.2 can be reconciled by minimising the total penalty associated with a rolling cycle.
- Equations (2.2)-(2.5) assure production of each slab exactly once by assuring that each slab is a source node only once and a sink node only once.
- Equation (2.2) assures mathematically that each slab that is produced is a sink node only once.
- Equation (2.3) assures mathematically that each slab is a source node only once.
- Equation (2.4) and (2.5) introduce "dummy" nodes which are added to each rolling cycle to ensure that the first node can only be a source node and the final node can only be a sink.
- Equation (2.6) ensures that there are no subtours, i.e.: Hamiltonian tours, in the model. This restriction assures the formation of a single continuous rolling cycle.
- Equation (2.7) impose binary conditions on the sequencing decision variable.

By representing the tandem mill production scheduling problem as a travelling salesman problem, any one of a number of previously proposed travelling salesman problem solution algorithms may be employed to find a near or optimal solution. Refer to Laporte [19] for a survey of exact and approximate algorithms for the travelling salesman problem. Kosiba *et al.* [17] employed the Miller and Pekny solution algorithm [19] to find an exact and optimal solution to the rolling cycle scheduling problem formulated above.

A flow diagram that illustrates the scheduling model proposed by Kosiba *et al.* [17] is presented in figure 2.4. Like products are grouped into order-blocks of identical width, hardness and gauge. Once order-blocks have been generated, rolling cycle penalty levels can be determined using the objective function given in equation (2.1). These penalties are based on the penalty structures for width, gauge and hardness presented in table 2.2 to 2.4. An optimum solution to the objective function can then be found by applying an exact solution algorithm. The computational results obtained by Kosiba *et al.* [17] are presented in the following paragraph.

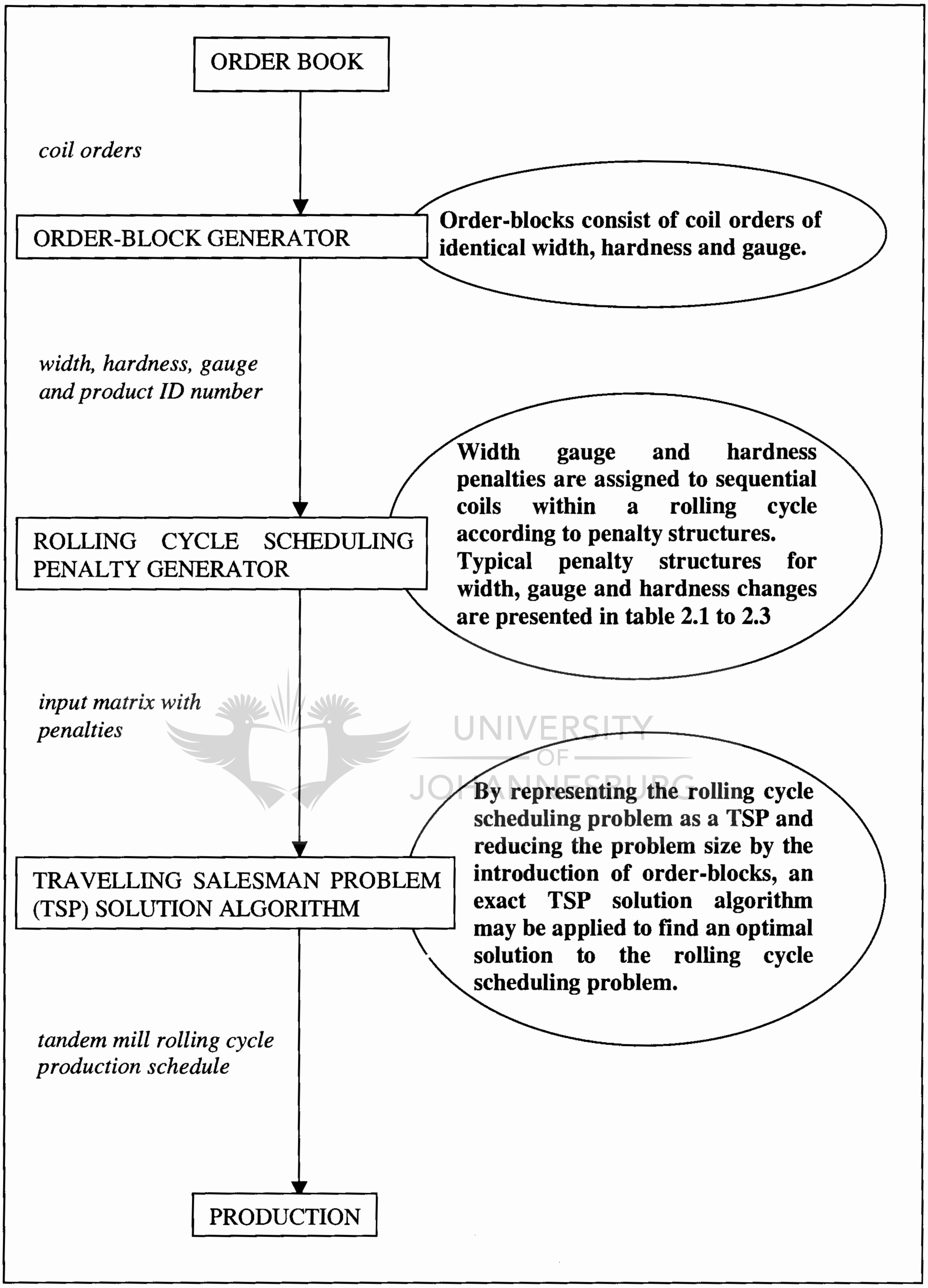



**Figure 2.4 A flow chart of the TSP model proposed by Kosiba *et al.* [17].**

#### 2.4.1.4 Computational results

Kosiba *et al.* [17] used four sample tandem mill schedules to compare the solutions obtained from their method (presented in the previous section) to the set of solutions obtained with the traditional scheduling procedures used in the plant, as well as to the solutions obtained with UMPIRE (Using Minimum Penalties to Improve Rolling Efficiency) method of Wright and Houck [32]. On the basis of total penalty values, their modelling approach was shown to be superior to the other methods, achieving a total rolling cycle schedule penalty improvement of 44% in the worst case and 78% in the best case.

#### 2.4.1.5 Synopsis

Kosiba *et al.* [17] formulate the tandem mill scheduling problem as a travelling salesman problem (TSP). Their rolling cycle scheduling model focuses on reducing work roll wear as the main scheduling objective. Work roll wear is evaluated by penalty structures that reflect penalties for big jumps in width, gauge, and hardness. The main objective of the scheduling model is to evaluate and minimise the total rolling cycle schedule penalty and hence produce near optimum rolling cycle schedules.

Kosiba *et al.* introduce order-blocks to overcome the scheduling objective of product consistency maximisation. Grouping slabs into order-blocks carries no additional penalty and significantly reduces the number of nodes in the network, thereby reducing the size of the problem. By reducing the size of the problem, the Miller and Pekny [19] solution algorithm could be employed to find an exact and optimal solution to the rolling cycle scheduling problem.

Kosiba *et al.* [17] assume that all the existing orders will be processed, and therefore neglect to perform the selection task described by Balas [3]. They also do not consider the maximisation of reheat furnace efficiency, priority orders or on-time delivery in their study. Furthermore, the assumption that sequentially scheduling an unlimited number of similar coils carries no penalty is not accurate as this will adversely impact on product quality. Therefore, there should be an upper limit on the number of slabs scheduled sequentially.

The following section presents the tandem mill production scheduling model formulated by Chen *et al.* [6]. The model formulated by Chen *et al.* [6] is more comprehensive than the model proposed by Kosiba *et al.* [17], because it includes rolling cycle capacity constraints and considers position limitations, such as delivery times.

### 2.4.2 THE VEHICLE ROUTING PROBLEM WITH TIME WINDOWS AS A MODEL FOR TANDEM MILL PRODUCTION SCHEDULING

Chen *et al.* [6] formulate the tandem mill scheduling problem as a vehicle routing problem with time windows (VRPTW). The vehicle routing problem (VRP) of combinatorial optimisation plays a central role in the field of physical distribution and logistics management [20]. Various algorithms previously proposed to solve the VRP [20] may be used to find a solution to the tandem mill scheduling problem. By formulating the tandem mill production campaign scheduling problem as a VRPTW, Chen *et al.* [6] are able to incorporate the position limitations of slabs in a rolling cycle into the mathematical model as time constraints. After formulating the production campaign scheduling problem mathematically, Chen *et al.* [6] employ a number of heuristic algorithms to generate near optimal solutions.

#### 2.4.2.1 The vehicle routing problem with time windows

The vehicle routing problem (VRP) involves the design of a set of minimum-cost vehicle delivery or collection routes, originating and terminating at one or several central depots, for a fleet of vehicles that serves a set of geographically scattered cities or customers with known demands [20, 28]. Each customer is served exactly once and all the customers must be assigned to vehicles without exceeding vehicle capacities.



The VRP may be described as a multiple travelling salesmen problem with capacity constraints [27]. Research on the VRP has not only focused on minimising travelling distance, as is the case for TSP research, but also on improving vehicle capacity utilisation.

In the vehicle routing and scheduling problem with time windows (VRPTW), the VRP is reformulated to include the added complexity of allowable delivery times, or time windows, stemming from the fact that some customers impose delivery deadlines and earliest-delivery-time constraints [6, 27, 28, 29].

Chen *et al.* [6] formulate a mathematical model for tandem mill production campaign scheduling based on the vehicle routing problem with time windows. According to Chen *et al.* [6], solutions to the production campaign scheduling problem based on the travelling salesman problem (TSP) [Kosiba *et al.* [17]] and vehicle routing problem (VRP) are not precise, because position limitations of some slabs in a rolling cycle schedule are not considered. The VRPTW model overcomes this problem by quantifying the position limitations of slabs as time constraints. The rolling cycle scheduling objectives considered by Chen *et al.* [6] in the formulation of the mathematical model is presented in the following paragraph.

#### 2.4.2.2 Rolling cycle scheduling objectives

Like the model proposed by Kosiba *et al.* [17], the model proposed by Chen *et al.* [6] identifies minimising work roll wear between roll changes as the main scheduling objective in order to improve product quality, production rate and product consistency. Roll wear is evaluated with a penalty structure that reflects penalties for big jumps in the following three characteristics [6]:

- Width
- Gauge
- Hardness

In the penalty structure, penalties can be assessed from slab to slab by direct computation. Refer to table 2.2 to 2.4 for typical penalty structures for width, gauge and hardness changes. Processing of identical slabs sequentially carry no penalty. An artificially large outgoing penalty was added to the penalty structure to ensure a coffin shape rolling cycle width profile.

The rolling cycle scheduling objectives presented in this section were considered by Chen *et al.* [6] in the formulation of the mathematical model for tandem mill production campaign scheduling shown in the following paragraph.

#### 2.4.2.3 Mathematical model for tandem mill production campaign scheduling

The vehicle routing problem with time windows as applied by Chen *et al.* [6] to represent the mathematical model for tandem mill production campaign scheduling is presented in this paragraph.



This model differs from the model proposed by Kosiba *et al.* [17] presented in paragraph 2.4.1.3 in that Chen *et al.* [6] include rolling cycle capacity constraints, which reflect more closely the practical tandem mill production campaign scheduling problem. Furthermore, the model proposed by Chen *et al.* [6] generates rolling cycles for the production campaign as a whole and considers position limitations such as delivery deadlines. Whereas the model proposed by Kosiba *et al.* [17] generates an optimum rolling cycle schedule and it does not consider the effect of time constraints on the objective function.

The objective of the scheduling model proposed by Chen *et al.* [6] is to minimise the total scheduling penalty of each rolling cycle throughout a production campaign, without exceeding the capacity constraint of any one rolling cycle. Initially all symbols are defined, followed by the mathematical model.

- Consider a graph $G=(V, A)$ that represents a series of tandem mill orders where:
  - $n$ is the number of production slabs;
  - $K$ is the number of rolling cycles;
  - $A$ is the set of arcs that links adjacent slabs in the rolling sequence;
  - $V$ is the set of vertices representing slabs to be produced; $V=\{0,1, 2,\ldots, n\}$; where 0 is the "dummy" slab as the beginning and end of each rolling cycle. Let $c_{0i}=c_{i0}=c$, $c$ is a given positive number or zero, $i\in V$;
  - $S$ is an arbitrary subset of $V$.
- $c_{ij}$ is the total penalty to produce slab $i$ immediately ahead of slab $j$ as given by the penalty structure: $c_{ij}=P_{ij}^{w} + P_{ij}^{g} + P_{ij}^{h}$ where:
  - $P_{ij}^{w}$ represents the width penalty;
  - $P_{ij}^{g}$ represents the gauge penalty;
  - $P_{ij}^{h}$ represents the hardness penalty;
  - $Q$ is the value of the total penalty of all the slabs included in all the rolling cycle solutions of the optimal production campaign scheduling solution.
- $D$ is the capacity constraint of the rolling cycle in weight:
  - $w_i$ is the weight of the $i$th slab.
- $a_i$, $b_i$ are the time restrictions of the $i$th slab. These position limitations of slabs in a rolling cycle are dominated by delivery deadlines.
  - $p_i$ is the processing time of the $i$th slab;
  - $t_i$ is the time when processing of the $i$th slab begins;
  - $T$ is a very large number.
- $y_{ik}$ is the assignment decision variable:
  - $y_{ik} = 1$ if the $i$th slab is assigned to the $k$th rolling cycle;
  - $y_{ik} = 0$ if the $i$th slab is not assigned to the $k$th rolling cycle.
- $x_{ijk}$ is the sequencing decision variable:
  - $x_{ijk} = 1$ if the $k$th rolling cycle produces slab $i$ before $j$, $i \neq j$;
  - $x_{ijk} = 0$ if the $k$th rolling cycle does not produce slab $i$ before $j$, $i \neq j$.

The mathematical model proposed by Chen *et al.* [6] to evaluate and minimise the production campaign schedule penalty is represented by the following objective function [6, 9, 20]:

$$\text{Minimise } Q = \sum_{k=1}^{K} \sum_{i \neq j} c_{ij} x_{ijk} \qquad (2.8)$$

Subject to the following constraints

$$\sum_{i=0}^{n} w_i y_{ik} \leq D \quad (k = 1, ..., K,) \tag{2.9}$$

$$\sum_{k=1}^{K} y_{ik} = \begin{cases} K, & (i = 0) \\ 1, & (i = 1,...,n) \end{cases} \tag{2.10}$$

$$\sum_{i=0}^{n} x_{ijk} = y_{jk}(j = 0,...,n;\ k = 1,...,K), \tag{2.11}$$

$$\sum_{j=0}^{n} x_{ijk} = y_{ik}(i = 0,...,n;\ k = 1,...,K), \tag{2.12}$$

$$\sum_{ij \in S} x_{ijk} \leq |S| - 1 \quad (S \subset V; |S| \geq 2;\ k = 1,...,K), \tag{2.13}$$

$$t_j \begin{cases} \geq t_i + p_i - (1 - x_{ijk})T \\ \leq t_i + p_i + (1 - x_{ijk})T \end{cases} \quad (i, j = 0, ..., n;\ k = 1,...,K) \tag{2.14}$$

$$a_i \leq t_i \leq b_i \quad (i = 1, ..., n) \tag{2.15}$$

$$x_{ijk} \in \{0, 1\} \quad (i, j = 0, ..., n;\ k = 1,...,K) \tag{2.16}$$

$$y_{ik} \in \{0, 1\} \quad (i = 0, ..., n;\ k = 1,...,K) \tag{2.17}$$

- The objective function (2.8) evaluates a series of orders that have to be produced during a tandem mill production campaign in order to minimise the total penalty associated with all the rolling cycles throughout the production campaign. Chen *et al.* [6] maintain that the rolling cycle scheduling objectives presented in section 2.4.2.2 can be reconciled by minimising the total penalty associated with the production campaign as a whole.
- Equations (2.9)-(2.13), (2.16) and (2.17) are general vehicle routing problem constraints.
- Equations (2.9), (2.10) and (2.17) assign the slabs to specific rolling cycles without exceeding the capacity constraints of each rolling cycle. The rolling cycle capacity constraint is a function of the roll wear that necessitates work roll changes between rolling cycles as discussed in section 2.3.1.1.
- Equations (2.11)-(2.13) and (2.16) are classic travelling salesman problem constraints which specify the sequence of slabs in each rolling cycle.
- Equations (2.14) and (2.15) are time constraints of the *i*th slab. Equation (2.14) describes the compatibility requirements between $x_{ijk}$, that forms the sequence, and the time $t_i$, that gives the schedules, whilst equation (2.15) establishes the time windows within which each slab must be produced.
- Note that if the *i*th slab is not adjacent to the *j*th slab in any rolling cycle, $x_{ijk}$ is equal to 0 for all $k$ and equation (2.15) is then not effective; otherwise, $x_{ijk}$ is equal to 1 for some $k$ and then $t_j = t_i + p_i$.

By representing the tandem mill production campaign scheduling problem as a vehicle routing problem with time windows, any one of a number of previously proposed vehicle routing problem with time windows solution algorithms may be employed to find a near optimal solution. Refer to Laporte [20] for a survey of exact and approximate algorithms for the vehicle routing problem.

Due to the additional constraints the size of the model proposed by Chen *et al.* [6] is much larger than the model proposed by Kosiba *et al.* [17]. Therefore, exact solution methods, such as the Miller and Pekny algorithm [19] used by Kosiba *et al.* [17] to find an optimal solution, have to be substituted by less computer intensive heuristics approximation algorithms used to search for near optimal solutions [10]. Heuristics are approximation algorithms based on knowledge, experience and rules of thumbs; they are iterative and seek a near optimal schedule that can be justified empirically [31].

A flow diagram that illustrates the scheduling model proposed by Chen *et al.* [6] is presented in figure 2.5. All the orders to be produced during a specific production campaign are evaluated and allocated to specific rolling cycles based on penalty functions, rolling cycle capacity constraints and order delivery deadlines.

Chen *et al.* [6] use a number of heuristics approximation algorithms to find a near optimal solution to the tandem mill production campaign scheduling problem:

- Solomon's insertion heuristic model [28].
- The generic algorithm [6] is an order-based approximation algorithm which uses Blanton's MX crossover operator [5] followed by the Davis encoding method [8] to partition the slabs into different rolling cycles.
- Route improvement heuristics [6,27]. The 2-opt* and Or-opt exchange route improvement heuristics could be used to improve the initial solutions obtained by employing either the insertion heuristic or generic algorithms.

These heuristics approximation algorithms are employed by Chen *et al.* [6] to solve the tandem mill production campaign scheduling problem objective function given in equation (2.8). The computational results obtained by Chen *et al.* [6] are presented in the following paragraph.

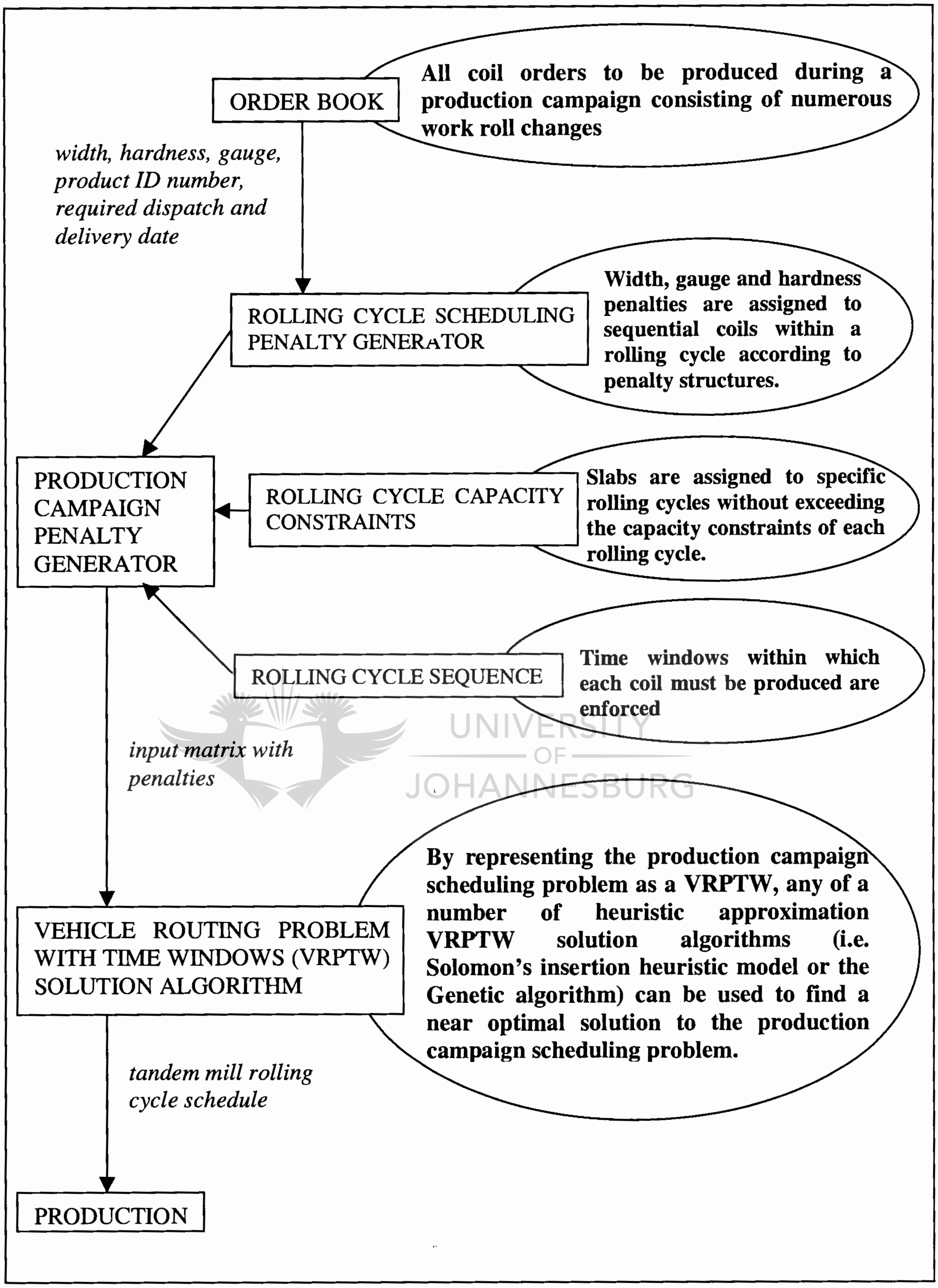





**Figure 2.5 A flow chart of the VRPTW model proposed by Chen *et al.* [6]**

#### 2.4.2.4 Computational results

Chen *et al.* [6] compare the objective function penalty results obtained by employing the insertion heuristic, genetic algorithm and route exchange heuristics solution methods to the original tandem mill rolling cycle schedules produced manually for four actual rolling cycles. Chen *et al.* [6] report that the insertion heuristic modelling approach achieves a total objective function penalty improvement of 41% in the worst case and 51% in the best. The genetic algorithm modelling approach achieves a total objective function penalty improvement of 41% in the worst case and 57% in the best case. Significant reductions in aggregate objective function penalty over conventional methods are achieved, especially when the slabs in a rolling cycle are more varied in terms of required physical properties.

#### 2.4.2.5 Synopsis

Chen *et al.* [6] formulate the vehicle routing problem with time widows (VRPTW) as a model for scheduling the daily operation of a tandem mill. Similar to the model formulated by Kosiba *et al.* [17] the model proposed by Chen *et. al* [6] focuses on reducing work roll wear as the main scheduling objective. Work roll wear is evaluated with a penalty structure that reflects penalties for big jumps in width, gauge, and hardness. The objective of the scheduling model proposed by Chen *et al.* [6] is to evaluate and minimise the production campaign scheduling penalty, thereby producing near optimal rolling cycle schedules throughout the production campaign.



Chen *et al.* [6] highlight that models that do not adequately consider the position limitations of slabs in a rolling cycle are not precise because these models do not accurately portray the importance of maximising on-time delivery, as was discussed in section 2.3.1.5. The vehicle routing problem with time windows model overcomes this problem by quantifying the position limitations of slabs as time constraints. Having represented the problem as a vehicle routing problem with time windows, the insertion heuristic [28], generic algorithm [6], and route improvement heuristics [6, 27] approximate algorithms are employed to find a near optimal solution to the tandem mill production campaign scheduling problem.

The tandem mill production campaign scheduling model proposed by Chen *et al.* [6] more closely reflects the actual tandem mill scheduling problem than the model proposed by Kosiba *et al.* [17]. Rolling cycle scheduling is considered over the production campaign as a whole and aims to achieve near optimum rolling cycles throughout the campaign. Position limitations such as on-time delivery of orders and scheduling of priority orders are incorporated into the model by imposing time constraints on the objective function. However, the model does not restrict the number of slabs within each rolling cycle with identical widths, which could adversely effect product quality as stated in section 2.3.1.2. Furthermore, the model does not take into consideration the maximisation of reheat furnace efficiency as discussed in paragraph 2.3.1.4.

The following section presents the tandem mill production scheduling model formulated by Lopez *et al.* [21]. This model is more comprehensive than the models proposed by Kosiba *et. al* . [17] and Chen *et al.* [6] because it includes rolling cycle capacity constraints, scheduling of priority orders and reheat furnace efficiency objectives.

### 2.4.3 THE PRIZE COLLECTING TRAVELLING SALESMAN PROBLEM AS A MODEL FOR TANDEM MILL PRODUCTION SCHEDULING

Lopez *et al.* [21] formulate the tandem mill scheduling problem as a prize collecting travelling salesman problem (PCTSP), a generalisation of the travelling salesman problem (TSP). The problem is formulated as combination of the PCTSP mathematical model presented by Balas [3] and a set of additional constraints. Lopez *et al.* [21] employ a heuristic method based on Tabu Search, Glover [11], to determine near optimal solutions for daily production scheduling at a tandem mill.

#### 2.4.3.1 The prize collecting travelling salesman problem

The prize collecting travelling salesman problem can be interpreted as a salesman seeking the shortest and most profitable route though a number of cities. The prize collecting travelling salesman problem is a generalisation of the travelling salesman problem [21].

Balas [3] formulates the prize collecting travelling salesman problem as follows:

- A salesman who travels between pairs of cities at a cost depending on the pair, obtains a prize for every city visited and pays a penalty for every city not visited, wishes to find a tour that minimise his travel costs and net penalties, while visiting enough cities in his tour to collect a predetermined amount of prize money.

Lopez *et al.* [21] formulate a mathematical model for tandem mill rolling cycle scheduling based on the prize collecting travelling salesman problem. The rolling cycle scheduling objectives considered by Lopez *et al.* [21] in the formulation of the mathematical model are presented in the following paragraph.

#### 2.4.3.2 Rolling cycle scheduling objectives

Lopez *et al.* [21] focus their research on the development of an analytical procedure for the optimisation of daily production through a tandem mill. Lopez *et al.* [21] consider the following production objectives, which include maximising product quality and production rate that were identified as primary production scheduling objectives by Kosiba *et al.* [17]:

- Maximising production rate
- Maximising product quality
- Maximising process efficiency
- Maximising on-time delivery

Similar to the models proposed by Kosiba *et al.* [17] and Chen *et al.* [6], Lopez *et al.* [21] attempt to minimise work roll wear in order to improve production rate and product quality. In addition Lopez *et al.* [21] also consider maximising process efficiency and on-time delivery in their model for daily tandem mill production scheduling. Lopez *et al.* [21] evaluate these objectives using a penalty structure that reflects penalties for changes in the following five elements:

- Width
- Gauge
- Hardness
- Retention time (the heating time that a slab must be in the reheat furnace to achieve the required processing temperature)
- A penalty for not including priority orders



Refer to table 2.5 to 2.7 for the penalty structures employed by Lopez *et al.* [21] to evaluate changes in width, gauge, hardness, or retention time of sequential slabs. The width penalty structure presented in table 2.5 assigns penalties for sequentially scheduling slabs within various width ranges. During the wide-out phase sequentially scheduling slabs of widths that increase in increments between 20 mm to 30 mm do not carry a width penalty. During the coming-down phase sequentially scheduling slabs of widths that decrease in increments between 0 mm to 100 mm do not carry a width penalty. In addition to these width, gauge, hardness, and retention time penalties, a penalty of 100 units is added to the penalty structure if a scheduled order is not a priority order.

**Table 2.5 Tandem mill rolling cycle scheduling width penalty structure [Table 1 Lopez *et al.* [21]]**

| Break-in phase | | Wide-out phase | | Coming-down phase | |
|---|---|---|---|---|---|
| 2-6 narrow slabs that are easy to process. | | 5-15 progressively wider slabs that are not too hard. | | Progressively narrower slabs. | |
| Width difference = w(*i* - 1) – w(*i*) [mm] | Width penalty [points] | Width difference = w(*i* - 1) – w(*i*) [mm] | Width penalty [points] | Width difference = w(*i* - 1) – w(*i*) [mm] | Width penalty [points] |
| -100 ≤ WiDif ≤ 0 | 0 | < -100 | 1000 | < -50 | 1000 |
| < -100 | 1000 | < -50 | 500 | < -25 | 500 |
| > 0 | 1000 | < -30 | 200 | < 0 | 100 |
| | | < -20 | 0 | < 100 | 0 |
| | | < 0 | 200 | < 125 | 100 |
| | | > 0 | 1000 | < 150 | 500 |
| | | | | >150 | 1000 |

Table 2.6 presents the gauge and hardness penalty structure for big jumps in gauge or hardness of slabs that have been scheduled sequentially. The reheat furnace retention time penalty structure, for slabs that have been scheduled sequentially is presented in table 2.7.

**Table 2.6 Tandem mill rolling cycle scheduling gauge and hardness penalty structure [Table 2 Lopez *et al.* [21]]**

| Difference in gauge group | Gauge group penalty | Difference in hardness group | Hardness group penalty |
|---|---|---|---|
| ≤ 2 | 0 | ≤ 2 | 0 |
| > 2 | 1000 | > 2 | 1000 |

**Table 2.7 Retention time penalty structure [Table 3 Lopez *et al.* [21]]**

| Difference in retention time of sequentially scheduled slabs | Retention time penalty |
|---|---|
| ≤ Maximum allowed retention time difference | 0 |
| ≤ Maximum allowed retention time difference + 10 | 200 |
| ≤ Maximum allowed retention time difference + 20 | 500 |
| > Maximum allowed retention time difference + 20 | 1000 |

Lopez *et al.* [21] refer to a solution for the daily rolling cycle scheduling problem as a line-up (LU). A line-up consists of three consecutive rolling cycles. Generally there is one rolling cycle per eight-hour production shift. A rolling cycle schedule has to satisfy some or all the restrictions on smooth changes in width, hardness, grade, and gauge, and the restrictions related to surface quality, special pieces for the wide-out phase and reheat furnace retention time.

The rolling cycle scheduling objectives presented in this paragraph were considered by Lopez *et al.* [21] in the formulation of the mathematical model for tandem mill production campaign scheduling shown in the following paragraph.

#### 2.4.3.3 Mathematical model for tandem mill rolling cycle scheduling

The prize collecting travelling salesman problem as applied by Lopez *et al.* [21] to represent the mathematical model for daily tandem mill production scheduling is presented in this paragraph. Lopez *et al.* [21] formulate the problem as a combination of the PCTSP mathematical model presented by Balas [3] and a set of additional constraints.

The PCTSP mathematical model proposed by Balas [3] distinguishes between two important scheduling tasks that have to be solved jointly:

- The selection of slabs, which can be represented by a knapsack problem. In order to fill orders, slabs are selected from inventory and must satisfy a lower bound on total weight. Refer to [22] for a comprehensive list of references on the knapsack problem. The knapsack problem is fundamental in the field of combinatorial optimisation. Generally, a knapsack problem consists of a knapsack of limited capacity that has to be filled. Given a set of items with a weight and value associated with each item, the objective is to find a feasible subset of the set of items that yields a maximum profit [12].
- Sequencing slabs using the TSP. The sequence in which these orders have to be processed must be determined by a penalty structure. Refer to table 2.2 to 2.4 for typical penalty structures for width, gauge and hardness changes.

The PCTSP mathematical model proposed by Balas [3] and a set of additional constraints are incorporated by Lopez *et al.* [21] in their mathematical model for tandem mill production scheduling. The PCTSP mathematical model proposed by Balas [3] consists of selecting and sequencing tasks. The set of additional constraints ensures that the production scheduling objectives of maximising product quality and efficiency are fulfilled. Initially all symbols are defined, followed by the mathematical model.

- Consider a graph $G=(N, A \cup O)$ that represents a series of tandem mill orders where:
  - $N$ is a set of nodes that represents all the orders;
  - $A$ is the set of arcs that represents the links between orders;
  - $O$ is a set of loops that represents a number of rolling cycles;
  - $n$ is the number of orders that have to be scheduled.
- $x_{ij}$ is the sequencing decision variable:

- $x_{ij} = 1$ if slab $j$ is scheduled right after slab $i$, with a penalty $c_{ij}$;
- $x_{ii} = 1$ if slab $i$ is not scheduled; therefore the length $w_i$ is not produced and a penalty $c_{ii}$ should be charged in the objective function;
- $x_{ii} = 0$ if slab $i$ is scheduled, and the length $w_i$ is produced.

- $c_{ij}$ is the total penalty to produce slab $i$ immediately ahead of slab $j$ as given by the penalty structure: $c_{ij} = P_{ij}^{w} + P_{ij}^{g} + P_{ij}^{h} + P_{ij}^{f} + P_{ij}^{p}$ where:
  - $P_{ij}^{w}$ represents the width penalty;
  - $P_{ij}^{g}$ represents the gauge penalty;
  - $P_{ij}^{h}$ represents the hardness penalty;
  - $P_{ij}^{f}$ represents the furnace retention time penalty;
  - $P_{ij}^{p}$ represents the penalty for excluding priority orders;
  - $Z$ is the value of the total penalty of all the slabs included in a single rolling cycle.
- $w_i$ is defined as the weight or length of slab $i$:
  - $\Sigma_{i \in N} w_i$ represents the total length of all available ordered slabs that could be scheduled;
  - $\Sigma_{i \in N} w_i x_{ii}$ represents the length of all the ordered slabs not included in the rolling cycle schedule;
  - $\Sigma_{i \in N} w_i$ - $\Sigma_{i \in N} w_i x_{ii}$ represents the length of all the ordered slabs that are included in the rolling cycle.

Lopez *et al.* [21] propose that the lower and upper limits on the weight or length that can be processed between work roll changes can be implemented as follows:

- $w_0 \leq \Sigma_{i \in N} w_i - \Sigma_{i \in N} w_i x_{ii} \leq w_1$ which means that the total length processed during a rolling cycle should be between two limits.
- By setting $L = \Sigma_{i \in N} w_i - w_1$ and $U = \Sigma_{i \in N} w_i - w_0$, the limit equation can be re-written as:
  $L \leq \Sigma_{i \in N} w_i x_{ii} \leq U$.

In addition, the PCTSP as posed by Balas [3] finds a tour whereas the rolling cycle scheduling problem requires a sequence. Therefore, Lopez *et al.* [21] ad a "dummy" slab 0 with no sequence cost and a width of zero into the model.

The mathematical model proposed by Lopez *et al.* [21] to evaluate and minimise the total rolling cycle schedule penalty is represented by the following objective function:

$$\text{Minimise} Z = \sum_{i=0}^{n} \sum_{j=0}^{n} c_{ij} x_{ij} \tag{2.18}$$

$$\sum_{j=0}^{n} x_{ij} = 1 \qquad i = 0,\ldots,n \tag{2.19}$$

$$\sum_{i=0}^{n} x_{ij} = 1 \qquad j = 0,\ldots,n \tag{2.20}$$

$$L \leq \sum_{i=0}^{n} w_i x_{ii} \leq U \tag{2.21}$$

$$x_{00} = 0 \tag{2.22}$$

$$x_{ij} \in \{0,1\} \qquad i, j = 0,\ldots,n \tag{2.23}$$

$G(x)$ has exactly one cycle of length $\geq 2$ (2.24)
Surface quality constraint, (2.25)
Special pieces for the wide-out constraint, (2.26)
Reheat furnace constraint. (2.27)

- Equation (2.21) places a limitation on the number of slabs in the rolling cycle. Production rate is improved by limiting the minimum number of slabs in a rolling cycle because the number of work roll changes can be reduced. Furthermore, product quality is improved by restricting the total processing length of a rolling cycle, (refer to section 2.3.1.1). By restricting the number of slabs in a rolling cycle, the formation of undesirable subtours are also prevented.
- Equation (2.22) ensures that the "dummy" slab 0 is included in the optimal solution. The travelling salesman problem tour originates and terminates at the same central depot, whereas the first and last slabs in a rolling cycle schedule are different slabs. Therefore, by including a "dummy" slab, the travelling salesman problem tour is converted to a rolling cycle sequence.
- Equation (2.23) imposes binary conditions on the sequencing decision variable.
- Lopez *et al.* [21] state that restrictions (2.25)-(2.27) cannot easily be written in mathematical form. According to the authors [21], restrictions (2.25) and (2.26) include "if, then, else" type of questions and restriction (2.27) is a simulation. Unfortunately, no further details pertaining to these restrictions are given by the authors [21].

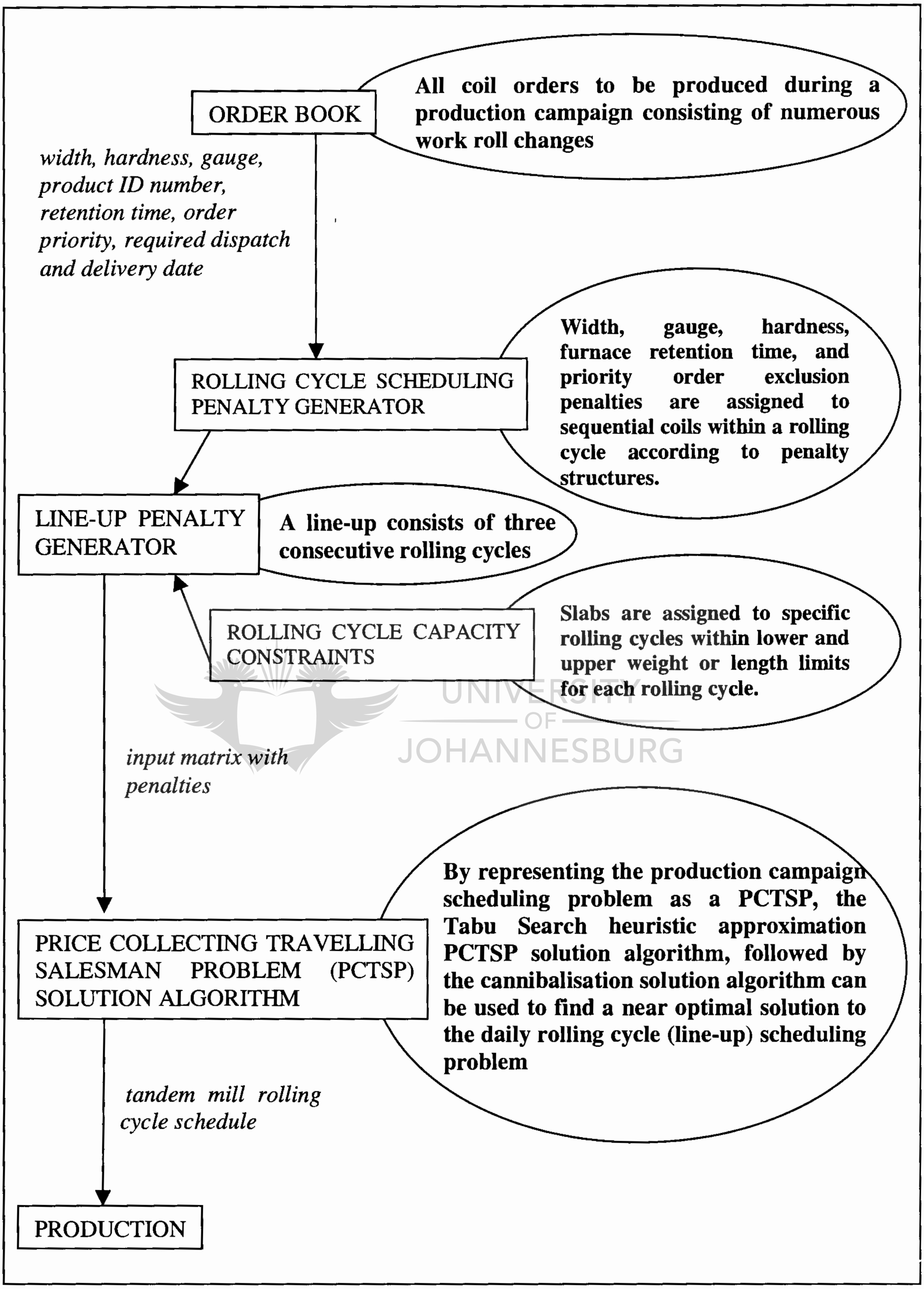





**Figure 2.6 A flow chart of the PCTSP model proposed by Lopez *et al.* [21]**

A flow diagram that illustrates the scheduling model proposed by Lopez *et al.* [21] is presented in figure 2.6. All the orders to be produced during a specific production campaign are evaluated and allocated to the daily production line-up based on penalty functions and rolling cycle capacity constraints.

Lopez *et al.* [21] use a solution algorithm based on the Tabu Search (TS) heuristic [11] to a find near optimal solutions to solve the rolling cycle scheduling problem objective function, given in equation (2.18). Furthermore, a cannibalisation method [21] was incorporated into the solution algorithm to improve the prevailing solution by exchanging groups of slabs from different solutions. The computational results obtained by Lopez *et al.* [21] are presented in the following paragraph.

#### 2.4.3.4 Computational results

Lopez *et al.* [21] compare the objective function penalty results obtained by employing the Tabu Search heuristic [11] and cannibalisation solution algorithm [21] to the original schedules produced by the manual "computer-assisted" method used at Dofasco in Hamilton, Ontario, Canada to generate sets of three rolling cycles. The authors [21] report that the average penalty is reduced by 82% before optimisation and by 89% with the cannibalisation method. The inclusion of the cannibalisation method reduces the rolling cycle average penalty of the initial solutions by 39%. The authors [21] highlighted that their heuristic method also outperformes the manual approach in several other aspects: size of rolling cycles, percentage of priority slabs included, and the time to generate rolling cycles.



#### 2.4.3.5 Synopsis

Lopez. *et al.* [21] present the prize collecting travelling salesman problem (PCTSP) as a model for scheduling the daily operation of a tandem mill. The model focuses on reducing work roll wear with consideration of reheat furnace efficiency and on-time delivery constraints. The objective of the scheduling model proposed by Lopez. *et al.* [21] is to evaluate and minimise the total rolling cycle schedule penalty and hence produce near optimum daily rolling cycle schedules.

Lopez *et al.* [21] formulate and solve the prize collecting travelling salesman problem (PCTSP) as a model for scheduling the daily operation of a tandem mill. The problem is formulated as combination of the PCTSP mathematical model presented by Balas and a set of additional constraints. Lopez *et al.* [21] employ a heuristic method based on Tabu Search and Cannibalisation to find near optimal solutions to the daily tandem mill production scheduling problem.

The daily tandem mill production scheduling model formulated by Lopez *et al.* [21] is more comprehensive than the models formulated by Kosiba *et al.* [17] and Chen *et al.* [6]. Rolling cycle scheduling is considered on a daily basis, consisting of three near optimum rolling cycles. On-time delivery of priority orders and reheat furnace efficiency scheduling objectives are incorporated into the penalty structure. The width penalty structure restricts the number of same width slabs within each rolling cycle. Furthermore, the number of slabs in a rolling cycle is limited, in order to enhance product quality, by imposing constraints on the objective function.

The following section presents the tandem mill production scheduling model formulated by Jacobs *et al.* [16]. The model formulated by Jacobs *et al.* [16] is based on the goal programming approach which varies from the model formulated by Kosiba *et al.* [17], Chen *et al.* [6] and Lopez *et al.* [21] in that the production objectives are evaluated as the sum of deviations away from a set of weighted goals and not by a penalty structure.

### 2.4.4 A GOAL PROGRAMMING MODEL FOR TANDEM MILL PRODUCTION SCHEDULING

Jacobs *et al.* [16] formulate and solve a goal programming model for scheduling the daily operation of a tandem mill. They show that the overall production efficiency can be improved through incorporating non pre-emptive goal programming into a scheduling methodology that considers inter-process inventories, product revenues and product volume requirements.



#### 2.4.4.1 The goal programming approach

According to Jacobs *et al.* [16], goal programming is a specialisation of linear programming in which the sum of deviations away from a set of weighted goals is minimised. The hierarchy of the goals is established through the use of priority factors and weighting coefficients in the objective functions. The important aspects of the problem are reflected in the structure of the goal program, which is a system of equations that reflects the objectives and constraints.

Jacobs *et al.* [16] propose that a goal programming model can be used to provide information that can aid the scheduling department in developing a production schedule for the tandem mill. The rolling cycle scheduling objectives considered by Jacobs *et al.* [16] in the formulation of the mathematical model are presented in the following paragraph.

#### 2.4.4.2 Rolling cycle scheduling objectives

Jacobs *et al.* [16] focus their research on the development of a goal program for the optimisation of production scheduling through a tandem mill with consideration of the following production scheduling objectives:

- Maximising production rate or productivity
- Maximising product quality
- Maximising revenues
- Minimising inventory

Jacobs *et al.* [16] reconcile throughput and quality maximisation by combining these goals into the single objective of optimising the total length of slabs processed during a rolling cycle. The goal programming approach varies from the models proposed by Kosiba *et al.* [17], Chen *et al.* [6] and Lopez *et al.* [21] in that the production objectives are not evaluated by a penalty structure but rather as the sum of deviations away from a set of weighted goals. These goals are based on monetary considerations and physical limitations.

Jacobs *et al.* [16] suggest the following tandem mill production scheduling goals:

- Maximise revenues: The amount of revenue required for the tandem mill to be profitable during each rolling cycle could be used to set a revenue goal for each rolling cycle.
- Minimise inventory: Inventory cost is directly proportional to the number of slabs stockpiled in the slab yard. The number of slabs required for continuous production could therefore be used to set an inventory goal.
- Physical limitations of the mill: The total quantity of steel that can be produced between work roll changes can be expressed in terms of the total length of the coils that are processed. The length of a coil is a physical characteristic of the grade, gauge, width and hardness. The goal would therefore be to achieve the target length before a roll change, as total length less than the target will increase production costs and surpassing the target in this way could compromise product quality.

The objective of the goal programming approach is to minimise the total deviation from these goals as a whole. The rolling cycle scheduling objectives presented in this section were considered by Jacobs *et al.* [16] in formulating the goal programming model for tandem mill rolling cycle scheduling presented in the following paragraph.

#### 2.4.4.3 Mathematical model for tandem mill rolling cycle scheduling

The goal programming model proposed by Jacobs *et al.* [16] to represent the rolling cycle scheduling problem is presented in this paragraph. The objective of the goal programming model is to minimise the total rolling cycle deviation from the weighted goals presented in the previous section. Initially all symbols are defined, followed by the mathematical model and the solution method proposed by Jacobs *et al.* [16].

- $n$ is the number of order-blocks being considered (An order-block is a group of slabs consistent in type and customer);
- $d_k^-$ represents the under achievement of a designated goal ($k$);
- $d_k^+$ represents the over achievement of a designated goal ($k$);
- Cost$(t)_i$ is the cost of each order-block as a function of time it remains in inventory;
- Profit$(t)_i$ is the revenue gained when a finished order block is delivered;
- Length$_i$ is the processing length of each order-block $i$;
- $W_k$ is a weighting coefficient associated with each specific goal. The weighting coefficients enforce a goal hierarchy by magnifying the deviation away from each individual goal. The weighting coefficients represent the relative importance of the goals considered in the model and are chosen by the scheduling department to reflect production objectives. Therefore, if a deviation from a specific goal is not acceptable, a relatively large weight can be assigned to the weighting coefficient in the objective function, thereby ensuring that the deviation is as small as possible.
- $x_i$ is the integer decision variable for any order-block $i$.

Like the model proposed by Kosiba *et al.* [17], the concept of order-blocks is introduced by Jacobs *et al.* [16] to assure product consistency and to reduce the size of the problem. Furthermore, the weighting coefficients represent the relative importance of the goals considered in the model. The mathematical model proposed by Jacobs *et al.* [16] to minimise the total rolling cycle deviation from weighted goals is represented by the following objective function:

$$\text{Minimise } Z = W_1 d_1^- + W_2 d_2^- + W_3 d_3^- + W_4 d_1^+ + W_5 d_2^+ + W_6 d_3^+ \quad (2.28)$$

Subject to

$$x_i = \begin{cases} 1 & \text{if and only if the order block is to be produced} \\ 0 & \text{otherwise} \end{cases} \quad (2.29)$$

$$\sum_{i=1}^{n} Cost(t)_i x_i + d_1^- - d_1^+ = \text{Inventory} \quad (2.30)$$

$$\sum_{i=1}^{n} Profit(t)_i x_i + d_2^- - d_2^+ = \text{Revenue} \quad (2.31)$$

$$\sum_{i=1}^{n} Length_i x_i + d_3^- - d_3^+ = \text{Length}_{\max} \quad (2.32)$$

$$d_k^-,\ d_k^+ \geq 0 \quad (2.33)$$

- The objective function (2.28) evaluates all the order-blocks available for scheduling from inventory in order to generate a rolling cycle schedule with minimum total deviation from the goals.
- Equation (2.30) represents the inventory goal. Inventory is a set level of inventory that is sufficient to span the delivery date of supplies. The inventory goal attempts to limit inventory for any given rolling cycle to a predetermined level.
- Equation (2.31) represents the revenue goal. Revenue is the projected revenue required to generate an acceptable profit. The revenue goal strives to achieve the projected level of revenue to be generated during any rolling cycle.
- Equation (2.32) represents the rolling cycle length goal. The processing length of an order-block is a physical characteristic of the type, gauge, width and hardness of the slabs included in the order-block. The length goal ensures that the total length of coil produced during any given rolling cycle is as close as possible to the maximum permissible length, $\text{Length}_{\max}$.

The authors [16] propose that the goal program model could be used intermittently to generate sequential rolling cycles. The problem size is reduced considerably by using the model in a discrete fashion rather than formulating a continuous model. A flow diagram that illustrates the scheduling model proposed by Jacobs *et al.* [16] is presented in figure 2.7.

Jacobs *et al.* [16] present the following solution procedure to the goal programming model:

- Select the number of rolling cycles that are to be considered as possible slots for any given set of slabs.
- Select from the current orders, with specific consideration of delivery dates; all the order-blocks that have to be produced within the number of rolling cycles selected above.

- Use time dependent functions to determine Cost($t$)$_i$ and Revenue($t$)$_i$ for each order-block being considered.
- Select the goals to be considered: inventory, revenue, and length.
- Expand the summations to account for all the order-blocks being considered. Substitute the values of Cost($t$)$_i$ and Profit($t$)$_i$ into the expanded equations. At this point all the goal equations are established.
- Select the goal hierarchy and assign weights.

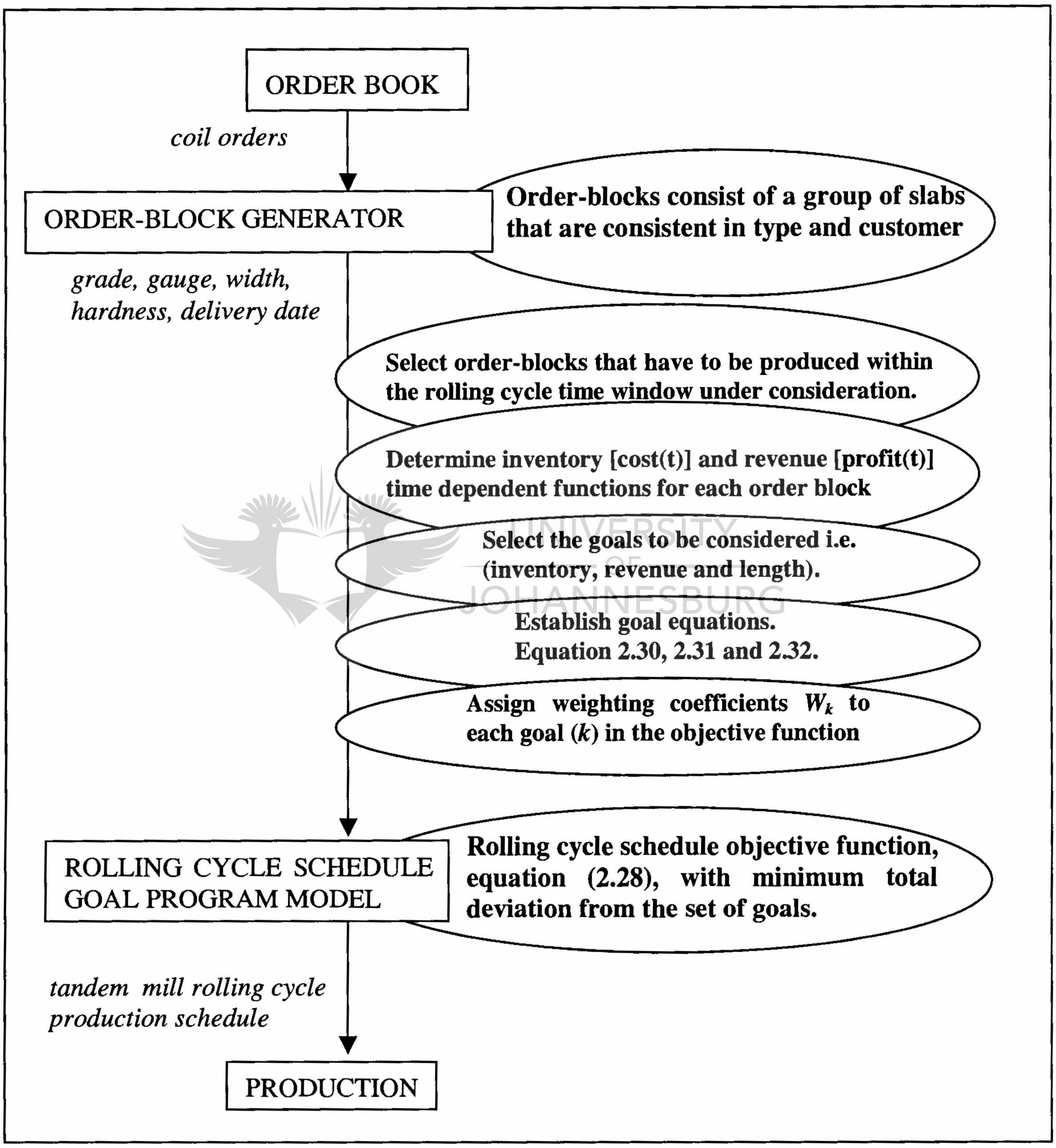



**Figure 2.7 A flow chart of the goal program model proposed by Jacobs *et al.* [16].**

According to Jacobs *et al.* [16] the key to the success of this model is the accurate development of inventory and revenue functions. A second factor is the selection of weighting coefficients for the objective function. Although these are more subjective than the inventory and revenue functions, Jacobs *et al.* [16] emphasise that the weighting coefficients are imperative to enforce the hierarchy of the goals being pursued. The computational results obtained by Jacobs *et al.* [16] are presented in the following paragraph.

#### 2.4.4.4 Computational results

The model proposed by Jacobs *et al.* [16] is evaluated using data from Bethlehem Steel Corporation's Burns Harbor plant [4]. The solution is compared to a production schedule developed by the tandem mill scheduling department at Bethlehem Steel Corporation. Using hypothetical cost and revenue functions assumed to be typical of those that exist for actual production, the model realises a 20% improvement in production revenue when compared with actual production schedules. The authors [16] highlight the sensitivity of the model to the shape and position of the cost functions and point out that much work is still required to develop a workable version of the model for industrial use.

#### 2.4.4.5 Synopsis

Jacobs *et al.* [16] formulate a non pre-emptive goal programming model for optimising production through the tandem mill. The goal programming model imitates the way that schedulers select slabs to be produced in a given production campaign. The model selects orders based on expected revenue and inventory considerations and places them in the appropriate rolling cycles within a campaign.

Jacobs *et al.* [16] reconcile throughput and quality maximisation by combining these goals into the single objective of optimising the total length of slabs processed during a rolling cycle. The goal programming approach varies from the models formulated by Kosiba *et al.* [17], Chen *et al.* [6] and Lopez *et al.* [21] in that the production objectives are not evaluated by a penalty structure but rather as the sum of deviations away from a set of weighted goals. Furthermore, the model proposed by Jacobs *et al.* [16] does not explicitly consider the order in which slabs should be sequenced within rolling cycles.

Once accurate functional relationships for inventory and revenue goals have been developed, this method can provide information that will aid the scheduling department in drawing up production schedules for the tandem mill that will improve overall production efficiency.

### 2.4.5 CONCLUSION

An overview of scheduling models developed for production scheduling in a tandem mill has been presented in this section. Several mathematical models have been presented. These models are aimed at balancing various conflicting production objectives. Kosiba *et al.* [17], Chen *et al.* [6] and Lopez *et al.* [21] adapt the standard TSP, VRPTW and PCTSP respectively to incorporate a penalty structure for evaluating rolling cycle schedules. Jacobs *et al.* [16] proposes a goal programming approach to evaluate schedules based on the objective function's deviation from set goals.

The adapted PCTSP model developed by Lopez *et al.* [16] is the most comprehensive, incorporating a broader range of production objectives than any of the other models. Due to the complexity and size of the rolling cycle scheduling problem, heuristic methods are generally used to find near optimal solutions to the problem. These solutions show significant improvement over the conventional manual rolling cycle schedules.

## 2.5 CONCLUSION

In this chapter an overview of production scheduling has been presented, highlighting the challenge of balancing various conflicting production objectives. The main part of the chapter focuses on hot strip mill production scheduling.



The hot strip mill, identified by a number of authors [16, 17] as the bottleneck to overall production in an integrated iron and steel works, faces a number of conflicting production objectives, viz.: maximising production rate, product quality, process efficiency and on time delivery. These conflicting hot strip mill production objectives have been examined and the differences between steckel mill and tandem mill production schedules have been highlighted.

Four tandem mill production scheduling models have been presented. These models which aim to reconcile the tandem mill production scheduling objectives show significant improvement over conventional manual rolling cycle scheduling. The literature survey shows that the prize collecting travelling salesman problem model proposed by Lopez *et al.* [16] is the most comprehensive tandem mill production scheduling model. This model incorporates all the primary hot strip mill production objectives.

The following chapter presents an overview of the current production scheduling practice at the flat products complex of Highveld [13].

# CHAPTER 3

## *PRODUCTION SCHEDULING AT HIGHVELD'S FLAT PRODUCTS COMPLEX*

## 3.1 INTRODUCTION

This chapter describes the current scheduling practice at the flat products complex of Highveld Steel. The chapter highlights physical plant limitations and provides an overview of the production scheduling procedure and parameters that are being used to schedule plate and coil orders at the flat products.

## 3.2 PHYSICAL PLANT PRODUCTION LIMITATIONS

This section presents physical plant limitations of the plate mill (plate production) and the steckel mill (coil production) at the flat products. In both cases product ranges are restricted by size and mass limitations of the furnaces, mills and finishing end lines.

### 3.2.1 PLATE MILL PLATE PRODUCTION

The plate mill's gauge/width ratios as well as the mass and length limitation of the hot banks are the main restrictions to plate production at the plate mill. Refer to figure 3.1 for an illustration of the plate production process flow.

Some important plate production parameters are as follows [13]:



- **Pusher furnace** **(Refer to figure 3.1 number 3)**
  Slab thickness : 180 or 250 mm
  Slab sizes : 1450 mm x 850 mm min
  : 2760 mm x 2100 mm max
  : 10.9 ton input max

- **Plate mill** **(Refer to figure 3.1 number 4)**
  Gauge : 4.5 – 160 mm
  Width : Trimmed : 1200 – 2650 mm
  : Untrimmed : 960 – 2750 mm

- **Hot banks** **(Refer to figure 3.1 number 6)**
  Plate mass : 12 ton max
  Length : 31 m max including crops

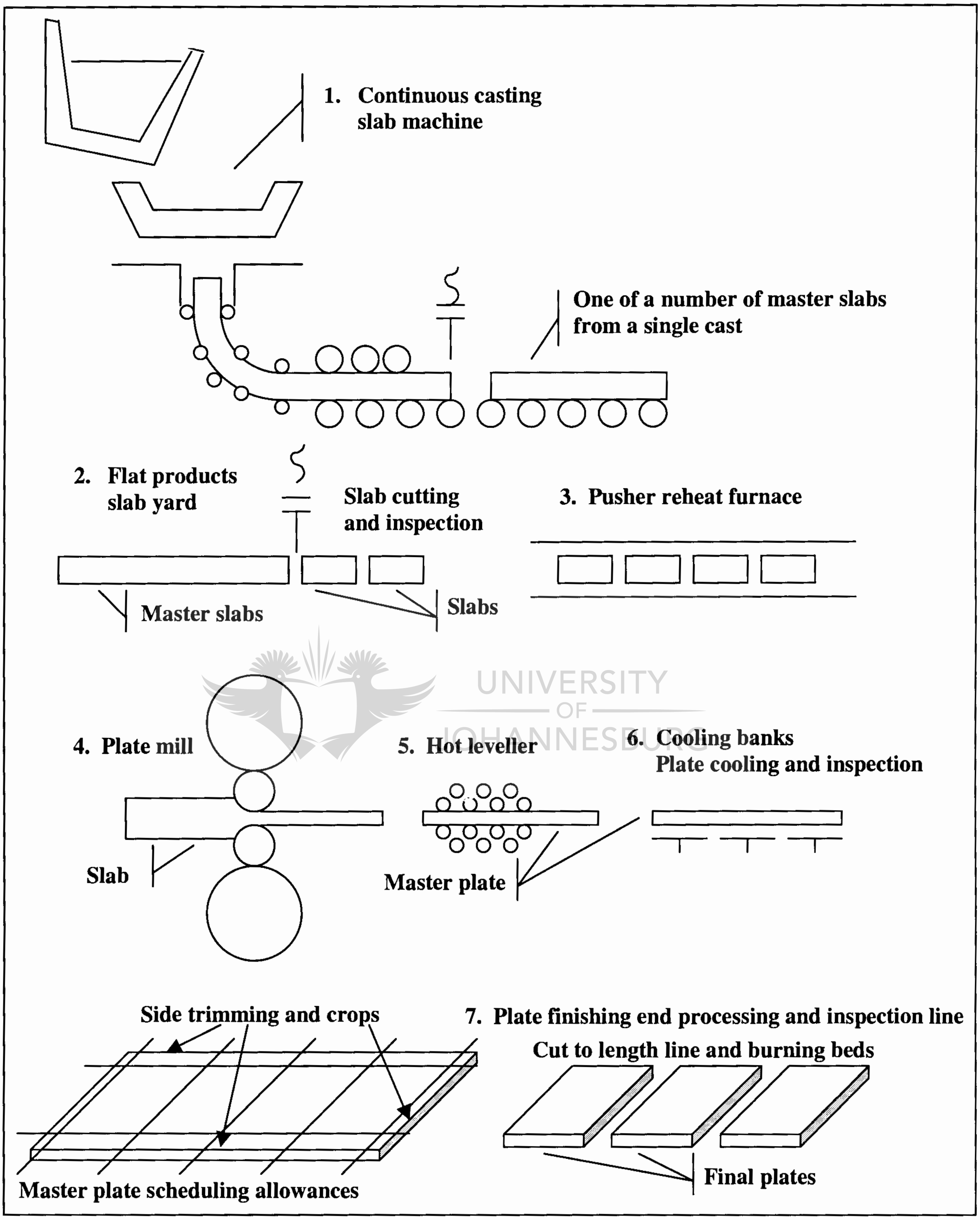



**Figure 3.1 Process flow illustration of plate production from the continuous slab caster to the plate finishing end line.**

- **Shear line** **(Refer to figure 3.1 number 7)**
  Gauge : 4.5 – 16 mm
  Width : 1200 – 2650 mm
  Length : 1.0 – 30 m

- **Burning beds**
  Gauge : 16 – 160 mm
  Width : 960 – 2750 mm
  Length : 31 m max (as restricted by hot banks)

- **Normalising furnace**
  Gauge : 12 – 160 mm
  Width : 1200 – 2650 mm
  Length : 14.5 m max

These plate production parameters are important because they limit production and product ranges. All the plates produced by the plate mill have to cool on the hot banks, therefore the maximum plate order length is restricted by the size of the hot banks. Light and medium gauge plates (gauges less than 16 mm), are processed on the shear line, and heavy gauge plates (gauges larger than 16 mm), on the burning beds.



The processing speed of the shear line that uses blades to cut the plates to the required width and length is greater than the burning beds. However, the gauges that can be processed on the shear line are limited, therefore heavy plate gauges are cut to the required size using the automated acetylene cutting torches of the burning beds.

The processing speed of the shear line is constrained by the inline automated marking machine. This results in a bottleneck at the marking machine during the production of chock bars, plates of length 1200 mm and width 2500 mm. As many as twenty-five chock bars could be cut from a single master plate. Each chock bar has to be marketed individually resulting in a bottleneck that restricts plate production though the plate mill. Processing of chock bars from coils via the de-coil line during coil production campaigns is one of the main advantages of plate via coil production.

This study aims to develop a scheduling model that will aid the flat products scheduling department to utilise the excess processing capacity of the plate finishing end, cut to length shear line, through plate via coil production, during coil production campaigns.

### 3.2.2 STECKEL MILL COIL PRODUCTION

The steckel mill's mass and gauge/width ratio constraints, as well as the length limitation of the walking beam furnace, are the main restrictions to coil production at the steckel mill. Refer to figure 3.2 for an illustration of the coil production process flow. Some important coil production parameters are as follows [13]:

- **Walking beam furnace (Refer to figure 3.2 number 3)**

  Slab thickness : 180 or 250 mm

  Slab width : 1000 – 2025 mm

  Slab length : 2200 – 10000 mm

  The walking beam furnace charging pattern limitations for 250 mm thick slabs destined for coil production are shown in table 3.1. The charging pattern limitations are introduced to improve furnace efficiency and to reduce sagging of slab ends. When processing slabs that are less than 5 m long, the slabs should be charged next to each other into the walking beam furnace to make full use of the furnace width in order to improve furnace efficiency. This is achieved through double and treble charging.

  The design of a walking beam furnace calls for slabs to be supported by a set of fixed water cooled beams and cycled through the furnace by another set of water cooled moving beams. The moving beams lift the slabs up from the fixed beams before moving forward inside the furnace and lowering them back onto the fixed beams. If a slab is charged incorrectly, the fixed beams do not adequately support the ends causing them to sag. This sagging of slab ends results in costly production delays that can be prevented by staggered and outside double charging.



**Table 3.1 Walking beam 250 mm slab charging pattern [13]**

| | Charging position: 250 mm slab thickness | | | | |
|---|---|---|---|---|---|
| Slab length (mm) | Centre | Staggered | Double | Outside double | Treble |
| 2200 – 2800 | | | | | X |
| 2800 – 3700 | | | | X | |
| 3700 – 4900 | | | X | | |
| 5200 – 6000 | X | | | | |
| 6000 – 8200 | | X | | | |
| 8200 – 10000 | X | | | | |

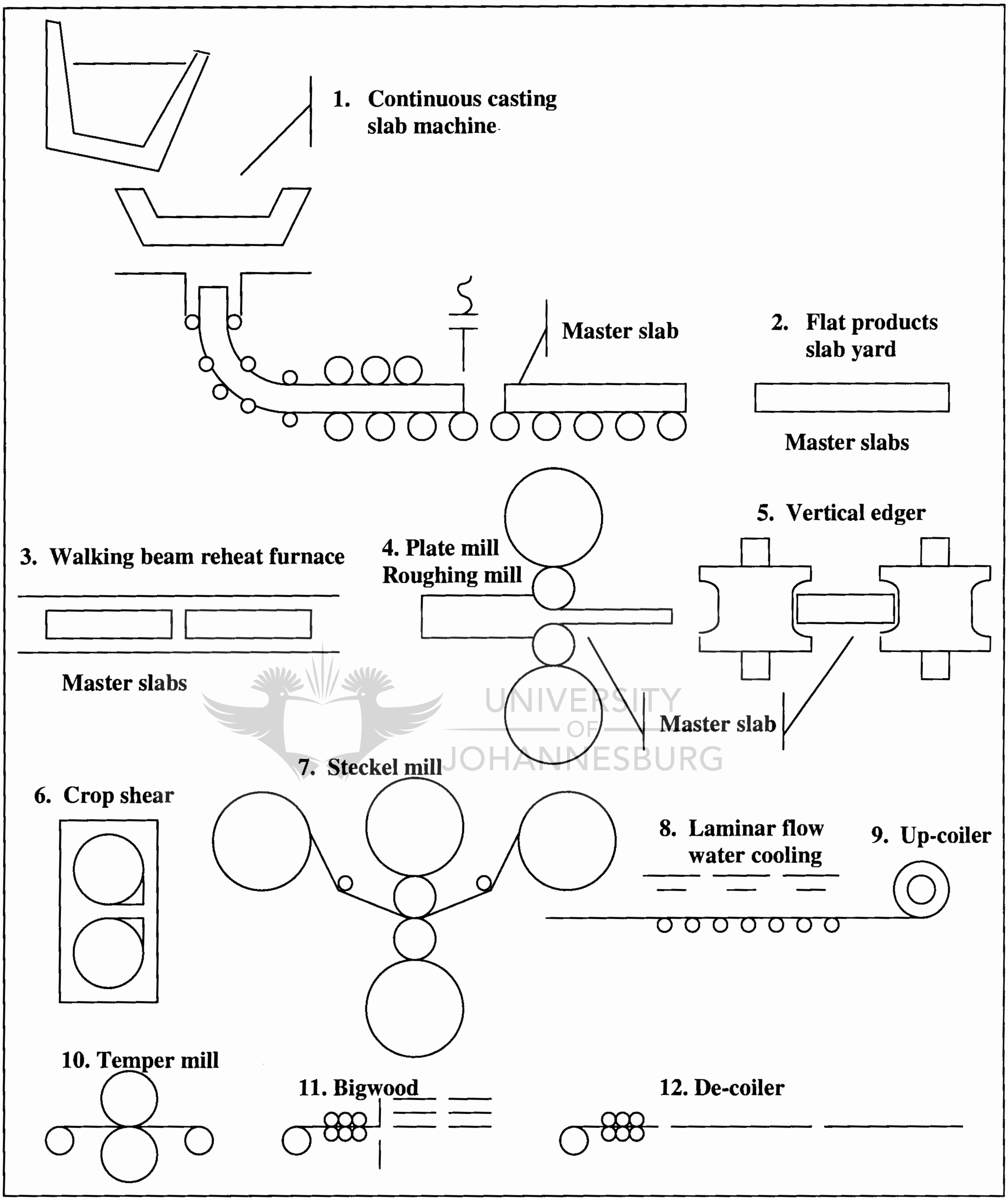
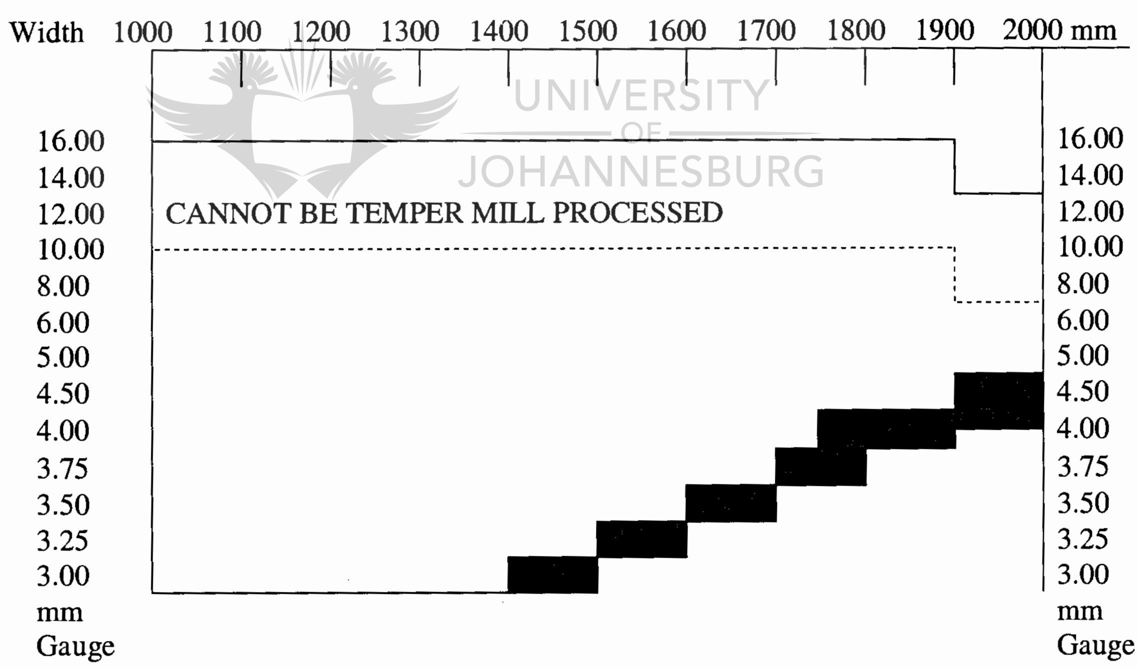



**Figure 3.2 Process flow illustration of coil and plate via coil production from the continuous slab caster to the coil finishing end line and de-coiler.**

- **Rougher mill, plate mill stand (Refer to figure 3.2 number 4)**
  Width : 1000 – 2500 mm

- **Steckel mill (Refer to figure 3.2 number 7)**
  Gauge : 2 – 16 mm
  Width : 1000 – 2050 mm (Gauge/width ratios as per figure 3.1)
  Coil mass : 30 ton max

When placing an order, figure 3.3 is typically used as a guide to determine the maximum gauge/width ratio that can be produced by the steckel mill. The maximum gauge/width ratio of a coil produced by the steckel mill can be determined by drawing a horizontal line at the required gauge until a solid vertical line is crossed; this indicates the maximum width that can be produced at that specific gauge. For example, a 3 mm gauge coiled strip can be processed to a width of 1400 mm and, if required, to a maximum width of 1500 mm, depending of the steel grade.






1.0 – 3.00 mm gauge coils can only be ordered by special arrangement

■ Difficult product that, when possible, should be avoided by ordering a different combination.

**Figure 3.3 Steckel mill production gauge/width size range [13]**

- **Temper mill** **(Refer to figure 3.2 number 10)**

  Gauge : 2 – 10 mm

  Width : 1000 – 2000 mm

- **Bigwood** **(Refer to figure 3.2 number 11)**

  Table 3.2 shows coil gauge/width size ranges than can be processed into plates of lengths ranging from 1 to 8 m through the Bigwood cut to length machine. As the width range increases, the maximum gauge that can be processed decreases due to Bigwood machinery limitations. Furthermore the minimum gauge that can be processed at increasing widths is restricted by the gauge/width ratios that can be produced by the steckel mill. For example, an order of 1800 mm wide plates can be processed via the Bigwood from a coil that is side trimmed to a width of 1800 mm as long as the ordered gauge falls within the 5 – 6 mm range and the ordered length does not exceed 8 m.

**Table 3.2 Bigwood plates cut to length via coil gauge/width size ranges [13]**

| Order width range (mm) | Gauge range (mm) | Cutting length range (mm) |
|---|---|---|
| 1000 – 1200 | 2.0 – 8 | 1000 – 8000 |
| 1201 – 1300 | 2.5 – 8 | 1000 – 8000 |
| 1301 – 1400 | 3.0 – 8 | 1000 – 8000 |
| 1401 – 1500 | 3.5 – 8 | 1000 – 8000 |
| 1501 – 1600 | 4.0 – 8 | 1000 – 8000 |
| 1601 – 1700 | 4.5 – 8 | 1000 – 8000 |
| 1701 – 1800 | 5.0 – 6 | 1000 – 8000 |
| 1801 – 2000 | 5.0 – 6 | 1000 – 8000 |



- **Sample machine**

  Gauge : 2 – 12 mm

  Width : 1000 – 2000 mm

One coil per cast of direct dispatched coils, which are not processed on the temper mill, is sent to the sample machine. All prime coils of gauge larger than 10 mm are dispatched directly to the customer without being reprocessed on the strip mill finishing end line. The sample machine is used to cut off a section of the last rap of a coil destined for direct dispatch. This coil sample is sent to the metallurgical department for analysis.

- **De-coil line** **(Refer to figure 3.2 number 12)**

  Gauge : 6 – 16 mm

  Width : 1200 – 2000 mm

  Plate orders of gauges larger than 8 mm and lengths up to 20 m for road and 24 m for rail dispatches can be processed from coil through the de-coil line. The de-coiler unwraps and levels the coil before it is processed on the plate mill shear line. High carbon grades i.e SS10/200 are too tough to be processed via the de-coiler.

Similar to plate production, the coil production parameters are important because it limits production and product ranges. The size of the walking beam furnace restricts the maximum length of slabs that can be processed into coils to 10 000 mm. Furthermore, the gauge/width ratios of the steckel mill restrict the product range that can be produced by the mill.

All coils of gauge less than 10 mm can be processed through the temper mill. During cold rolling at the temper mill coils are inspected and rectified. The Bigwood cut to length line is used primarily for recovery. During Bigwood recovery, downgraded coils of gauges up to 8 mm are processed into plates. All coil gauges larger than 8 mm can only be processed into plate via the de-coil line, which is also used primarily for recovery of plates from downgraded coils.



### 3.2.3 CONCLUSION

The physical plant limitations that have been presented in this section restrict the range of products that can be produced in the flat products complex. All customer enquiries are evaluated against these physical plant limitations to ensure that the request can be met.

Machinery and equipment upgrades as well as plant expansion projects can be motivated by evaluating customer enquiries that fall on the limit of or outside current physical plant limitations. However, most upgrades or expansion projects require large capital investment which is often difficult to justify. Therefore, increased utilisation and enhanced efficiency of existing machinery and equipment through improved production scheduling is an attractive lower cost alternative.

The steel ordering and scheduling procedure that is currently being applied at the flat products is outlined in the following section.

## 3.3 STEEL ORDERING AND SCHEDULING

This section describes the steel ordering and scheduling procedure that is currently being used by the flat products scheduling department of Highveld [13]. Firstly, the customer enquiry received by the order services department is evaluated to ensure that the request falls within the physical plant production limitations described in the previous section and, more importantly, that the delivery date can be met.

Once an enquiry is accepted, the order services department allocates a works order number to it. The order services information system (OASIS) generates a piece up card (P-Card) for each works order number. The OASIS system apply various scheduling parameters, that will be presented in section 3.4, to the order information of each works order number in order to generate P-Cards. These P-Cards are used by the flat products scheduling department to determine the steel order program for a specific month.

### 3.3.1 CUSTOMER ENQUIRIES

The steel ordering and scheduling process is initiated by a customer enquiry. Refer to figure 3.4 for an illustration of the customer enquiry evaluation process. All local and foreign customer enquiries are directed to Highveld's order services department. Enquiries for plate and coil products received by order services are forwarded to the flat products and metallurgical divisions for evaluation.



The following information regarding customer enquiries is forwarded to the flat products scheduling department and the metallurgical division for evaluation:

- Product delivery date
- Name of the customer
- Steel grade (metallurgical composition of the steel required)
- Ordered tonnage and dimensions
- Requested form of delivery, i.e. rail or road, export or local

Using this information, the flat products scheduling department determines whether the requested product falls within physical plant production limitations presented in section 3.2 and if the requested delivery date can be met. All queries regarding the steel grade are referred to the metallurgical division for investigation.

Order services allocate works order numbers to an enquiry, once the order has been evaluated and accepted. These works order numbers for plate and coil orders, accompanied by information such as the customer's name, plate and coil sizes, tonnage, steel grade and delivery date, are forwarded to the flat products scheduling department on a daily basis.

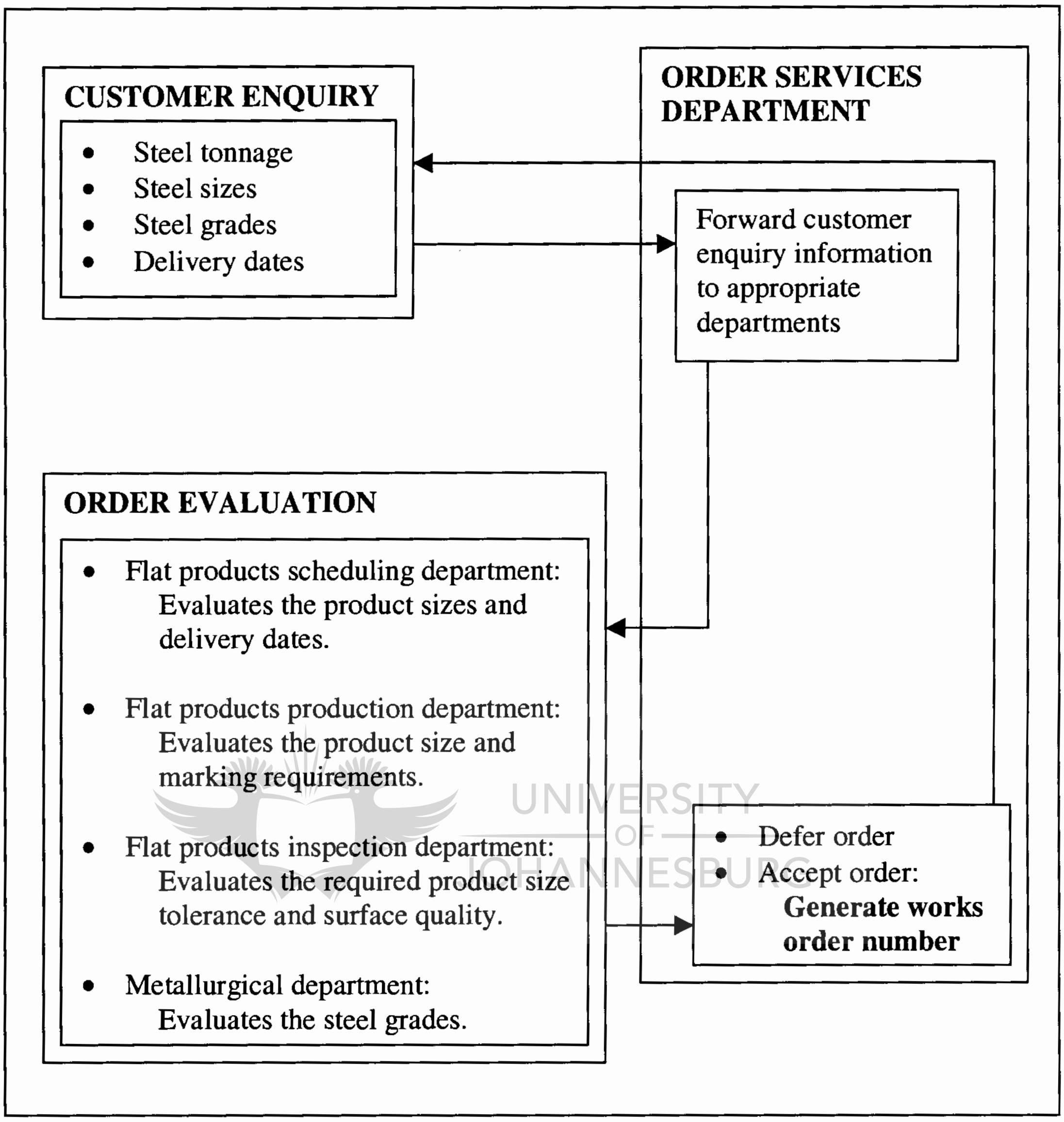



**Figure 3.4 Customer enquiry evaluation process**

The flat products scheduling department uses these works order numbers to print the P-Cards, generated for each works order by the OASIS system [13]. P-Cards, discussed in more detail in the following section, are currently being used in the manual scheduling process of all plate and coil orders at Highveld's flat products division.

**Table 3.3 Example plate order information data**

| CUSTOMER | CUSTOMER ORDER NO. | ORDER TONNAGE | FINAL PLATE SIZE | WORKS ORDER NO. | P-CARD and SLAB NO. | CUT SLAB SIZE | MASTER SLAB NO. | STEEL GRADE |
|---|---|---|---|---|---|---|---|---|
| A | A20 | 28 | 18 Plates, 1.57 ton each 3 plates/cut slab | 366/1 | | 6 Cut slabs, 5.252 ton each | | FLANGE |
| A | | | 3 off 25 X 2000 X 4000 | | 1001 | 250 X 2025 X 1330 | 7060 A | |
| A | | | 3 off 25 X 2000 X 4000 | | 1002 | 250 X 2025 X 1330 | 7060 A | |
| A | | | 3 off 25 X 2000 X 4000 | | 1003 | 250 X 2025 X 1330 | 7060 W | |
| A | | | 3 off 25 X 2000 X 4000 | | 1004 | 250 X 2025 X 1330 | 7060 W | |
| A | | | 3 off 25 X 2000 X 4000 | | 1005 | 250 X 2025 X 1330 | 7062 A | |
| A | | | 3 off 25 X 2000 X 4000 | | 1006 | 250 X 2025 X 1330 | 7062 A | |
| B | B355 | 70 | 9 Plates, 7.536 ton each 1 plate/cut slab | 620/1 | | 9 Cut slabs, 8.355 ton each | | 300WA |
| B | | | 1 off 40 X 2400 X 10000 | | 1343 | 250 X 2025 X 2090 | 7060 A | |
| B | | | 1 off 40 X 2400 X 10000 | | 1344 | 250 X 2025 X 2090 | 7060 A | |
| B | | | 1 off 40 X 2400 X 10000 | | 1345 | 250 X 2025 X 2090 | 7060 A | |
| B | | | 1 off 40 X 2400 X 10000 | | 1346 | 250 X 2025 X 2090 | 7060 W | |
| B | | | 1 off 40 X 2400 X 10000 | | 1347 | 250 X 2025 X 2090 | 7060 W | |
| B | | | 1 off 40 X 2400 X 10000 | | 1348 | 250 X 2025 X 2090 | 7060 W | |
| B | | | 1 off 40 X 2400 X 10000 | | 1349 | 250 X 2025 X 2090 | 7061 A | |
| B | | | 1 off 40 X 2400 X 10000 | | 1350 | 250 X 2025 X 2090 | 7061 A | |
| B | | | 1 off 40 X 2400 X 10000 | | 1351 | 250 X 2025 X 2090 | 7061 A | |
| B | B355 | 45 | 6 Plates, 7.348 ton each 1 plate/cut slab | 620/2 | | 6 Cut slabs, 8.213 ton each | | 300WA |
| B | | | 1 off 30 X 2400 X 13000 | | 1492 | 250 X 2025 X 2080 | 7062 A | |
| B | | | 1 off 30 X 2400 X 13000 | | 1493 | 250 X 2025 X 2080 | 7062 A | |
| B | | | 1 off 30 X 2400 X 13000 | | 1494 | 250 X 2025 X 2080 | 7062 A | |
| B | | | 1 off 30 X 2400 X 13000 | | 1495 | 250 X 2025 X 2080 | 7062 W | |
| B | | | 1 off 30 X 2400 X 13000 | | 1496 | 250 X 2025 X 2080 | 7062 W | |
| B | | | 1 off 30 X 2400 X 13000 | | 1497 | 250 X 2025 X 2080 | 7062 W | |
| C | C2341 | 22 | 14 Plates, 1.57 ton each 3 or 4 plates/cut slab | 747/1 | | 4 Cut slabs, 5.252 ton each | | 300WA |
| C | | | 3 off 25 X 2000X 4000 | | 2339 | 250 X 2025 X 1330 | 7061 A | |
| C | | | 3 off 25 X 2000X 4000 | | 2340 | 250 X 2025 X 1330 | 7061 A | |
| C | | | 4 off 25 X 2000X 4000 | | 2341 | 250 X 2025 X 1770 | 7061 W | |
| C | | | 4 off 25 X 2000X 4000 | | 2342 | 250 X 2025 X 1770 | 7061 W | |
| D | D115 | 8 | 8 Plates, 0.942 ton each 8 plates/cut slab | 703/1 | | 1 Cut slab, 8.41 ton each | | 300WA |
| D | | | 8 off 40 X 1200 X 2500 | | 0981 | 250 X 2025 X 2130 | 7061 W | |
| D | D115 | 12 | 16 Plates, 0.754 ton each 8 plates/cut slab | 703/2 | | 2 Cut slabs, 6.357 ton each | | 300WA |
| D | | | 8 off 40 X 1550 X 1550 | | 2767 | 250 X 2025 X 1610 | 7061 W | |
| D | | | 8 off 40 X 1550 X 1550 | | 2768 | 250 X 2025 X 1610 | 7061 W | |
| E | E 98 | 10 | 6 Plates, 1.57 ton each 3 plates/cut slab | 651/1 | | 2 Cut slabs, 5.252 ton each | | FLANGE |
| E | | | 3 off 25 X 2000 X 4000 | | 0887 | 250 X 2025 X 1340 | 7062 W | |
| E | | | 3 off 25 X 2000 X 4000 | | 0888 | 250 X 2025 X 1340 | 7062 W | |

### 3.3.2 THE ORDER SERVICES INFORMATION SYSTEM

The order services information system (OASIS) plays a significant role in simplifying the scheduling process by generating piece up cards (P-Cards) based on certain scheduling parameters [13]. These scheduling parameters will be presented in section 3.4. The OASIS system also covers functions such as invoicing, trading accounts, foreign exchange control and debt analysis.

P-Cards [13] contain the following important scheduling and production information:

- Works order number
- A unique slab number
- Customer's name
- Steel grade
- Master cast information, i.e. gauge, width, length and weight
- Plate or strip information, i.e. gauge, width, length, weight, required number of plates, total weight, processing week
- Production information, i.e. processing gauge, processing width, required number of final plates

The flat products scheduling department uses works order numbers to request and print all the P-Cards generated, for each works order, by the OASIS system. Each P-Card is identified by a unique slab number. This slab number is used for identification and tracking in the flat products. P-Cards that are not required for immediate delivery are filed for scheduling during future campaigns.



In order to fulfil the steel requirements of an order placed by a single customer, one or more works orders could have to be raised. Refer to customers B and D in table 3.3 for examples of more than one works order number allocated per customer order. Similarly, one or more P-Cards could be allocated to a single works order number to fulfil the works order requirements. Refer to table 3.3 where six slab numbers were allocated to works order 366/1, nine to works order 620/1 and six to works order 620/2.

There are some P-Cards that require special attention during scheduling such as piggy back orders. These are introduced in the following section.

### 3.3.3 PIGGY BACK ORDERS

Plate orders of lengths that can only be produced in conjunction with another order of a different length of same gauge and width are known as piggy back orders [13]. A piggy back order is linked to another order during scheduling by manually adjusting the P-Card of the other order to show details of the piggy back order. Once the piggy back order has been linked to another order, the P-Card of the piggy back order is discarded.

Plate via coil production scheduling, which is the focus of the scheduling model proposed in Chapter 4, is similar to scheduling of piggy back orders. In plate via coil production, a number of plate orders of matching gauge, width and steel grade can be linked to make up a single or a multiple of coils produced by the steckel mill. Currently, plate via coil scheduling is performed manually. The objective of this dissertation is to produce a scheduling model that will assist the scheduling department to assess plate via coil production more easily.

The monthly steel order program, drawn up by the flat products scheduling department, is briefly discussed in the following section. The monthly steel order tonnage of each steel grade is determined from the information contained on the P-Cards. All the plate orders that form part of the monthly plate order program have to be evaluated, using the model presented in Chapter 4, to determine the suitability of each order for plate via coil scheduling.

### 3.3.4 STEEL ORDERS

The size of the monthly steel order required by the flat products division is determined from the ordered tonnage of all the P-Cards assigned to a specific month. The total size of all the monthly steel orders is used to determine the number of casts required from continuous casting to fulfil plate and coil order production requirements during a specific month.

Once the flat products scheduling department has obtained P-Cards for all the works orders to be produced during a specific month, these P-Cards are sorted according to steel grade categories. Before any casts are ordered from the steel plant, the flat products scheduling department has to check the available slabs in stock to determine whether or not any are suitable to be scheduled into orders.

Careful consideration of steel grades allows more efficient use of the steel the plant's facilities. The metallurgical composition ranges of steel grades overlap, allowing the scheduling department to combine orders of similar steel grade. This reduces costly production delays caused by frequent changes in the steel grade of casts at the steel plant. Refer to table 3.3 where FLANGE and 300WA grade steel plate orders are produced from a single cast with two master slabs 7060A and 7060W.

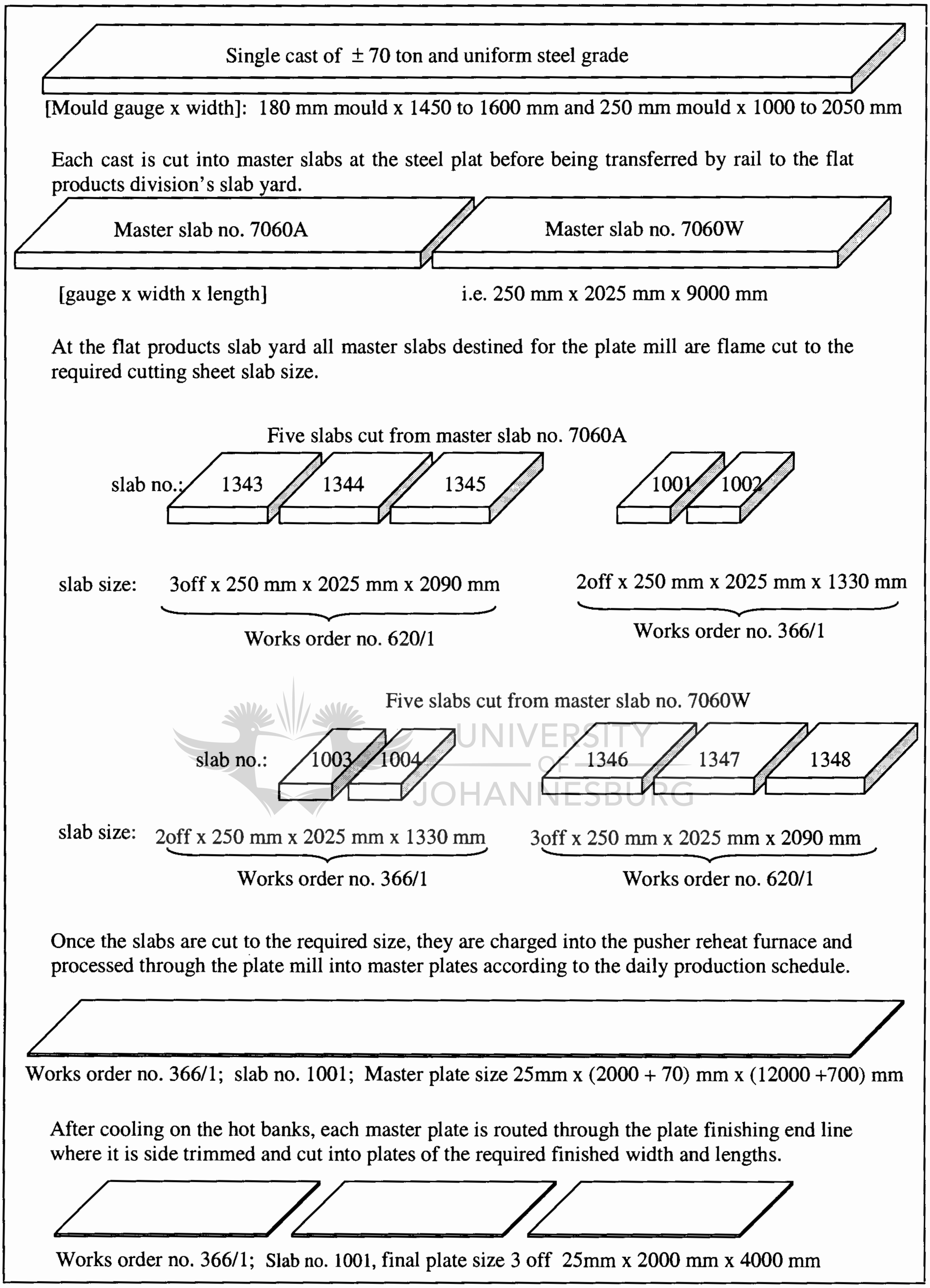



**Figure 3.5 Illustration of the plate production process flow, from the cast to final plate sizes for slab no. 1001 in table 3.3.**

The total monthly slab tonnage for each steel grade category is calculated and divided by 70 ton, the average cast tonnage, to determine the number of casts required during a specific month. Refer to table 3.3 where 7060A and 7060W (35.5 ton + 35.5 ton ≈ 70 ton) are two master slabs produced from a single 70 ton cast. Slab no. 1001, 1002, 1343, 1344 and 1345 totalling 35.5 ton are cut from master slab 7060A. Slab no. 1003, 1004, 1346, 1347 and 1348 totalling 35.5 ton are cut from master slab 7060W.

The monthly steel order program is used for medium-term production planning. However, the flat products scheduling department places daily steel orders with the steel plant to fulfil the short-term production scheduling requirements. These daily steel order programs are discussed in the following paragraph.

#### 3.3.4.1 Daily steel orders

The flat products scheduling department issues daily steel order programs to the steel plant. Due to the fact that Highveld does not produce plate or coil to stock but only to order, the number of master slabs in the slab yard are limited by short term plate or coil production demands. In general, there are enough master slabs in the slab yard, for two days worth of plate or coil production. Therefore, deviations from the daily steel order placed with the steel plant could result in undesirable changes in the rolling cycle schedule due to limited slab availability.

The flat products daily steel order program contains the following information:

- The cast number from which the new daily steel order will start.
- The required master slab lengths to be cut by the steel plant.
- The required tonnage, steel grade and size of each master slab.

The following paragraph presents an overview of the various slabs that can be cast by the slab caster at the continuous casting plant.

#### 3.3.4.2 Cast slabs

The continuous slab caster can produce master slabs for processing at the flat products complex of either 250 mm or 180 mm thick [13], as illustrated in figure 3.1, figure 3.2 and figure 3.5.

- The 180 mm mould

  The optimum size for plate production using the 180 mm mould is 1450 mm wide and it is processed into final plate gauges from 4.7 – 9.5 mm. Therefore, all 180 mm mould master slabs are cast 1450 mm wide and flame cut to the required length in the slab yard. By taking into consideration that the average cast weight from the slab caster is 70 ton, a number of four master slabs at a length of 8600 mm totalling 70 ton are usually ordered to reduce cast mixing.

- The 250 mm mould

  Slab widths from 1000 – 2050 mm can be cast in the 250 mm mould. The optimum size for plate production using the 250 mm mould is 2025 mm wide and it is processed into finished plate gauges from 10 – 160 mm. Therefore, all 250 mm mould master slabs destined for plate production are cast 2025 mm wide and cut to the required length in the slab yard. Refer to table 3.3 where the final plate gauges are all larger than 10 mm. Therefore, all these orders are processed from 250 mm mould casts and the master slabs are all 2025 mm wide, as illustrated in figure 3.5.

  Due to the 70 ton average cast weight, two master slabs are usually ordered at a length of 9000 mm. Refer to table 3.3 and figure 3.5 where the total length of the slabs cut from master slab 7060A is (2 x 1330 mm) + (3 x 2090 mm) + (4 x 20 mm slab cutting allowance) ≈ 9000 mm

  The 250 mm slab caster also provides all the steckel mill slabs. These slab sizes are usually 25 mm wider than the ordered coil width and the length is determined from coil weight required by the customers. The slab caster at the continuous casting plant casts slabs in either the wide mould (1601 mm – 2050 mm) or narrow mould (1150 mm – 1600 mm) width ranges.

  The vertical edger, positioned between the plate mill and steckel mill, is used to deform the slab to achieve the required ordered width before the slab is transferred to the steckel mill for final hot processing. Refer to figure 3.2 number 5 for an illustration of the vertical edger. Therefore, various coil orders of similar but not necessarily identical widths can be produced from the same cast. This reduces set-up time at the continuous caster, thereby improving overall plant efficiency.

All casts are cut to the required master slab length at the continuous casting plant before being transferred to the flat products slab yard by rail. Plate and coil master slabs are discussed in the following two paragraphs.

#### 3.3.4.3 Plate master slabs

Master slabs that were ordered for plate production are inspected in the flat products slab yard before being cut into slabs, as illustrated in figure 3.1 and 3.5. Slabs are numbered according to slab cutting sheets issued by the flat products scheduling department. The scheduling department allocates one or more P-Cards/slabs to a single master slab of desired steel grade and size. Once the slabs have been cut to the required size, they are ready to the charged into the pusher furnace according to the daily plate mill production schedule. Master slabs ordered for coil production are discussed in the following paragraph.

#### 3.3.4.4 Coil master slabs

Master slabs that have been ordered for coil production on the steckel mill are cut to the required length at continuous casting before being transported to the flat products, as illustrated in figure 3.2. These master slabs are inspected, numbered and left to cool in the flat products slab yard.

### 3.3.5 CONCLUSION

Many checks and balances have been built into the steel ordering procedure to ensure that customer requirements are met and that the progress of works orders is adequately monitored. The OASIS system eases the scheduling process by processing works orders into P-Cards that are used by the flat products scheduling department to establish monthly steel requirements and schedule rolling cycles. P-Cards are generated from works orders based on various scheduling parameters that are presented in the following section.

## 3.4 SCHEDULING PARAMETERS



In this section the scheduling parameters used by the OASIS system to generate P-Cards are presented [13]. Order allocation is divided into two categories:

- Flat mode (plate), illustrated in figure 3.1
- Coil mode (plate and strip), illustrated in figure 3.2

The flat mode scheduling parameters for plate orders processed through the plate mill are presented in the following section. The OASIS plate order mass calculations and accompanying scheduling allowances are presented for the three plate gauge ranges.

### 3.4.1 FLAT MODE SCHEDULING PARAMETERS

Flat mode orders are those plate orders that are produced by the plate mill and its finishing end shear line or flame cutting beds. Refer to figure 3.1 for an illustration of flat mode production flow and side trimming and crop scheduling allowances. Flat mode scheduling parameters include slab and master plate mass calculations based on scheduling allowances for gauge, width, and length. Once plate orders have been grouped according to plate sizes, these master plates can be scheduled into a flat mode plate rolling cycle as shown in section 3.5.1.

#### 3.4.1.1 Flat mode definitions

Flat mode plate orders are allocated to one of the following gauge related groups [13]:

- 4.5 – 7.9 mm : Light plate
- 8 – 16 mm : Medium plate
- 16.1 – 160 mm : Heavy plate

All plate orders processed through the plate mill are allocated to the applicable gauge group by the OASIS system. The following paragraph presents the master plate and slab mass calculations based on gauge related allowances.

#### 3.4.1.2 Flat mode plate mass calculations

In this paragraph the equations used by the OASIS system to determine slab and master plate sizes are shown. The final plate size and mass, as per customer order, are converted to the size and mass of the master plate and slab.

A master slab produced by the continuous slab caster for plate production is cut into a number of slabs in the flat products slab yard. These slabs are charged into the pusher reheat furnace according to the daily plate mill production schedule. After reaching the required processing temperature, a slab is pushed out of the furnace and processed to the required master plate size by the plate mill. Finally the master plate is side trimmed and cut to the required final plate size as per customer order on the plate finishing end line. Refer to figure 3.1 for an illustration of the processing of slabs from the master slab to the final plate.



The size and mass of a master plate is determined by adding various scheduling allowances, presented in the following section and illustrated in figure 3.6, to the customer ordered final plate size. All slabs required to produce plates of ordered gauges 4.7 mm – 9.5 mm are cut to the required length from 180 mm x 1450 mm master slabs [13]. Similarly, all slabs required to produce plates of ordered gauges from 10 mm to 160 mm are cut to the required length from 250 mm x 2025 mm thick and wide master slabs [13]. The length of a slab is derived from calculating the mass of the master plate to be produced from the slab.

The mass of each master plate is calculated by the OASIS system and shown on individual P-Cards. These are combined by the scheduling department to determine the monthly master slab order tonnage required for plate production.

The OASIS system performs plate order mass calculations based on the following equations [13]:

- Final plate mass as ordered by a customer =
  (final plate length)(final plate width)(final plate gauge)(7.85) (3.1)

- Master plate mass =
  (final plate length + crop allowance [*table 3.7*])(final plate width + side trim allowance [*table 3.5*])(final plate gauge)(gauge related factor [*table 3.4*])(7.8) (3.2)

- Slab mass =
  (slab length)(slab width)(slab gauge)(7.8) (3.3)

  (slab width)(slab gauge) =
  [*1450 mm x 180 mm (for ordered gauge 4.7 – 9.5 mm)*] (3.3 a)
  [*2050 mm x 250 mm (for ordered gauge 10 – 160 mm)*] (3.3 b)

The following example illustrates how the equations shown above are utilised in determining the required master plate and slab mass.

**Example 3.1 Scheduled plate and slab mass calculation**

Refer to table 3.3 for final plate size and slab size of slab no. 1001.
Refer to table 3.7 for crop allowance
Refer to table 3.5 for side trim allowance
Refer to table 3.4 for gauge allowance



W/O no. 620/1 slab no. 1001

- Final plate size as per customer order :
  3 off 4.000 m x 2.000 m x 0.025 m (3.4)

- Final plate mass as per customer order :
  3 x 4.000 x 2.000 x 0.025 x 7.85 = 3 x 1.57 ton (3.5)

- Master plate mass :
  (3)(4.000+0.700+0.020)(2.000+0.070)(0.025)(1.020)(7.8) = 5.24 ton (3.6)

- Slab length :
  5.24 ton /(2.025 m x 0.250 m x 7.8) = 1.33 m (3.7)

- Slab mass ≈ master plate mass :
  1.33 x 2.025 x 0.250 x 7.8 = 5.25 ton ≈ 5.24 ton (3.8)

In this example the scheduling allowances used by the OASIS system for determining slab sizes of plate orders have been illustrated. The following paragraph presents the flat mode plate scheduling allowances that apply to all plate orders processed via the plate mill and plate finishing end production lines.

#### 3.4.1.3 Flat mode plate scheduling allowances

Allowances for gauge, width, length and crop overages as well as cut slab size limitations are incorporated into the OASIS system for determining flat mode slab and master plate sizes. Refer to figure 3.6 for an illustration of master plate width and length overages that result in the required final plate size after processing on the finishing end line. Flat mode plate size overages and size limitations are given below [13]. These overages ensure that the final plate sizes are as per customer order requirements and within tolerance.

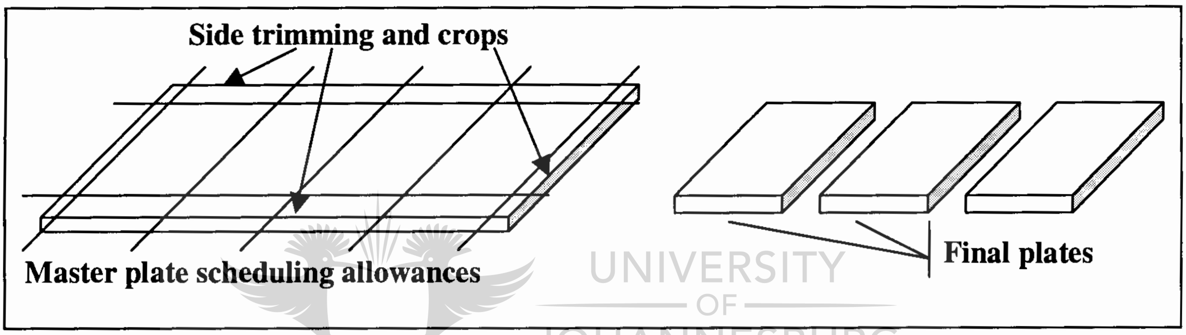





**Figure 3.6 Illustration of flat mode plate scheduling allowances**

- **Gauge** 4.5 – 160 mm
  Gauge related factors shown in table 3.4 compensate for production yield losses which increase as the gauge decreases.

**Table 3.4 Flat mode master plate gauge allowances [13]**

| | Gauges in mm | | | |
|---|---|---|---|---|
| | 4.5 – 11.9 | 12 – 13.9 | 14 – 17.9 | 18 and up |
| Gauge related factor | 1.050 | 1.040 | 1.035 | 1.020 |

- **Width** Trimmed : 1250 – 2650 mm
  Untrimmed : 960 – 2750 mm
  Plates that have to conform to narrow width tolerances are given side trim allowances for the shear line and burning beds. Refer to table 3.5 for master plate width allowances that have to be added to ordered width.

**Table 3.5 Flat mode master plate width allowances [13]**

| Gauge | Standard allowance | Allowance for splits that are added to twice the ordered width | |
|---|---|---|---|
| | | Shear line | Burning beds |
| 4.5 – 16 mm | 100 mm | No splits from 4.5 – 16 mm gauges | |
| 16.1 – 39.9 mm | 70 mm | 80 mm | 90 mm |
| 40 – 60 mm | 80 mm | 90 mm | 100 mm |
| 60.1 – 119.9 mm | 90 mm | 100 mm | 110 mm |
| 120 – 160 mm | 100 mm | 110 mm | 120 mm |

- **Length**

  Table 3.6 is a guide to width/gauge/length limits during master plate production. Light gauges are more difficult to produce than medium and heavy gauges.

  Plate production consists of two phases. During the first phase a slab is formed in one direction until the required width is achieved. The master plate is then rotated 90° and during the second phase it is formed to achieve the required gauge with little change in width. Due to this procedure, the production time of light gauge master plates is much longer than medium and heavy gauge master plates. The longer the processing time the more heat is lost and, at these lower processing temperatures, product quality suffers due to higher loads in the mill.

**Table 3.6 Flat mode master plate length allowances [13]**

| Ordered width in mm | Gauges in mm | | | |
|---|---|---|---|---|
| | 4.5 – 5.7 | 5.8 – 6.4 | 6.5 – 7.9 | 8 and up |
| 1250 – 1850 | 28 m | 28 m | 28 m | 30 m (to slab |
| 1851 – 2250 | 24 m | 26.6 m | 28 m | 30 m mass / |
| 2251 – 2500 | 21 m | 24.4 m | 26 m | 30 m length |
| 2501 – 2650 | 18 m | 20 m | 20 m | 20 m limits) |

The length allowance for cutting off the head and tail of the master plate after processing is referred to as the crop length allowance. Refer to table 3.7 for crop length allowances that have to be added to the ordered length. Due to fishtails, the head and tail of the master plate frequently falls outside of the customer specifications and therefore have to be cut off.

**Table 3.7 Flat mode master plate crop length allowances [13]**

| | Gauges in mm | | |
|---|---|---|---|
| | 4.5 – 16 | 16 – 39.9 | 40 – 160 |
| Crop allowance | 1000 mm | 700 mm | 400 mm |

- **Plate slab sizes** : 1450 X 850 min
  : 2760 X 2100 max
  : Standard rounding off to the nearest cm is used
  : A 20 mm slab cutting allowance is given
  : A +30 mm –10 mm master slab optimisation allowance is used as required.

The flat mode plate scheduling allowances for gauge, width, length and crop overages presented in this paragraph have been incorporated into the OASIS system. The OASIS system utilises these allowances to determine the slab and master plate sizes that are required to produce the plate sizes ordered by a customer. The flat products scheduling department allocates slabs, represented by P-Cards, of equal gauge and width to master slabs as discussed in section 3.3.

The coil mode scheduling parameters for coil orders processed through the steckel mill are presented in the following section. The coil order mass calculations and accompanying scheduling allowances are presented.



### 3.4.2 COIL MODE SCHEDULING PARAMETERS

Coil mode orders are coiled strip and plate orders that are processed via the steckel mill with the plate mill functioning as a roughing mill. Refer to figure 3.2 for an illustration of the coil mode production flow. As with plate mode scheduling, coil mode scheduling parameters include slab mass calculations as well as allowances for gauge, tonnage and width [13]. Once coil orders have been grouped according to width and grade, these coils can be scheduled into a coil mode rolling cycle as shown in section 3.5.2.

#### 3.4.2.1 Coil mode definitions

Coil orders are allocated to one of the following gauge related groups [13]:

- 2 – 4.5 mm : Coiled strip
- 4.6 – 16 mm : Coiled plate

All coil orders processed though the steckel mill are allocated to the applicable gauge group by the OASIS system. The following paragraph presents the coil order mass calculation.

#### 3.4.2.2 Coil mode mass calculations

Coil mass is optimised to suit the walking beam furnace, steckel mill, and temper mill requirements within the tolerance specified by the customer.

A crop and scale allowance of 3% is added to the furnace charging mass of all slabs destined for coil production [13]. The head and tail of all the slabs are cropped at the flying crop shear during transfer from the plate mill to the steckel mill. Iron oxide scale forms on the slabs when they are reheated in the walking beam furnace as well during processing when the steckel furnaces on either side of the mill stand heat up the coil. The de-scale system, a high-pressure water system, is used to remove the scale from the coil during processing. Refer to figure 3.2 for an illustration of the processing of slabs from the slab caster to the coil finishing end production line.

The mass of scheduled coil orders are calculated by the OASIS system and shown on individual P-Cards. These are combined by the scheduling department to determine the monthly master slab order tonnage required for coil production. The OASIS system performs coil order mass calculations based on the following equations [13]:



- Number of coils required to fill local order tonnage =
  (coil ordered tonnage + additional overage slabs [*table 3.9*])(yield factor [*table 3.8*])(1.03 [*crop and scale allowance*])/slab size [*customer ordered coil weight*] (3.9)

Export order tonnage overages are determined from the customer's prescribed minimum and maximum order tonnage as presented in the customer quality plan. The maximum order tonnage in the quality plan is used in calculating the number of coils required by using equation (3.10)

- Number of coils required to fill export order tonnage =
  (maximum coil ordered tonnage)(yield factor [*table 3.8*])(1.03 [*crop and scale allowance*])/slab size [*customer ordered coil weight*] (3.10)

The following paragraph presents the coil mode plate scheduling allowances that apply to all coil orders processed via the steckel mill and coil finishing end lines.

#### 3.4.2.3 Coil mode scheduling allowances

Allowances for gauge, width, length and crop overages as well as slab size limitations are incorporated into the OASIS system when coil mode slab sizes are determined. Coil mode overages and slab size limitations are given below [13]. These overages ensure that the final coil sizes are as per customer order requirements and within tolerance.

- **Gauge**

  Gauge related factors compensate for production yield losses, which increase as the gauge decreases.

**Table 3.8 Coil mode gauge yield factor allowances [13]**

| | Gauges in mm | | | | |
|---|---|---|---|---|---|
| | 2 – 2.99 | 3 – 4.5 | 4.51 – 6 | 6.1 – 8 | 8 and up |
| Yield factor | 1.07 | 1.06 | 1.05 | 1.04 | 1.035 |

- **Order tonnage overages**

  Coil order tonnage overages built into the OASIS system aim to ensure that the customer ordered tonnage will be fulfilled. Refer to table 3.9 for coil order tonnage overages. All customer orders specify maximum and minimum coil tonnage to be delivered. The order tonnage overages aim to ensure that a customer order will be filled without having to reorder steel from the steel plant and reschedule an order tonnage shortfall during a coil production campaign.

  However, production difficulties could occur that require the production of a number of additional coils in excess of the order tonnage overage. These additional coils for which steel have to be reordered near the end of a specific coil production campaign, in order to reach the minimum customer order coil tonnage, are referred to as coil droppings. Order tonnage overages have been devised to reduce costly production losses, such as continuous caster set-up time, caused by droppings, which could include a wide range of product sizes and steel grades.

**Table 3.9 Coil mode local order tonnage overages [13]**

| Ordered tonnage | Additional overage |
|---|---|
| 0 – 40 | 0 x ordered coil mass |
| 40 – 400 | 1 x ordered coil mass |
| Above 500 | 2 x ordered coil mass |

- **Width** 1000 – 2050 mm
  Slab sizes are usually 25 mm wider than the ordered coil width in order for the vertical edger to achieve the required coil width during roughing mill passes. Refer to table 3.10 for slab width allowances. The edger reduces the slab width through two vertical rolls that exert a horizontal force perpendicular to the processing direction. Edging is performed during subsequent roughing mill passes on slabs of thickness from 250 mm to 100 mm.

  In some cases the slab width could be 50 mm greater than the ordered width. This is done to either achieve increased uniformity of cast widths or to reduce the "necking" problem experienced when producing 1200 &1225 mm wide coil orders. Figure 3.7 illustrates the necking phenomena.

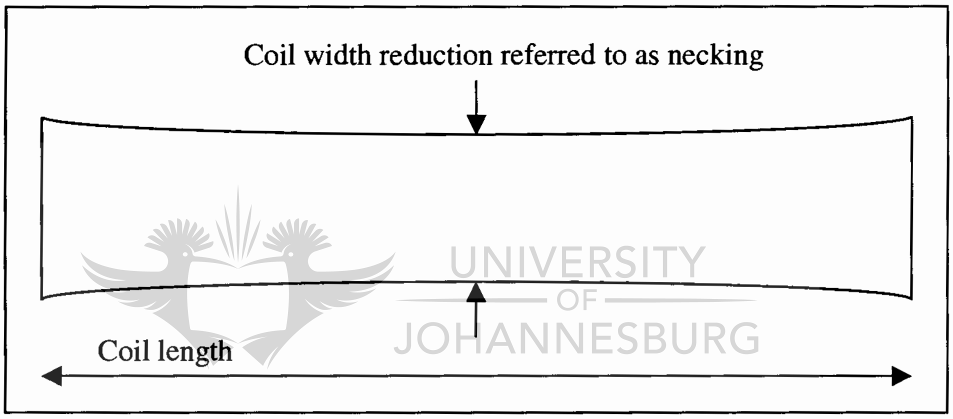



**Figure 3.7 Necking**

**Table 3.10 Coil mode slab width allowances [13]**

| | Ordered width in mm | | |
|---|---|---|---|
| | 1000 – 1249 | 1250 – 2000 | 2000 and up |
| Standard slab size | 50 mm overage | 25 mm overage | 0 mm |

Table 3.11 presents the side trim allowances that have to be added to the ordered slab width for coil orders destined for Bigwood and de-coil line processing.

**Table 3.11 Coil mode slab width side trim allowances [13]**

| | |
|---|---|
| De-coil | 100 mm |
| Bigwood | 50 mm |

The coil mode slab width calculation performed by the OASIS system is based on the following equation [13]:

- Slab width = (ordered coil width + additional width overage [*table 3.10*] + side trim allowance(if required) [*table 3.11*]) (3.11)

The coil mode scheduling allowances for gauge, tonnage and width overages presented in this paragraph are incorporated into the OASIS system. The OASIS system utilises these allowances to determine the slab widths and the number of slabs required to satisfy a customer order.

### 3.4.3 CONCLUSION

The flat and coil mode scheduling allowances that are incorporated into the OASIS system have been presented in this section. The OASIS system utilises these allowances to determine slab sizes required to fulfil customer orders. As discussed in section 3.3, the flat products scheduling department uses P-Cards that represent slabs generated by the OASIS system to determine plate and coil steel requirements.

During a production campaign slabs are scheduled into rolling cycles according to the plate and coil rolling cycle scheduling guidelines presented in the following section. These guidelines are used by the flat products scheduling department to manually generate flat and coil mode rolling cycle schedules.



## 3.5 ROLLING CYCLE SCHEDULING GUIDELINES

This section presents the rolling cycle scheduling guidelines used by the flat products scheduling departments. These scheduling guidelines are rules of thumb developed over many years from practical plate and coil production experience. The flat mode plate rolling cycle scheduling guidelines presented first apply to each plate mill rolling cycle during a plate campaign. The coil mode rolling cycle scheduling guidelines presented last apply to steckel mill rolling cycles.

### 3.5.1 FLAT MODE PLATE ROLLING CYCLE SCHEDULING

A plate rolling cycle is made up of a large number of slabs that are processed between work roll changes. The rolling cycle is generated manually by the flat products scheduling department and sequenced according to the basic guidelines presented in table 3.12, figure 3.8 and figure 3.9.

**Table 3.12 Flat mode plate rolling cycle scheduling guidelines [13]**

| Suggested tonnage | Width constraints (Plate widths) | Gauge |
|---|---|---|
| 200 ton average | Intermediate heavies (1500 – 2100 mm) | Above 16 mm |
| 150 ton average | Wide mediums (2400 – 2600 mm) | 8 – 16 mm |
| 450 ton maximum | Wide lights (2400 – 2600 mm) | Below 8 mm |
| 150 ton maximum | Wide mediums (2400 – 2600 mm) | 8 – 16 mm |
| 300 ton maximum | Wide heavies (2400 – 2600 mm) | Above 16 mm |
| 300 ton maximum | Average width mediums (1800 – 2400 mm) | 8 – 16 mm |
| 150 ton maximum | Intermediate lights (1800 – 2100 mm) | Below 8 mm |
| 300 ton maximum | Average width heavies (1800 – 2400 mm) | Above 16 mm |
| 300 ton maximum | Narrow mediums (1400 – 1800 mm) | 8 – 16 mm |
| 150 ton maximum | Narrow lights (1400 – 1800 mm) | Below 8 mm |
| 300 ton maximum | Narrow width heavies (1400 – 1800 mm) | Above 16 mm |

Total lights (gauge 4.5 – 7.9 mm) : 750 ton
Total mediums (gauge 8 – 16 mm) : 900 ton
Total heavies (gauge 16.1 – 160 mm) : 1100 ton
Total rolling cycle : 2750 ton

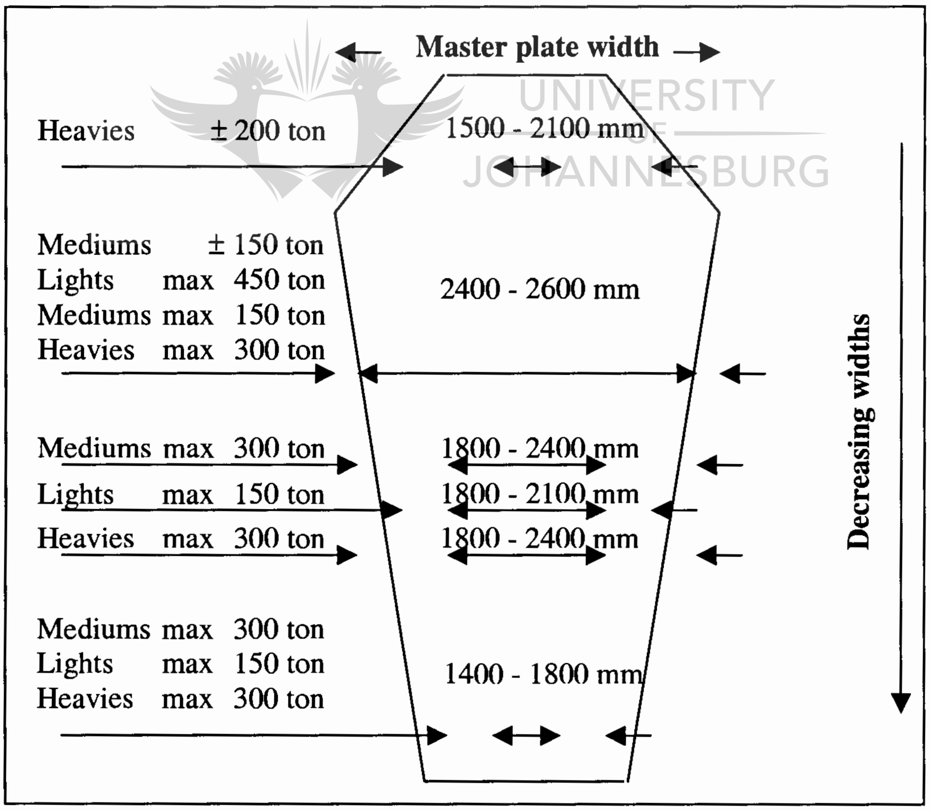




**Figure 3.8 Coffin shape width profile and tonnage guidelines for flat mode plate rolling cycle scheduling [13]**

The plate mill rolling cycle schedule is based on the coffin shape width profile presented in figure 3.8. The plate rolling cycle coffin shape width profile is similar to the tandem mill rolling cycle coffin shape width profile presented in paragraph 2.3.1.2. The plate mill rolling cycle starts with a wide-out phase consisting of heavy plates of gauge between 16.1 mm to 160 mm. After the wide-out phase, the window exists for processing wide light plates of gauge between 4.5 mm to 7.9 mm. During the coming-down phase, gradual decreasing of width is required due to work roll wear.

During a rolling cycle, slabs are grouped together in equal width groups and gauge jumps are incremental. This facilitates mill operation, resulting in improved quality and gauge consistency. Refer to figure 3.9 for an illustration of the incremental jumps in final plate gauges of sequentially scheduled gauge groups within uniform width groups. The plate mill utilises electro mechanical screws to adjust the roll gap. There is no automatic gauge control as is the case at the steckel mill that uses position feedback and hydraulic capsules to perform instantaneous roll gap adjustments. The mill operator depends on physical measurement of the final gauge of each plate to make small corrections to the roll gap for the next plate.

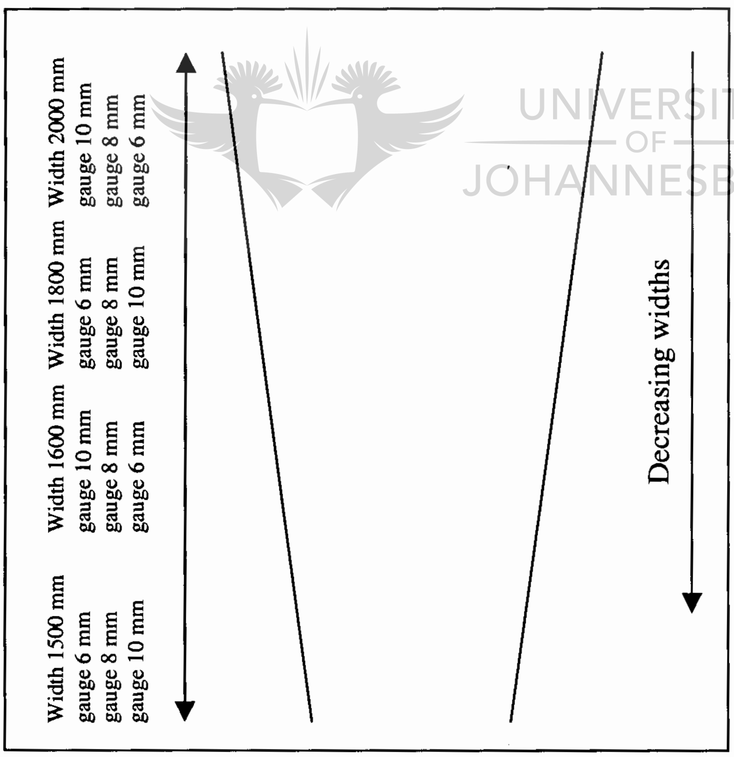



**Figure 3.9 Incremental gauge changes, up or down, of sequentially scheduled homogeneous gauge and width groups within a plate mill rolling cycle.**

The flat mode rolling cycle scheduling guidelines used by the flat products scheduling departments to manually generate plate mill rolling cycle schedules have been presented in this paragraph. The following paragraph presents the coil mode rolling cycle scheduling guidelines.

### 3.5.2 COIL MODE ROLLING CYCLE SCHEDULING

A coil mode schedule comprises a number of rolling cycles arranged so as to maximise the steckel mill's backup roll life, as shown in figure 3.10 [13]. The rolling cycles form a coffin shape width profile over the duration of the production campaign between backup roll changes which consists of a wide-out and coming-down phase.

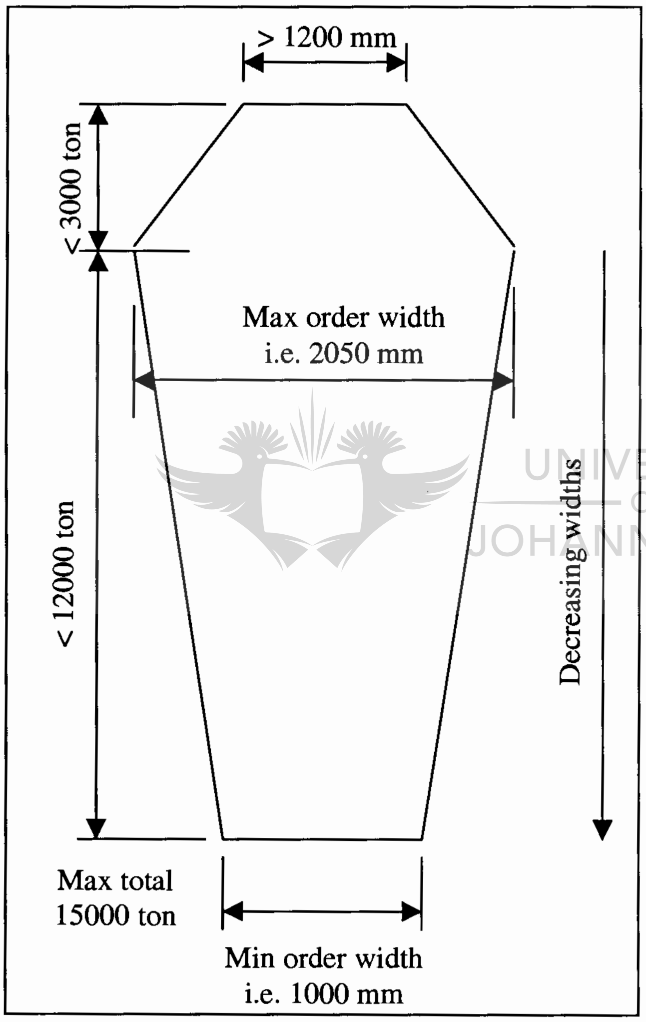



**Figure 3.10 Coffin shape coil scheduling framework between backup roll changes**

**Table 3.13 Roll wear meterage for 10 ton slabs [13]**

| Gauge (mm) | 1000 1050 | 1050 1100 | 1100 1150 | 1150 1200 | 1200 1250 | 1250 1300 | 1300 1350 | 1350 1400 | 1400 1450 | 1450 1500 | 1500 1550 | 1550 1600 | 1600 1650 | 1650 1700 | 1700 1750 | 1750 1800 | 1800 1850 | 1850 1900 | 1900 1950 | 1950 2000 | 2000 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.00 | 2374 | 2263 | 2163 | 2071 | 1986 | 1908 | 1836 | | | | | | | | | | | | | | |
| 2.20 | 2175 | 2074 | 1982 | 1897 | 1820 | 1748 | 1682 | | | | | | | | | | | | | | |
| 2.50 | 1889 | 1801 | 1721 | 1648 | 1581 | 1519 | 1461 | 1380 | 1332 | 1287 | 1245 | 1205 | | | | | | | | | |
| 2.70 | 1815 | 1730 | 1653 | 1583 | 1518 | 1459 | 1404 | 1353 | 1305 | 1261 | 1220 | 1181 | | | | | | | | | |
| 2.80 | 1690 | 1612 | 1540 | 1474 | 1414 | 1395 | 1308 | 1260 | 1216 | 1175 | 1136 | 1100 | | | | | | | | | |
| 3.00 | 1554 | 1481 | 1415 | 1355 | 1300 | 1249 | 1202 | 177 | 1135 | 1097 | 1061 | 1027 | 1043 | 1012 | 982 | 955 | 928 | 904 | 880 | | |
| 3.25 | 1442 | 1375 | 1314 | 1258 | 1206 | 1159 | 1115 | 1140 | 1100 | 1062 | 1027 | 995 | | | | | | | | | |
| 3.50 | 1367 | 1304 | 1246 | 1193 | 1144 | 1099 | 1058 | 1028 | 992 | 959 | 927 | 898 | 870 | 844 | 820 | 797 | 775 | 754 | 735 | | |
| 3.80 | | | | | | | | 936 | 903 | 872 | 844 | 817 | 831 | 806 | 783 | 761 | 740 | 720 | 701 | | |
| 4.00 | 1255 | 1197 | 1144 | 1095 | 1050 | 1009 | 971 | 899 | 867 | 838 | 810 | 785 | 776 | 753 | 731 | 711 | 691 | 673 | 655 | | |
| 4.10 | | | | | | | | 880 | 849 | 820 | 794 | 768 | | | | | | | | | |
| 4.20 | 845 | 806 | 770 | 737 | 707 | 679 | 654 | | | | | | 737 | 715 | 694 | 675 | 656 | 639 | 622 | | |
| 4.50 | 795 | 758 | 725 | 694 | 666 | 639 | 615 | 825 | 796 | 769 | 743 | 720 | 698 | 677 | 657 | 639 | 621 | 605 | 589 | 606 | 591 |
| 4.70 | 771 | 735 | 702 | 672 | 645 | 619 | 596 | 815 | 787 | 760 | 735 | 712 | 690 | 669 | 650 | 632 | 614 | 598 | 582 | 593 | 579 |
| 5.00 | 733 | 699 | 668 | 640 | 614 | 589 | 567 | 723 | 697 | 674 | 652 | 631 | 659 | 639 | 620 | 603 | 586 | 571 | 556 | 561 | 547 |
| 5.70 | 659 | 628 | 600 | 575 | 551 | 530 | 510 | 500 | 483 | 466 | 451 | 437 | | | | | | | | 484 | 472 |
| 6.00 | 634 | 604 | 577 | 553 | 530 | 510 | 490 | 472 | 456 | 440 | 426 | 412 | 564 | 548 | 532 | 517 | 503 | 489 | 476 | 477 | 466 |
| 6.30 | | | | | | | | 454 | 438 | 423 | 409 | 396 | 533 | 517 | 502 | 488 | 475 | 462 | 450 | 452 | 440 |
| 6.40 | 597 | 569 | 544 | 520 | 499 | 480 | 461 | 445 | 429 | 415 | 401 | 388 | | | | | | | | | |
| 6.50 | | | | | | | | 445 | 429 | 415 | 401 | 388 | 517 | 502 | 487 | 474 | 461 | 448 | 437 | | |
| 6.80 | | | | | | | | 426 | 411 | 397 | 384 | 372 | | | | | | | | 439 | 428 |
| 7.00 | 534 | 510 | 487 | 466 | 447 | 430 | 413 | 417 | 402 | 389 | 376 | 364 | | | | | | | | | |
| 7.50 | 522 | 498 | 476 | 455 | 437 | 420 | 404 | | | | | | | | | | | | | | |
| 7.80 | | | | | | | | 389 | 375 | 363 | 351 | 340 | | | | | | | | | |
| 8.00 | 497 | 474 | 453 | 434 | 416 | 400 | 385 | 380 | 367 | 354 | 342 | 332 | 361 | 350 | 340 | 330 | 321 | 313 | 304 | 361 | 352 |
| 8.70 | | | | | | | | 371 | 358 | 345 | 334 | 324 | | | | | | | | | |
| 9.00 | | | | | | | | 343 | 331 | 320 | 309 | 299 | 306 | 297 | 288 | 280 | 272 | 265 | 258 | | |
| 9.50 | 286 | 273 | 260 | 249 | 239 | 230 | 221 | | | | | | 282 | 274 | 266 | 258 | 251 | 245 | 238 | 239 | 233 |
| 10.00 | 273 | 261 | 249 | 239 | 229 | 220 | 212 | 324 | 313 | 302 | 292 | 283 | 274 | 266 | 258 | 251 | 244 | 238 | 232 | 232 | 226 |
| 11.10 | 249 | 237 | 226 | 217 | 208 | 200 | 192 | | | | | | | | | | | | | | |
| 11.35 | | | | | | | | 306 | 295 | 285 | 276 | 267 | | | | | | | | | |
| 12.00 | 236 | 225 | 215 | 206 | 198 | 190 | 183 | 185 | 179 | 173 | 167 | 162 | 243 | 236 | 229 | 222 | 216 | 211 | 205 | 194 | 189 |
| 12.80 | 211 | 201 | 192 | 184 | 177 | 170 | 163 | | | | | | | | | | | | | | |
| 14.00 | 224 | 213 | 204 | 195 | 187 | 180 | 173 | 157 | 152 | 147 | 142 | 137 | 141 | 137 | 133 | 129 | 126 | 122 | 119 | | |
| 15.60 | | | | | | | | 148 | 143 | 138 | 134 | 129 | | | | | | | | | |
| 15.80 | 199 | 190 | 181 | 173 | 166 | 160 | 154 | | | | | | | | | | | | | | |
| 16.00 | 199 | 190 | 181 | 173 | 166 | 160 | 154 | 139 | 134 | 130 | 125 | 121 | 125 | 122 | 118 | 115 | 112 | 109 | 106 | | |

Within the coffin shape width framework of sequentially scheduled rolling cycles, the following guidelines apply for individual rolling cycles as presented section 2.3.1.3, table 2.1:

- The maximum rolling cycle length is restricted to 35 km due to work roll wear.
- A minimum of 2 "warmers" (gauge approximately 6 mm) should be processed at the start of each rolling cycle to achieve uniform thermal crown on the work rolls.
- The thinnest gauges should be scheduled directly after the warmers. All material less than 3 mm in gauge should be scheduled within the first 20 km of the cycle.
- Ideally the rolling cycle should end on thicker gauges, because material thinner than 3 mm should not be produced in the last 15 km, and ascending gauges should be scheduled to the end of the cycle. The quality of heavy gauge products is less sensitive to work roll wear than light gauge products.
- Rolling cycle length calculation [13]:
  The rolling cycle length is calculated by using table 3.13. The combined first to last pass coil length of each slab is determined from table 3.13 by using the coil width and final gauge. Table 3.13 was developed for 10 ton slabs therefore a simple calculation is required to convert the value to that of the slab under investigation.

  $$\text{Rolling cycle length} = \Sigma(\text{roll wear meterage } [\textit{table 3.13}])(\text{slab weight}/10 \text{ ton}) \quad (3.12)$$

  $$\text{Rolling cycle length} < 35 \text{ km} \quad (3.13)$$
- Generally, all rolling cycles should consist of coils of uniform width. Where it is necessary to incorporate a range of widths, these should be scheduled in decreasing width, with the widest directly after the warmers.

The coil mode rolling cycle scheduling guidelines used by the flat products scheduling departments to manually generate steckel mill rolling cycle schedules have been presented in this paragraph.

### 3.5.3 CONCLUSION

Rolling cycle scheduling guidelines have been presented in this section. These rolling cycle scheduling guidelines are used by the flat products scheduling department to manually generate rolling cycle programmes to be processed between work roll and backup roll changes.

The mathematical models that have been developed for tandem mill rolling cycle scheduling, presented in Chapter 2, could be adapted for plate and steckel mill production scheduling at Highveld's flat products complex. Such mathematical rolling cycle scheduling models can aid the scheduling department to improve production rate, product quality, process efficiency and on time delivery.

This study aims to develop a scheduling model that will aid the flat products scheduling department to utilise the excess processing capacity of the plate finishing end, cut to length shear line, through plate via coil production during coil production campaigns.

## 3.6 CONCLUSION

An overview of the current production scheduling practice at the Highveld integrated iron and steel works' flat products complex has been presented in this chapter.

Physical limitations of the flat products complex have been presented in this chapter and restrictions to product ranges have been highlighted. In addition, the current steel ordering and scheduling procedures used by the flat products scheduling department has been overviewed. The import role of the OASIS system that eases scheduling by processing works orders into P-Cards has been underlined. Furthermore, scheduling parameters, such as slab mass calculations and size allowances, which are used in generating P-Cards, have been presented followed by an overview of rolling cycle scheduling guidelines.



The following chapter presents a scheduling model that will aid the flat products scheduling department to allocate plate orders to plate via coil production.

# CHAPTER 4

## *PLATE VIA COIL PRODUCTION SCHEDULING MODEL*

## 4.1 INTRODUCTION

This chapter presents the scheduling model developed for production of plate via coil at the flat products complex of Highveld Steel. The need for a computerised model for scheduling plate via coil orders was identified by the management of the flat products complex during August 1999. The aim was to improve overall plant efficiency by producing plates from hot rolled coils. Plant efficiency could benefit from increased utilisation of excess finishing end processing line capacity and higher production throughput through the plate and steckel mills.

## 4.2 PLATE VIA COIL PRODUCTION

Plate orders that can be combined into a single or multiple of coils that are produced by the steckel mill and then cut to the required plate order length on either the de-coil or Bigwood finishing-end lines are referred to as plate via coil production.

This section presents an overview of the advantages of plate via coil production over conventional plate production, followed by a detailed description of the plate via coil production scheduling model.



### 4.2.1 IMPROVED PLANT EFFICIENCY

Production efficiency at the flat products complex of Highveld could be enhanced through improved utilisation of processing capacity and increased production throughput.

#### 4.2.1.1 Improved utilisation of processing capacity

Plate via coil production could utilise excess finishing end processing line capacity. Coils could be de-coiled and cut to length on either the plate finishing or the Bigwood coil finishing end processing line. The plate finishing end cut to length processing line is not utilised during a coil production campaign. In addition, the Bigwood coil finishing end processing line is not being operated at capacity and is utilised primarily to recover down graded coils by cutting the coil into plates. Therefore, excess finishing end processing line capacity exists that could be utilised through plate via coil production.

#### 4.2.1.2 Increased production throughput

Production throughput through the plate and steckel mill could be enhanced through plate via coil production. The production delays caused by chock bar processing as discussed in section 3.2.1 could be overcome by plate via coil production. Furthermore, the production rate through the steckel mill is about 65% higher than through the plate mill, as can be seen from the average production figures shown in table 4.1

**Table 4.1 Plate mill versus steckel mill production capacity [13]**

| Conventional plate production | | Coil production | |
|---|---|---|---|
| Average daily plate production during a plate campaign | ± 850 ton | Average daily coil production during a coil campaign | ± 1400 ton |
| Pusher furnace capacity | max 60 ton/hour | Walking beam furnace capacity | max 100 ton/hour |

Production figures show that approximately 20% of all light and medium gauge plate orders produced during the first eleven months of the year 2000 are of the suitable width and length for plate via coil production [13]. If these orders were produced through plate via coil production, it would result in approximately 2% additional production capacity per month.

This paragraph highlighted the advantages of plate via coil production over conventional plate production. The plate via coil scheduling model that has been developed to assist the flat products scheduling department to identify plate orders that are suitable for plate via coil production is presented in the following paragraph.



### 4.2.2 PLATE VIA COIL SCHEDULING MODEL

The objective of the scheduling model is to aid the flat products scheduling department to allocate numerous plate orders of matching grade, width and gauge to one or more coils. The plate via coil scheduling model is similar to the order-block generator introduced by Kosiba *et al.* [17] and discussed in paragraph 2.4.1.3. The order-block generator assigns slabs of identical width, gauge, and hardness that have to be produced for the same customer to an order-block. The plate via coil scheduling model presented in the following paragraph groups all plate orders according to grade, width, gauge and delivery dates.

#### 4.2.2.1 Plate via coil order allocation model

The plate via coil scheduling model takes the physical plant limitations, presented in section 3.2, into account when evaluating all available plate orders for plate via coil production. Once all the available orders have been identified, they are evaluated and allocated to numerous plate via coil order groups of homogeneous grade, width, and gauge.

The following model has been used for grouping plate orders according to grade, width and gauge:

- **Step 0 (Identify plate orders suitable for plate via coil production)**

  *Compare the width and length of each slab in the P-Card table.*

  If the length is less than the width, interchange the two values and update the P-Card table.

  (Ordered plates of widths wider than the maximum coil width but with lengths less than the maximum coil width could, therefore, be processed from a coil. The coil can then be cut to lengths equal to the ordered plate width.)

  *Evaluate the width of each slab in the P-Card table.*

  If the width is greater than 1950 mm, the slab is excluded from the P-Card table.

  If the width is less than 1200 mm, the slab is excluded from the P-Card table

  *Evaluate the gauge of each slab in the P-Card table.*

  If gauge is greater than 16 mm, the slab is excluded from the P-Card table.

- **Step 1 (Grouping according to grade)** (metallurgical composition)

  *Group all P-Cards into single grade groups.*

  - allocate all P-Cards to respective grade groups



- **Step 2 (Group according to width)**

  *Generate homogeneous grade-width groups.*

  - for each grade group, allocate P-Cards into equal width groups

- **Step 3 (Group according to gauge)** (product thickness)

  *Group all grade-width groups by ordered gauge.*

  - for each grade-width group, allocate P-Cards into equal gauge groups

- **Step 4 (Sequence according to delivery dates)**

  *Sequence slabs within each homogeneous grade-width-gauge group according to delivery date.*

- **Step 5 (Evaluate mass of each grade-width-gauge group)**

  *For each homogeneous grade-width-gauge group, determine combined total weight of all P-Cards in the group.*

All plate orders of width greater than 1950 mm and less than 1200 mm are excluded from consideration for plate via coil production. The maximum slab width for coil production is 2050 mm, which translates to a maximum final plate width of 1950, after side trimming on the de-coil line. Furthermore, the minimum ordered plate width that can be processed via the de-coil line is 1200 mm. In addition, all plate orders of gauge greater than 16 mm (i.e. heavies) are excluded from consideration for plate via coil production because the maximum gauge that can be processed on the de-coil line is 16 mm.

Each plate order can be evaluated for suitability for plate via coil production and grouped into homogeneous grade-width-gauge groups using the order allocation model. The implementation of the plate via coil order allocation model is discussed in the following paragraph.

#### 4.2.2.2 Plate via coil order allocation model implementation

The plate via coil order allocation model presented in the previous paragraph has been implemented by using sample plate order data and Microsoft Access [23]. The sample plate order data was imported into an order table. The plate order table was filtered by using queries and a report in which the orders are grouped into homogeneous grade-width-gauge groups was generated.



Using the Microsoft Access [23] query functions, the sample plate order data was filtered according to Step 0 in paragraph 4.2.2.1. In the resulting table, ordered plate width and length values were swapped if ordered widths were greater than lengths. Once the width and length values were evaluated and swapped where necessary, all orders of width greater than 1950 mm or gauge larger than 16 mm were excluded from the filtered plate order table.

After executing the query functions, Step 1, Step 2 and Step 3, a report was generated that grouped the filtered plate order table into grade tables, according to width and gauge. In addition, within the report, slabs within these reconciled grade-width-gauge groups were sequenced according to delivery dates, Step 4. Finally, the total mass and length of all the ordered plates within a homogeneous grade-width-gauge group were determined, Step 5. Refer to Appendix A for the plate via coil order report that was generated using the plate via coil order allocation model.

### 4.2.3 CONCLUSION

This section shows how plate via coil production could result in improved plant efficiency through improved utilisation of processing capacity and improved production throughput. Once the plate via coil scheduling model presented in this section has been implemented, it can be used to allocate plate orders to homogeneous grade-width-gauge groups. All available plate orders can then be evaluated and reports generated on a daily basis. The flat products scheduling department can utilise the information contained in the report to combine plate orders from homogeneous grade-width-gauge groups into coils. These coils can be produced during a coil campaign and processed into plates via the plate finishing end cut to length or Bigwood coil finishing end processing lines.

## 4.3 CONCLUSION

The plate via coil scheduling model that has been presented in this chapter should assist the flat products scheduling department to readily assess the suitability of plate orders for plate via coil production. The model can be used as a tool to simplify the laborious task of manually grouping plate orders into homogeneous grade-width-gauge groups for plate via coil production. The small portion of plate orders that are currently allocated to plate via coil production can be significantly increased though the use of the plate via coil scheduling model. This will result in improved utilisation of process capacity and increased production throughput at Highveld's flat products complex. The following chapter concludes this research dissertation and provides some recommendations on production scheduling at Highveld's flat products complex.

# CHAPTER 5

## *CONCLUSION AND RECOMMENDATIONS*

## 5.1 INTRODUCTION

The primary goal of this research dissertation has been to develop a scheduling model that should assist the flat products scheduling department at Highveld to schedule plates cut to length, via coil produced in the hot reversing strip mill. The aim has been to improve overall plant efficiency by producing plates from hot rolled coils that are cut to length on the finishing end processing lines, instead of producing plate through the plate mill.

## 5.2 OVERVIEW

The study consists of three main sections. The first section, which covers hot strip mill production scheduling, is presented in Chapter 2. The second section, presented in Chapter 3, provides an overview of production scheduling at Highveld's flat products complex. The final section, presented in Chapter 4, provides a plate via coil scheduling model.

Chapter 2 focus on hot strip mill production scheduling. The challenge of balancing conflicting production objectives has been highlighted. Conflicting hot strip mill production objectives have been examined and the differences between steckel mill and tandem mill production schedules have also been highlighted. A number of hot strip mill production scheduling models have been presented from a literature survey. These models show significant improvement over conventional manual rolling cycle scheduling. The section illustrates the importance and benefits of computerised production scheduling models as an aid to hot strip mill production schedulers.

Chapter 3 focuses on the current production scheduling practice at Highveld's flat products complex. Physical plant limitations have been presented and restrictions to product ranges have been emphasised. The current steel ordering and scheduling procedures used by the flat products scheduling department have been discussed. Finally, scheduling parameters and rolling cycle scheduling guidelines have been presented. This section illustrates the complexity of the primarily manual production scheduling process at Highveld's flat products complex.

Chapter 4 presents a scheduling model that should assist the flat products scheduling department to allocate plate orders to plate via coil production. The model evaluates and allocates plate orders to homogeneous grade-width-gauge groups. Once the model queries have been executed, a report is generated. The report lists all the plate orders within grade-width-gauge groups according to delivery dates. The information should assist Highveld's flat products scheduling department to substantially increase the number of plate orders that has been allocated plate via coil production. This section illustrates how even basic computerised production scheduling models should benefit scheduling departments.

## 5.3 RECOMMENDATIONS

The important role played by production scheduling models in balancing various related but conflicting hot strip mill production objectives has been highlighted by this research dissertation. These hot strip mill production scheduling models aim to achieve increased process efficiency without sacrificing product quality.

The plate via coil scheduling model that has been presented in Chapter 4 can be used as an aid for increasing process efficiency and throughput without affecting product quality. The model can further be enhanced through the following additions.

- The model can be incorporated into the existing OASIS system and enhanced by computerising the daily steel ordering process.
- An in depth study of the production cost savings of plate orders produced via coil can be performed. A cost model could then be developed that will allow the scheduling department to evaluate and monitor the benefit of plate via coil production on an ongoing basis.
- Available coil orders can be incorporated into the plate via coil scheduling model. The model will allow plate via coil grade-width-gauge groups to be evaluated and linked more easily to existing coil orders.
- The manual scheduling of both plate and coil production campaigns can be simplified and improved by using computerised rolling cycle scheduling models. The model could be based on those presented in Chapter 2, but should be customised to overcome the differences between steckel mill and tandem mill production cycles. Due to the much lower production rate through a steckel mill, the rolling cycle scheduling model for steckel mill production should prove less complicated and smaller in size.

Production scheduling models within the hot strip mill production environment should continue to enhance process efficiency in the years ahead. These models are powerful tools that no hot strip mill production scheduling department should or can do without.

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# APPENDIX A

## *Plate via coil order allocation model implementation*

The plate via coil order allocation model presented in Chapter 4 has been implemented by using sample order data and Microsoft Access [23]. The sample plate order data has been imported into an order table. The plate order table has been filtered by using queries and a report in which the orders are grouped into homogeneous grade-width-gauge groups has been generated.

The plate via coil order report that has been generated using the plate via coil order allocation model is presented in this appendix. Within the report the filtered plate order data is grouped into grade tables, according to width and gauge, and sequenced according to delivery dates. The report presents the total mass and length of all the ordered plates within a homogeneous grade-width-gauge group.

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

## QUALITY: AS37

### PRODUCT WIDTH: 1829 *mm*

*Thickness:* *8 mm*

| | | | | |
|---|---|---|---|---|
| 200650 | 390341 | 2 | 10000 | 1998-09-23 |
| 200650 | 390342 | 2 | 10000 | 1998-09-23 |
| 200650 | 390343 | 2 | 10000 | 1998-09-23 |
| 200650 | 390344 | 2 | 10000 | 1998-09-23 |
| 200650 | 390345 | 2 | 10000 | 1998-09-23 |
| 200650 | 390346 | 2 | 10000 | 1998-09-23 |
| 200650 | 390347 | 1 | 10000 | 1998-09-23 |
| 200650 | 390340 | 2 | 10000 | 1998-09-25 |

*Total Length:* 150000 *mm* *Total Ton:* 17,229 *ton*

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

## QUALITY: AS40

### PRODUCT WIDTH: 1350 *mm*

*Thickness:* *5 mm*

| | | | | |
|---|---|---|---|---|
| 200653 | 390678 | 5 | 5500 | 1998-09-25 |
| 200653 | 390679 | 3 | 5500 | 1998-09-25 |
| 200653 | 390677 | 5 | 5500 | 1998-09-28 |

*Total Length:* **71500** *mm* *Total Ton:* **3,789** *ton*

### PRODUCT WIDTH: 1450 *mm*

*Thickness:* *5 mm*

| | | | | |
|---|---|---|---|---|
| 200653 | 390680 | 3 | 8000 | 1998-09-28 |

*Total Length:* **24000** *mm* *Total Ton:* **1,366** *ton*

### PRODUCT WIDTH: 1500 *mm*

*Thickness:* *5 mm*

| | | | | |
|---|---|---|---|---|
| 200653 | 390686 | 2 | 8000 | 1998-09-25 |
| 200653 | 390682 | 3 | 8000 | 1998-09-25 |
| 200653 | 390683 | 3 | 8000 | 1998-09-25 |
| 200653 | 390685 | 3 | 8000 | 1998-09-25 |
| 200653 | 390684 | 3 | 8000 | 1998-09-25 |
| 200653 | 390681 | 3 | 8000 | 1998-09-28 |



*Total Length:* **136000** *mm* *Total Ton:* **8,007** *ton*

### PRODUCT WIDTH: 1650 *mm*

*Thickness:* *5 mm*

| | | | | |
|---|---|---|---|---|
| 200653 | 390687 | 3 | 8000 | 1998-09-28 |

*Total Length:* **24000** *mm* *Total Ton:* **1,554** *ton*

### PRODUCT WIDTH: 1750 *mm*

*Thickness:* *5 mm*

| | | | | |
|---|---|---|---|---|
| 200653 | 390692 | 2 | 8000 | 1998-09-25 |
| 200653 | 390691 | 3 | 8000 | 1998-09-25 |
| 200653 | 390690 | 3 | 8000 | 1998-09-25 |

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 200653 | 390688 | 5 | 5020 | 1998-09-28 |
| 200653 | 390689 | 3 | 8000 | 1998-09-28 |

***Total Length:*** **113100** ***mm*** ***Total Ton:*** **7,769** ***ton***

## PRODUCT WIDTH: 1800 *mm*

***Thickness:*** ***5 mm***

| | | | | |
|---|---|---|---|---|
| 200652 | 390642 | 3 | 8000 | 1998-09-25 |
| 200652 | 390634 | 3 | 8000 | 1998-09-25 |
| 200652 | 390646 | 1 | 8000 | 1998-09-25 |
| 200652 | 390645 | 3 | 8000 | 1998-09-25 |
| 200652 | 390644 | 3 | 8000 | 1998-09-25 |
| 200652 | 390643 | 3 | 8000 | 1998-09-25 |
| 200652 | 390629 | 3 | 8000 | 1998-09-25 |
| 200652 | 390619 | 3 | 8000 | 1998-09-25 |
| 200652 | 390620 | 3 | 8000 | 1998-09-25 |
| 200652 | 390621 | 3 | 8000 | 1998-09-25 |
| 200652 | 390622 | 3 | 8000 | 1998-09-25 |
| 200652 | 390623 | 3 | 8000 | 1998-09-25 |
| 200652 | 390624 | 3 | 8000 | 1998-09-25 |
| 200652 | 390625 | 3 | 8000 | 1998-09-25 |
| 200652 | 390626 | 3 | 8000 | 1998-09-25 |
| 200652 | 390637 | 3 | 8000 | 1998-09-25 |
| 200652 | 390628 | 3 | 8000 | 1998-09-25 |
| 200652 | 390641 | 3 | 8000 | 1998-09-25 |
| 200652 | 390630 | 3 | 8000 | 1998-09-25 |
| 200652 | 390631 | 3 | 8000 | 1998-09-25 |
| 200652 | 390632 | 3 | 8000 | 1998-09-25 |
| 200652 | 390633 | 3 | 8000 | 1998-09-25 |
| 200652 | 390638 | 3 | 8000 | 1998-09-25 |
| 200652 | 390635 | 3 | 8000 | 1998-09-25 |
| 200652 | 390639 | 3 | 8000 | 1998-09-25 |
| 200652 | 390640 | 3 | 8000 | 1998-09-25 |
| 200652 | 390627 | 3 | 8000 | 1998-09-25 |
| 200652 | 390636 | 3 | 8000 | 1998-09-25 |
| 200652 | 390618 | 3 | 8000 | 1998-09-28 |

***Total Length:*** **680000** ***mm*** ***Total Ton:*** **48,042** ***ton***



## PRODUCT WIDTH: 1850 *mm*

***Thickness:*** ***5 mm***

| | | | | |
|---|---|---|---|---|
| 200653 | 390693 | 5 | 5020 | 1998-09-28 |

## *Plate via Coil Orders*

| *Order Number* | *Slab Number* | *Number Of Pieces* | *Prod Length* | *Rolling Week* |
|---|---|---|---|---|

*Total Length:* 25100 *mm* *Total Ton:* 1,823 *ton*

# *Plate via Coil Orders*

**QUALITY:** BS51

**PRODUCT WIDTH:** 1500 *mm*

*Thickness:* *8 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48717 | 390719 | 2 | 12100 | 1998-09-25 |
| 48717 | 390722 | 2 | 12100 | 1998-09-25 |
| 48717 | 390720 | 2 | 12100 | 1998-09-25 |
| 48717 | 390718 | 2 | 12100 | 1998-09-25 |
| 48717 | 390717 | 2 | 12100 | 1998-09-25 |
| 48717 | 390716 | 2 | 12100 | 1998-09-25 |
| 48717 | 390715 | 2 | 12100 | 1998-09-25 |
| 48717 | 390714 | 2 | 12100 | 1998-09-25 |
| 48717 | 390713 | 2 | 12100 | 1998-09-25 |
| 48717 | 390721 | 2 | 12100 | 1998-09-25 |
| 48717 | 390712 | 2 | 12100 | 1998-09-28 |

*Total Length:* 266200 *mm* *Total Ton:* 25,076 *ton*

**PRODUCT WIDTH:** 1550 *mm*

*Thickness:* *8 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48543 | 388811 | 2 | 12100 | 1998-09-16 |
| 48543 | 388810 | 2 | 12100 | 1998-09-16 |
| 48543 | 388814 | 2 | 12100 | 1998-09-16 |
| 48543 | 388813 | 2 | 12100 | 1998-09-16 |
| 48543 | 388812 | 2 | 12100 | 1998-09-16 |
| 48543 | 388816 | 2 | 12100 | 1998-09-16 |
| 48543 | 388817 | 2 | 12100 | 1998-09-16 |
| 48543 | 388815 | 2 | 12100 | 1998-09-16 |
| 48543 | 388819 | 2 | 12100 | 1998-09-16 |
| 48543 | 388818 | 2 | 12100 | 1998-09-16 |

*Total Length:* 242000 *mm* *Total Ton:* 23,556 *ton*

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

## QUALITY: PM01

### PRODUCT WIDTH: 1200 *mm*

*Thickness:* *6 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48586 | 389274 | 7 | 3000 | 1998-09-16 |
| 48586 | 389273 | 16 | 3000 | 1998-09-16 |
| 48586 | 389272 | 16 | 3000 | 1998-09-16 |
| 48586 | 389271 | 16 | 3000 | 1998-09-16 |
| 48586 | 389270 | 16 | 3000 | 1998-09-16 |
| 48586 | 389269 | 16 | 3000 | 1998-09-16 |
| 48586 | 389264 | 16 | 3000 | 1998-09-16 |
| 48586 | 389260 | 16 | 3000 | 1998-09-16 |
| 48586 | 389257 | 16 | 3000 | 1998-09-16 |
| 48586 | 389258 | 16 | 3000 | 1998-09-16 |
| 48586 | 389266 | 16 | 3000 | 1998-09-16 |
| 48586 | 389259 | 16 | 3000 | 1998-09-16 |
| 48586 | 389268 | 16 | 3000 | 1998-09-16 |
| 48586 | 389261 | 16 | 3000 | 1998-09-16 |
| 48586 | 389262 | 16 | 3000 | 1998-09-16 |
| 48586 | 389263 | 16 | 3000 | 1998-09-16 |
| 48586 | 389256 | 16 | 3000 | 1998-09-16 |
| 48586 | 389265 | 16 | 3000 | 1998-09-16 |
| 48586 | 389267 | 16 | 3000 | 1998-09-16 |
| 48586 | 389525 | 20 | 2500 | 1998-09-17 |
| 48586 | 389533 | 20 | 2500 | 1998-09-17 |
| 48586 | 389532 | 20 | 2500 | 1998-09-17 |
| 48586 | 389531 | 20 | 2500 | 1998-09-17 |
| 48586 | 389530 | 20 | 2500 | 1998-09-17 |
| 48586 | 389528 | 20 | 2500 | 1998-09-17 |
| 48586 | 389529 | 20 | 2500 | 1998-09-17 |
| 48586 | 389534 | 14 | 2500 | 1998-09-17 |
| 48586 | 389519 | 20 | 2500 | 1998-09-17 |
| 48586 | 389518 | 20 | 2500 | 1998-09-17 |
| 48586 | 389527 | 20 | 2500 | 1998-09-17 |
| 48586 | 389520 | 20 | 2500 | 1998-09-17 |
| 48586 | 389521 | 20 | 2500 | 1998-09-17 |
| 48586 | 389522 | 20 | 2500 | 1998-09-17 |
| 48586 | 389523 | 20 | 2500 | 1998-09-17 |
| 48586 | 389524 | 20 | 2500 | 1998-09-17 |
| 48586 | 389526 | 20 | 2500 | 1998-09-17 |
| 48586 | 389517 | 20 | 2500 | 1998-09-23 |

*Total Length:* 1770000 *mm* *Total Ton:* 100,04 *ton*

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

***Thickness:*** ***8 mm***

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48587 | 389279 | 22 | 2500 | 1998-09-16 |
| 48587 | 389282 | 22 | 2500 | 1998-09-16 |
| 48587 | 389287 | 2 | 2500 | 1998-09-16 |
| 48587 | 389276 | 22 | 2500 | 1998-09-16 |
| 48587 | 389278 | 22 | 2500 | 1998-09-16 |
| 48587 | 389280 | 22 | 2500 | 1998-09-16 |
| 48587 | 389281 | 22 | 2500 | 1998-09-16 |
| 48587 | 389284 | 22 | 2500 | 1998-09-16 |
| 48587 | 389286 | 22 | 2500 | 1998-09-16 |
| 48587 | 389283 | 22 | 2500 | 1998-09-16 |
| 48587 | 389285 | 22 | 2500 | 1998-09-16 |
| 48587 | 389277 | 22 | 2500 | 1998-09-16 |
| 48587 | 389275 | 22 | 2500 | 1998-09-23 |

***Total Length:*** **665000** ***mm*** ***Total Ton:*** **50,114** ***ton***

***Thickness:*** ***10 mm***

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48588 | 389313 | 25 | 2500 | 1998-09-16 |
| 48588 | 389314 | 25 | 2500 | 1998-09-16 |
| 48588 | 389315 | 25 | 2500 | 1998-09-16 |
| 48588 | 389316 | 25 | 2500 | 1998-09-16 |
| 48588 | 389310 | 25 | 2500 | 1998-09-16 |
| 48588 | 389303 | 25 | 2500 | 1998-09-16 |
| 48588 | 389301 | 25 | 2500 | 1998-09-16 |
| 48588 | 389300 | 25 | 2500 | 1998-09-16 |
| 48588 | 389309 | 25 | 2500 | 1998-09-16 |
| 48588 | 389311 | 25 | 2500 | 1998-09-16 |
| 48588 | 389302 | 25 | 2500 | 1998-09-16 |
| 48588 | 389304 | 25 | 2500 | 1998-09-16 |
| 48588 | 389305 | 25 | 2500 | 1998-09-16 |
| 48588 | 389306 | 25 | 2500 | 1998-09-16 |
| 48588 | 389307 | 25 | 2500 | 1998-09-16 |
| 48588 | 389308 | 25 | 2500 | 1998-09-16 |
| 48588 | 389312 | 25 | 2500 | 1998-09-16 |
| 48588 | 389539 | 25 | 2500 | 1998-09-17 |
| 48588 | 389540 | 25 | 2500 | 1998-09-17 |
| 48588 | 389538 | 25 | 2500 | 1998-09-17 |
| 48588 | 389537 | 25 | 2500 | 1998-09-18 |

***Total Length:*** **1312500** ***mm*** ***Total Ton:*** **123,638** ***ton***

***Thickness:*** ***16 mm***

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48529 | 387756 | 22 | 2500 | 1998-09-18 |
| 48531 | 389698 | 22 | 2500 | 1998-09-18 |
| 48531 | 389697 | 22 | 2500 | 1998-09-18 |
| 48491 | 388719 | 22 | 2500 | 1998-09-18 |

***Total Length:*** **220000** ***mm*** ***Total Ton:*** **33,158** ***ton***

## PRODUCT WIDTH: 1500 *mm*

***Thickness:*** ***6 mm***

| | | | | |
|---|---|---|---|---|
| 48585 | 389213 | 9 | 3000 | 1998-09-16 |
| 48585 | 389255 | 4 | 3000 | 1998-09-16 |
| 48585 | 389225 | 9 | 3000 | 1998-09-16 |
| 48585 | 389224 | 9 | 3000 | 1998-09-16 |
| 48585 | 389223 | 9 | 3000 | 1998-09-16 |
| 48585 | 389222 | 9 | 3000 | 1998-09-16 |
| 48585 | 389221 | 9 | 3000 | 1998-09-16 |
| 48585 | 389220 | 9 | 3000 | 1998-09-16 |
| 48585 | 389219 | 9 | 3000 | 1998-09-16 |
| 48585 | 389218 | 9 | 3000 | 1998-09-16 |
| 48585 | 389217 | 9 | 3000 | 1998-09-16 |
| 48585 | 389216 | 9 | 3000 | 1998-09-16 |
| 48585 | 389254 | 9 | 3000 | 1998-09-16 |
| 48585 | 389214 | 9 | 3000 | 1998-09-16 |
| 48585 | 389209 | 9 | 3000 | 1998-09-16 |
| 48585 | 389212 | 9 | 3000 | 1998-09-16 |
| 48585 | 389211 | 9 | 3000 | 1998-09-16 |
| 48585 | 389210 | 9 | 3000 | 1998-09-16 |
| 48585 | 389226 | 9 | 3000 | 1998-09-16 |
| 48585 | 389208 | 9 | 3000 | 1998-09-16 |
| 48585 | 389206 | 9 | 3000 | 1998-09-16 |
| 48585 | 389205 | 9 | 3000 | 1998-09-16 |
| 48585 | 389204 | 9 | 3000 | 1998-09-16 |
| 48585 | 389215 | 9 | 3000 | 1998-09-16 |
| 48585 | 389239 | 9 | 3000 | 1998-09-16 |
| 48585 | 389253 | 9 | 3000 | 1998-09-16 |
| 48585 | 389229 | 9 | 3000 | 1998-09-16 |
| 48585 | 389207 | 9 | 3000 | 1998-09-16 |
| 48585 | 389230 | 9 | 3000 | 1998-09-16 |
| 48585 | 389231 | 9 | 3000 | 1998-09-16 |
| 48585 | 389232 | 9 | 3000 | 1998-09-16 |
| 48585 | 389233 | 9 | 3000 | 1998-09-16 |
| 48585 | 389234 | 9 | 3000 | 1998-09-16 |
| 48585 | 389235 | 9 | 3000 | 1998-09-16 |
| 48585 | 389236 | 9 | 3000 | 1998-09-16 |

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48585 | 389228 | 9 | 3000 | 1998-09-16 |
| 48585 | 389238 | 9 | 3000 | 1998-09-16 |
| 48585 | 389227 | 9 | 3000 | 1998-09-16 |
| 48585 | 389247 | 9 | 3000 | 1998-09-16 |
| 48585 | 389252 | 9 | 3000 | 1998-09-16 |
| 48585 | 389251 | 9 | 3000 | 1998-09-16 |
| 48585 | 389250 | 9 | 3000 | 1998-09-16 |
| 48585 | 389249 | 9 | 3000 | 1998-09-16 |
| 48585 | 389237 | 9 | 3000 | 1998-09-16 |
| 48585 | 389248 | 9 | 3000 | 1998-09-16 |
| 48585 | 389240 | 9 | 3000 | 1998-09-16 |
| 48585 | 389246 | 9 | 3000 | 1998-09-16 |
| 48585 | 389245 | 9 | 3000 | 1998-09-16 |
| 48585 | 389244 | 9 | 3000 | 1998-09-16 |
| 48585 | 389243 | 9 | 3000 | 1998-09-16 |
| 48585 | 389242 | 9 | 3000 | 1998-09-16 |
| 48585 | 389241 | 9 | 3000 | 1998-09-16 |
| 48585 | 390760 | 9 | 3000 | 1998-09-27 |
| 48585 | 390762 | 9 | 3000 | 1998-09-27 |
| 48585 | 389203 | 9 | 3000 | 1998-09-27 |
| 48585 | 390761 | 9 | 3000 | 1998-09-27 |

***Total Length:*** 1497000 *mm* ***Total Ton:*** 105,763 *ton*



***Thickness:*** ***10 mm***

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48593 | 389410 | 2 | 3000 | 1998-09-16 |
| 48593 | 389397 | 10 | 3000 | 1998-09-16 |
| 48593 | 389398 | 10 | 3000 | 1998-09-16 |
| 48593 | 389399 | 10 | 3000 | 1998-09-16 |
| 48593 | 389400 | 10 | 3000 | 1998-09-16 |
| 48593 | 389401 | 10 | 3000 | 1998-09-16 |
| 48593 | 389402 | 10 | 3000 | 1998-09-16 |
| 48593 | 389403 | 10 | 3000 | 1998-09-16 |
| 48593 | 389404 | 10 | 3000 | 1998-09-16 |
| 48593 | 389405 | 10 | 3000 | 1998-09-16 |
| 48593 | 389406 | 10 | 3000 | 1998-09-16 |
| 48593 | 389407 | 10 | 3000 | 1998-09-16 |
| 48593 | 389409 | 10 | 3000 | 1998-09-16 |
| 48593 | 389408 | 10 | 3000 | 1998-09-16 |
| 48593 | 389396 | 10 | 3000 | 1998-09-18 |

***Total Length:*** 426000 *mm* ***Total Ton:*** 50,162 *ton*

# *Plate via Coil Orders*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

## QUALITY: PM02

### PRODUCT WIDTH: 1200 *mm*

*Thickness:* *12 mm*

| | | | | |
|---|---|---|---|---|
| 48729 | 390937 | 25 | 2500 | 1998-09-28 |
| 48729 | 390938 | 25 | 2500 | 1998-09-28 |
| 48729 | 390942 | 25 | 2500 | 1998-09-28 |
| 48729 | 390936 | 25 | 2500 | 1998-09-28 |
| 48729 | 390941 | 25 | 2500 | 1998-09-28 |
| 48729 | 390940 | 25 | 2500 | 1998-09-28 |
| 48729 | 390939 | 25 | 2500 | 1998-09-28 |
| 48729 | 390943 | 2 | 2500 | 1998-09-28 |

*Total Length:* 442500 *mm* *Total Ton:* 50,02 *ton*

*Thickness:* *16 mm*

| | | | | |
|---|---|---|---|---|
| 48661 | 389572 | 22 | 2500 | 1998-09-17 |
| 48661 | 389574 | 22 | 2500 | 1998-09-17 |
| 48661 | 389576 | 2 | 2500 | 1998-09-17 |
| 48661 | 389573 | 22 | 2500 | 1998-09-17 |
| 48661 | 389571 | 22 | 2500 | 1998-09-17 |
| 48661 | 389570 | 22 | 2500 | 1998-09-17 |
| 48661 | 389567 | 22 | 2500 | 1998-09-17 |
| 48661 | 389569 | 22 | 2500 | 1998-09-17 |
| 48661 | 389568 | 22 | 2500 | 1998-09-17 |
| 48661 | 389575 | 22 | 2500 | 1998-09-17 |



*Total Length:* 500000 *mm* *Total Ton:* 75,36 *ton*

### PRODUCT WIDTH: 1500 *mm*

*Thickness:* *12 mm*

| | | | | |
|---|---|---|---|---|
| 48577 | 389116 | 10 | 3000 | 1998-09-16 |
| 48577 | 389433 | 10 | 3000 | 1998-09-16 |
| 48577 | 389115 | 10 | 3000 | 1998-09-16 |
| 48577 | 389432 | 10 | 3000 | 1998-09-16 |
| 48577 | 389114 | 10 | 3000 | 1998-09-23 |

*Total Length:* 150000 *mm* *Total Ton:* 21,195 *ton*

# Plate via Coil Orders

## QUALITY: SS30

### PRODUCT WIDTH: 1200 *mm*

*Thickness:* *6 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48561 | 388967 | 20 | 2500 | 1998-09-16 |
| 48561 | 388968 | 20 | 2500 | 1998-09-16 |
| 48561 | 388966 | 20 | 2500 | 1998-09-16 |
| 48561 | 388978 | 20 | 2500 | 1998-09-16 |
| 48561 | 388977 | 20 | 2500 | 1998-09-16 |
| 48561 | 388976 | 20 | 2500 | 1998-09-16 |
| 48561 | 388975 | 20 | 2500 | 1998-09-16 |
| 48561 | 388973 | 20 | 2500 | 1998-09-16 |
| 48561 | 388972 | 20 | 2500 | 1998-09-16 |
| 48561 | 388971 | 20 | 2500 | 1998-09-16 |
| 48561 | 388970 | 20 | 2500 | 1998-09-16 |
| 48561 | 388979 | 20 | 2500 | 1998-09-16 |
| 48561 | 388969 | 20 | 2500 | 1998-09-16 |
| 48561 | 388974 | 20 | 2500 | 1998-09-16 |
| 48561 | 388980 | 4 | 2500 | 1998-09-25 |

*Total Length:* 710000 *mm* *Total Ton:* 40,129 *ton*



*Thickness:* *16 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48428 | 389705 | 22 | 2500 | 1998-09-18 |
| 48390 | 390532 | 22 | 2500 | 1998-09-24 |
| 48390 | 390533 | 3 | 2500 | 1998-09-24 |

*Total Length:* 117500 *mm* *Total Ton:* 17,71 *ton*

### PRODUCT WIDTH: 1400 *mm*

*Thickness:* *8 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48605 | 390202 | 2 | 11700 | 1998-09-21 |
| 48605 | 390203 | 2 | 11700 | 1998-09-21 |
| 48605 | 390204 | 2 | 11700 | 1998-09-21 |
| 48605 | 390205 | 2 | 11700 | 1998-09-21 |
| 48605 | 390206 | 2 | 11700 | 1998-09-21 |
| 48605 | 390207 | 2 | 11700 | 1998-09-21 |
| 48605 | 390208 | 2 | 11700 | 1998-09-21 |
| 48605 | 390210 | 2 | 11700 | 1998-09-21 |
| 48600 | 390191 | 2 | 11970 | 1998-09-21 |
| 48605 | 390209 | 2 | 11700 | 1998-09-21 |
| 48605 | 390201 | 2 | 11700 | 1998-09-21 |

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48605 | 390200 | 2 | 11700 | 1998-09-21 |
| 48605 | 390199 | 2 | 11700 | 1998-09-21 |
| 48605 | 390198 | 2 | 11700 | 1998-09-21 |
| 48605 | 390197 | 2 | 11700 | 1998-09-21 |
| 48605 | 390196 | 2 | 11700 | 1998-09-21 |
| 48600 | 390194 | 2 | 11970 | 1998-09-21 |
| 48605 | 390211 | 2 | 11700 | 1998-09-21 |
| 48600 | 390192 | 2 | 11970 | 1998-09-21 |
| 48607 | 390222 | 2 | 11700 | 1998-09-21 |
| 48600 | 390190 | 2 | 11970 | 1998-09-21 |
| 48600 | 390193 | 2 | 11970 | 1998-09-21 |
| 48607 | 390223 | 2 | 11700 | 1998-09-21 |
| 48613 | 390234 | 2 | 11600 | 1998-09-21 |
| 48613 | 390233 | 2 | 11600 | 1998-09-21 |
| 48613 | 390232 | 2 | 11600 | 1998-09-21 |
| 48613 | 390231 | 2 | 11600 | 1998-09-21 |
| 48613 | 390230 | 2 | 11600 | 1998-09-21 |
| 48607 | 390229 | 2 | 11700 | 1998-09-21 |
| 48607 | 390228 | 2 | 11700 | 1998-09-21 |
| 48607 | 390227 | 2 | 11700 | 1998-09-21 |
| 48607 | 390220 | 2 | 11700 | 1998-09-21 |
| 48607 | 390225 | 2 | 11700 | 1998-09-21 |
| 48605 | 390212 | 2 | 11700 | 1998-09-21 |
| 48607 | 390221 | 2 | 11700 | 1998-09-21 |
| 48600 | 390189 | 2 | 11970 | 1998-09-21 |
| 48606 | 390219 | 2 | 11700 | 1998-09-21 |
| 48606 | 390218 | 2 | 11700 | 1998-09-21 |
| 48606 | 390217 | 2 | 11700 | 1998-09-21 |
| 48606 | 390216 | 2 | 11700 | 1998-09-21 |
| 48606 | 390215 | 2 | 11700 | 1998-09-21 |
| 48605 | 390214 | 2 | 11700 | 1998-09-21 |
| 48605 | 390213 | 2 | 11700 | 1998-09-21 |
| 48607 | 390226 | 2 | 11700 | 1998-09-21 |
| 48598 | 390171 | 2 | 11970 | 1998-09-21 |
| 48600 | 390188 | 2 | 11970 | 1998-09-21 |
| 48607 | 390224 | 2 | 11700 | 1998-09-21 |
| 48598 | 390161 | 2 | 11970 | 1998-09-21 |
| 48598 | 390162 | 2 | 11970 | 1998-09-21 |
| 48598 | 390163 | 2 | 11970 | 1998-09-21 |
| 48598 | 390164 | 2 | 11970 | 1998-09-21 |
| 48598 | 390165 | 2 | 11970 | 1998-09-21 |
| 48598 | 390166 | 2 | 11970 | 1998-09-21 |
| 48598 | 390167 | 2 | 11970 | 1998-09-21 |
| 48598 | 390168 | 2 | 11970 | 1998-09-21 |
| 48598 | 390170 | 2 | 11970 | 1998-09-21 |
| 48598 | 390172 | 2 | 11970 | 1998-09-21 |

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48598 | 390173 | 2 | 11970 | 1998-09-21 |
| 48598 | 390174 | 2 | 11970 | 1998-09-21 |
| 48599 | 390183 | 2 | 11970 | 1998-09-21 |
| 48600 | 390187 | 2 | 11970 | 1998-09-21 |
| 48600 | 390186 | 2 | 11970 | 1998-09-21 |
| 48598 | 390169 | 2 | 11970 | 1998-09-21 |
| 48599 | 390184 | 2 | 11970 | 1998-09-21 |
| 48598 | 390175 | 2 | 11970 | 1998-09-21 |
| 48599 | 390182 | 2 | 11970 | 1998-09-21 |
| 48599 | 390181 | 2 | 11970 | 1998-09-21 |
| 48598 | 390177 | 2 | 11970 | 1998-09-21 |
| 48600 | 390185 | 2 | 11970 | 1998-09-21 |
| 48598 | 390176 | 2 | 11970 | 1998-09-21 |
| 48599 | 390180 | 2 | 11970 | 1998-09-21 |
| 48598 | 390178 | 2 | 11970 | 1998-09-21 |
| 48598 | 390179 | 2 | 11970 | 1998-09-21 |
| 48598 | 390160 | 2 | 11970 | 1998-09-25 |
| 48605 | 390195 | 2 | 11700 | 1998-09-25 |
| 48598 | 390617 | 2 | 11970 | 1998-09-25 |
| 48598 | 390616 | 2 | 11970 | 1998-09-25 |

***Total Length:*** 1820780 *mm* ***Total Ton:*** 160,083 *ton*



**PRODUCT WIDTH: 1500** ***mm***

***Thickness:*** ***10 mm***

| | | | | |
|---|---|---|---|---|
| 48380 | 390534 | 5 | 6000 | 1998-09-24 |

***Total Length:*** 30000 *mm* ***Total Ton:*** 3,532 *ton*

**PRODUCT WIDTH: 1600** ***mm***

***Thickness:*** ***10 mm***

| | | | | |
|---|---|---|---|---|
| 48643 | 390831 | 4 | 7470 | 1998-09-28 |
| 48643 | 390827 | 4 | 7470 | 1998-09-28 |
| 48643 | 390828 | 4 | 7470 | 1998-09-28 |
| 48643 | 390829 | 4 | 7470 | 1998-09-28 |
| 48643 | 390830 | 4 | 7470 | 1998-09-28 |
| 48643 | 390833 | 4 | 7470 | 1998-09-28 |
| 48643 | 390834 | 4 | 7470 | 1998-09-28 |
| 48643 | 390835 | 4 | 7470 | 1998-09-28 |
| 48643 | 390836 | 4 | 7470 | 1998-09-28 |
| 48644 | 390837 | 4 | 7470 | 1998-09-28 |
| 48644 | 390841 | 4 | 7470 | 1998-09-28 |
| 48644 | 390839 | 4 | 7470 | 1998-09-28 |

# *Plate via Coil Orders*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48644 | 390838 | 4 | 7470 | 1998-09-28 |
| 48643 | 390832 | 4 | 7470 | 1998-09-28 |
| 48644 | 390840 | 4 | 7470 | 1998-09-28 |

***Total Length:*** **448200** ***mm*** ***Total Ton:*** **56,294** ***ton***

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

## QUALITY: SS31

### PRODUCT WIDTH: 1600 *mm*

*Thickness:* *14 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48548 | 388887 | 2 | 11400 | 1998-09-16 |
| 48548 | 388888 | 2 | 11400 | 1998-09-16 |
| 48548 | 388889 | 2 | 11400 | 1998-09-16 |
| 48549 | 388890 | 3 | 9700 | 1998-09-28 |
| 48550 | 388891 | 2 | 11700 | 1998-09-28 |

*Total Length:* **120900** *mm* *Total Ton:* **21,259** *ton*

### PRODUCT WIDTH: 1800 *mm*

*Thickness:* *16 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48694 | 389931 | 2 | 10500 | 1998-09-19 |
| 48694 | 389934 | 2 | 10500 | 1998-09-19 |
| 48694 | 389932 | 2 | 10500 | 1998-09-19 |
| 48694 | 389930 | 2 | 10500 | 1998-09-19 |
| 48694 | 389933 | 2 | 10500 | 1998-09-19 |
| 48694 | 389929 | 2 | 10500 | 1998-09-19 |
| 48694 | 389937 | 2 | 10500 | 1998-09-19 |
| 48694 | 389920 | 2 | 10500 | 1998-09-19 |
| 48694 | 389921 | 2 | 10500 | 1998-09-19 |
| 48694 | 389922 | 2 | 10500 | 1998-09-19 |
| 48694 | 389923 | 2 | 10500 | 1998-09-19 |
| 48694 | 389939 | 2 | 10500 | 1998-09-19 |
| 48694 | 389938 | 2 | 10500 | 1998-09-19 |
| 48694 | 389924 | 2 | 10500 | 1998-09-19 |
| 48694 | 389936 | 2 | 10500 | 1998-09-19 |
| 48694 | 389935 | 2 | 10500 | 1998-09-19 |
| 48694 | 389926 | 2 | 10500 | 1998-09-19 |
| 48694 | 389927 | 2 | 10500 | 1998-09-19 |
| 48694 | 389928 | 2 | 10500 | 1998-09-19 |
| 48694 | 389925 | 2 | 10500 | 1998-09-19 |
| 48694 | 389919 | 2 | 10500 | 1998-09-28 |

*Total Length:* **441000** *mm* *Total Ton:* **99,701** *ton*

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|

## QUALITY: W007

### PRODUCT WIDTH: 1200 *mm*

*Thickness:* *6 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48504 | 389029 | 20 | 2500 | 1998-09-16 |
| 48504 | 389028 | 20 | 2500 | 1998-09-16 |
| 48504 | 389027 | 20 | 2500 | 1998-09-16 |
| 48504 | 389026 | 20 | 2500 | 1998-09-16 |
| 48504 | 389030 | 20 | 2500 | 1998-09-16 |
| 48504 | 389031 | 20 | 2500 | 1998-09-16 |
| 48448 | 390121 | 20 | 2500 | 1998-09-21 |
| 48448 | 390123 | 11 | 2500 | 1998-09-21 |
| 48448 | 390122 | 20 | 2500 | 1998-09-21 |
| 48504 | 389025 | 20 | 2500 | 1998-09-23 |
| 48448 | 390120 | 20 | 2500 | 1998-09-23 |
| 48504 | 390920 | 20 | 2500 | 1998-09-28 |

*Total Length:* 577500 *mm* *Total Ton:* 32,64 *ton*

*Thickness:* *8 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48449 | 390125 | 22 | 2500 | 1998-09-21 |
| 48449 | 390126 | 10 | 2500 | 1998-09-21 |
| 48449 | 390124 | 22 | 2500 | 1998-09-23 |
| 48505 | 390927 | 22 | 2500 | 1998-09-28 |
| 48505 | 390929 | 22 | 2500 | 1998-09-28 |
| 48505 | 390928 | 22 | 2500 | 1998-09-28 |
| 48505 | 390926 | 22 | 2500 | 1998-09-28 |
| 48505 | 390925 | 22 | 2500 | 1998-09-28 |
| 48505 | 390924 | 22 | 2500 | 1998-09-28 |
| 48505 | 390922 | 22 | 2500 | 1998-09-28 |
| 48505 | 390921 | 22 | 2500 | 1998-09-28 |
| 48505 | 390923 | 22 | 2500 | 1998-09-28 |



*Total Length:* 630000 *mm* *Total Ton:* 47,477 *ton*

*Thickness:* *10 mm*

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48506 | 389050 | 20 | 2500 | 1998-09-16 |
| 48506 | 389049 | 25 | 2500 | 1998-09-16 |
| 48506 | 389047 | 25 | 2500 | 1998-09-16 |
| 48506 | 389048 | 25 | 2500 | 1998-09-16 |
| 48450 | 390130 | 25 | 2500 | 1998-09-21 |
| 48450 | 390131 | 14 | 2500 | 1998-09-21 |
| 48450 | 390537 | 25 | 2500 | 1998-09-24 |

# Plate via Coil Orders

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48450 | 390538 | 25 | 2500 | 1998-09-24 |
| 48450 | 390540 | 25 | 2500 | 1998-09-24 |
| 48450 | 390539 | 25 | 2500 | 1998-09-24 |
| 48450 | 390129 | 25 | 2500 | 1998-09-25 |
| 48746 | 391277 | 14 | 2500 | 1998-09-29 |
| 48746 | 391276 | 25 | 2500 | 1998-09-29 |
| 48746 | 391275 | 25 | 2500 | 1998-09-29 |

***Total Length:*** **807500** ***mm*** ***Total Ton:*** **76,066** ***ton***

***Thickness:*** ***12 mm***

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48507 | 389073 | 4 | 2500 | 1998-09-16 |
| 48507 | 389071 | 25 | 2500 | 1998-09-16 |
| 48507 | 389062 | 25 | 2500 | 1998-09-16 |
| 48507 | 389061 | 25 | 2500 | 1998-09-16 |
| 48507 | 389060 | 25 | 2500 | 1998-09-16 |
| 48507 | 389072 | 25 | 2500 | 1998-09-16 |
| 48507 | 389064 | 25 | 2500 | 1998-09-16 |
| 48507 | 389069 | 25 | 2500 | 1998-09-16 |
| 48507 | 389063 | 25 | 2500 | 1998-09-16 |
| 48507 | 389070 | 25 | 2500 | 1998-09-16 |
| 48507 | 389068 | 25 | 2500 | 1998-09-16 |
| 48507 | 389067 | 25 | 2500 | 1998-09-16 |
| 48507 | 389066 | 25 | 2500 | 1998-09-16 |
| 48507 | 389065 | 25 | 2500 | 1998-09-16 |
| 48507 | 389059 | 25 | 2500 | 1998-09-16 |
| 48451 | 390132 | 25 | 2500 | 1998-09-21 |
| 48451 | 390133 | 25 | 2500 | 1998-09-21 |
| 48451 | 390134 | 21 | 2500 | 1998-09-21 |
| 48367 | 390284 | 25 | 2500 | 1998-09-22 |

***Total Length:*** **1125000** ***mm*** ***Total Ton:*** **127,17** ***ton***

***Thickness:*** ***16 mm***

| Order Number | Slab Number | Number Of Pieces | Prod Length | Rolling Week |
|---|---|---|---|---|
| 48748 | 391280 | 22 | 2500 | 1998-09-29 |
| 48748 | 391281 | 5 | 2500 | 1998-09-29 |

***Total Length:*** **67500** ***mm*** ***Total Ton:*** **10,174** ***ton***