Design of a standard operating procedure for the loading of buckets in Camps Drift Remelt

by

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Executive Summary

Hulamin’s Camps Drift Remelt (CDR) facility recently underwent a substantial expansion to account for the supply issues regarding BHP-Billiton and rolling slab. Where bucket loading was a fairly simple task, it has now become essential to save every possible minute in the charging of furnaces in order to fully utilise the casting capacity of CDR.

This report deals with the establishment of a standard operating procedure (SOP) regarding the loading of scrap into buckets that considers the different furnace charging sequence scenarios. It includes the analysis of the CDR facility in terms of performance data and risks associated with delays experienced in the melting process. The results of said analyses were used in a simulation model to establish the different charging sequence scenarios that could occur and the probabilities of such occurrences. The decision on whether to allocate additional buckets to specific melt lines was addressed. The information gleaned so far was then incorporated into a linear programming model which considered different operations research techniques. The model was run through Lingo for each of the relevant scenarios, incorporating scenario specific constraints, and produced an optimal loading sequence and scrap breakdown for each scenario.

It was concluded that the establishing of an optimal loading sequence will affect the overall charge time of a furnace or combination of furnaces. However, data collection for the linear programming model shed light on supplementary problem areas to be targeted with possibly much more effect as presented in the observations and conclusions.
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1. Introduction

1.1 Background
Hulamin Rolled Products forms the major portion of Hulamin, an independent and Africa’s leading producer of fabricated and semi-finished aluminium products. It is situated in Pietermaritzburg, Kwa-Zulu Natal. Hulamin Rolled Products (from hereafter referred to as Hulamin) underwent an extensive expansion on the then newly acquired Camps Drift site which included the Camps Drift Remelt (CDR).

The production of aluminium rolled products begins with large 6m slabs of about 15 tons. These slabs are scalped, rolled through the Hot-Mill and then distributed to different departments for further processing. The majority of Hulamin’s slab supply has previously been provided by BHP Billiton’s Bayside facility (BHP-B), while scrap generated within the departments of Hulamin was melted down, added to pig (12kg blocks of aluminium melting ingot packaged in 1 ton bundles) provided by BHP-B and cast into slabs. However, in 2009, BHP-B informed Hulamin that they feel that the production of the unique rolling slab is too far downstream from their core business as a resource company and no longer economically feasible. Due to mandatory industry energy consumption cutbacks, BHP-B chose to shut down part of their Bayside smelting facility and have reduced the production of rolling slab by half to 90 000 tons per year. Uncertainty about the future slab supply remains as BHP-B intend to either discontinue the production of rolling slabs at the end of their contractual agreement with Hulamin at the end of June 2012 or sell the Bayside operation off to a third party.

In April 2010, necessity led to the commissioning of a R75 million expansion to the Remelt in the form of a third new furnace, Line 3. Additional loading buckets were also installed. With a shortage of rolling slab, Camps Drift Remelt (CDR) is the current bottleneck within the Hulamin system.

1.2 Problem
Any failure to utilise the full capacity of the CDR is a missed opportunity to produce slab which can directly be translated into lost sales. The CDR is currently falling short of its performance capacity due to a number of factors. This, along with the BHP-B supply situation, has led to a
shortage of metal in the system and the standing of the Hot-Mill which should in fact be the constraining factor or bottleneck of the system.

With the introduction of a third melting line, there is an increased probability of multiple furnaces becoming ready for charging within a small time frame. The decision has to be made as to which type of scrap to load into which specific bucket, of the eight available, to fill a certain line’s charge make-up while minimising the charge time between melting cycles. CDR melting furnaces are charged from above by buckets loaded with various inputs (floor scrap, pig and ASRS scrap) that are loaded using both the ASRS and forklift trucks. An ASRS is an Automated Storage and Retrieval System which, in this case, is a device designed for the housing and fetching of bins filled with scrap of different alloys. Each furnace has a different capacity and therefore requires a different number of buckets to charge as well as having a different melt cycle time.

One of the factors hindering the full capacity utilisation on CDR is the inefficient and extended wait times during the charging of furnaces. Recent data shows an upward trend of the average charge times, the most of which are above the “accepted” target of 45 minutes let alone the targeted charging time of 30 minutes.

![Figure 1: Average furnace charging time (in minutes) as compared to the targeted charging time.](image-url)
Currently, the Standard Operating Procedure (SOP) states that the three buckets closest to Line 1 and Line 2 and the two closest to the smaller Line 3 should be allocated to their respective closest lines with the decision falling on the ASRS operator who then informs the shift leader of the planned schedule (CDR Logistics and Technical, 2011). There is no formal consideration of the finishing order scenarios and, with four operators over different shifts, there is additional variation in charging times.

2. Project Scope

The project will consider the allocation and sequence of the loading of the buckets in the CDR with light floor scrap, heavy floor scrap, pig and ASRS scrap. Forklift trucks and the ASRS are the only two material handling mechanisms that are to be considered in the filling of buckets as they are both currently operational. The process will be repeated for the most commonly occurring finishing scenarios.

Figure 2: ASRS: storage, outlets and operation room.

The limitations of the overhead cranes and the fact that Line 1 and Line 2 share a lid crane must be taken into consideration. There is a serious risk in simply filling all the required buckets for a single line as unforeseen delays could occur anywhere between the melting furnace, holding
furnace and casting pit and cause the whole line to stand, stranding the buckets. Often, lines are running different alloys and so the filled buckets are unusable except for the intended line. By loading 5 buckets for Line 1, a delay would leave only 3 buckets to charge both Line 2 and Line 3 which together usually require 7.

A general charge make-up is to be utilised with the assumption that the required scrap is both available and accessible. Loading of ingots into the furnaces is to be excluded as it eases the pressure to fill buckets and should lessen the load time rather than add to the challenge.

3. Project Aim
To establish an SOP for loading scrap into buckets in the CDR to minimise the charge time on furnaces while considering the relevant finishing order scenarios.

4. Literature Study

4.1 Methods

**BES and ERPs**
Enterprise Resource Planning (ERP) systems are complex Enterprise Systems (ES), systems established to support end-to-end processes, focusing primarily on intra-company processes (Magal & Word, 2012). ERP systems support functions within an organisation including operations, sales and distribution, human resources, logistics, finance and procurement. The core function of an ERP is the database that allows for the integration of various processes through the flow of information and storage of process related data.

Three categories of data are stored within an ERP namely organizational, master and transactional data. Organizational data represents the structure of the organisation. Master data comprises the entities related to various processes including customers, vendors and materials. Transactional data is a combination of organisational, master and process-specific data resulting from the execution of each stage of a process, e.g. dates, quantities, process times, prices and delays.
Figure 3: Departments integrated through and associated with the input of data into an ERP (ERP Software Selection and Implementation, 2011).

The ERP system designed specifically for Hulamin is called BES or Business Execution System. The Information Technology (IT) department is able to extract data pertaining to specific processes, departments, products or orders from BES. This is where most of the historical data regarding production times and delays in CDR was obtained.

**Decision Tree**

Decision trees are graphical models used in structuring decision problems involving uncertainty. Decisions are made by considering both the expected value of an outcome and the probability of its occurrence. The model consists of nodes representing the moment in time when an event occurs and branches depicting the possible paths of a scenario. Event nodes are denoted by circles and decision nodes are represented by squares (Evans, 2010).

TreePlan is a Microsoft Excel add-in that enables the efficient construction of decision tree diagrams through the use of dialogue boxes (TreePlan for Decision Trees, 2011). It was developed by Dr. Michael Middleton who is the author of Data Analysis using Microsoft Excel. The diagram structure allows for the swift entering of both “payout” values as well as the probabilities of different events occurring.

Decision trees were ruled out for the risk analysis as the delays within the melting cycle are not mutually exclusive as is required for decision trees. However, decision trees were used in the
decision making process regarding the utilisation of an additional bucket for charging once the risk analysis was complete.

Risk can be described by a scenario, the probability of that scenario occurring and the consequence of such an occurrence (Kaplan & Garrick, 1980). Data regarding delays along the furnace lines need to be analysed to establish probabilities of the different delays occurring as well as to establish an average time delay which is to be considered the consequence or penalty. The delays in question would cause the melting furnace to stand and therefore filled buckets to become inoperative due to scrap incompatibility with the other lines. Once the probabilities and consequences are known, an informed decision can be made as to whether or not the filling of an additional bucket should be considered.

**Simulation**

Computer simulation allows for the simulating of an abstract model of a specific system (Computer Simulation, 2011). Either simulation software or an Excel spreadsheet could be used to develop the charging sequence scenarios by running the different melt cycle times of the three furnace lines in order to record how often two or more lines are waiting to be charged simultaneously or within a certain time period. Spreadsheet modeling or analysis generally evaluates a system by using a single point in time or average values which is adequate in approximating results for a static system, but it does not take the inherent variable nature of most processes into consideration. By excluding the variability, the ability to comprehend the true performance of a system is limited and this can lead to flawed analysis including the overapproximation of capacity and availability as well as the underestimation of costs and wait times (Arena: Frequently Asked Questions, 2011).

Simulation allows for the true emulation of system behaviour through the use of statistical distributions that curve fittings have found the system mimics. There are a few simulation software packages available, but due to time constraints in learning new software and having been acquainted with both Simio and Rockwell Automation’s Arena they are the only software to be considered. Arena was chosen as it is convenient and familiar. Although Simio has the advantage of rapidly constructing 3D models (Simio: Forward Thinking, 2010), the simulation required does not need visual appeal but only accurate data output.
Linear Programming Model

Winston and Venkataramanan (2003) refer to operations research as “the scientific approach to decision making that seeks to best design and operate a system”. Different problems were researched to be considered in the formulation of the model to be designed. The problem at hand may be a combination and/or variation of some of the following:

Transportation problem: a programming problem that aims to establish the optimal route or pattern for delivering or allocating goods from multiple points of origin to multiple destinations (McGraw-Hill Dictionary of Scientific & Technical Terms, 2003). In Hulamin’s case, the “cost factor” to be minimised would be wait time for charging. The demand would be the required charge make-up.

A transportation problem can generally be specified by three items (Winston & Venkataramanan, 2003):

1) A set of \( m \) supply points. The capacity of supply point \( i \) is limited to \( s_i \) units.

2) A set of \( n \) demand points. \( d_j \) represents the number of units required by demand point \( j \).

3) A known variable cost, \( c_{ij} \), should be incurred by each unit that is produced at supply point \( i \) and delivered to demand point \( j \).

In a case where:

\[ x_{ij} \triangleq \text{the number of units shipped from supply point } i \text{ to demand point } j \]

the formulation of the transportation problem would be:

\[
\begin{align*}
\text{min} & \quad \sum_{i=m}^{i=n} \sum_{j=1}^{j=n} c_{ij} x_{ij} \\
\text{s.t.} & \quad \sum_{j=1}^{j=n} x_{ij} \leq s_i \quad i = (1, 2, ..., m) \quad \text{(Supply Constraints)} \\
& \quad \sum_{i=1}^{i=m} x_{ij} \geq d_j \quad j = (1, 2, ..., n) \quad \text{(Demand Constraints)} \\

x_{ij} & \geq 0 \quad (i = 1, 2, ..., m; j = 1, 2, ..., n)
\end{align*}
\]
The transportation problem theory is used to establish the load time of each bucket by multiplying the number of trips to each bucket carrying a specific scrap type by the time taken to do so. Similarly, the movement of buckets being charged is a unique value for each bucket emptied into each of the three furnaces.

**Assignment problem:** by name, the “assignment problem”, a specific type of transportation problem sounded appropriate due to the allocation aspect of the problem, but by definition assignment problems have an identical number of sources and assignments with an equal supply and demand of one (McGraw-Hill Dictionary of Scientific & Technical Terms, 2003). This does not seem applicable with the four scrap types being assigned to seven buckets in order to charge three furnaces.

**Scheduling problem:** concerned with establishing the optimal schedule considering various objectives and constraints on the system including diverse job characteristics and machine environments (Hochbaum, 1999). A scheduling aspect needs to be included into the model not only to generate a loading sequence but also to account for the possibility of refilling a bucket once it has been charged into the furnace to once again be charged into that same furnace. Scheduling problems frequently replace total system costs with performance measures such as machine idle time, job waiting time or job lateness (Baker, 1974), and delays associated with the reloading of buckets are an example of such waiting times.

**Lingo**
The linear programming model is to be built and executed in LINGO, a comprehensive program designed by Lindo Solutions to solve mathematical optimization problems (Lindo Systems Inc., 2010) such as the bucket loading sequence and scrap breakdown model that makes up this project. The linear nature of the model allow for the use of LINGO over other options such as MATLAB which handles non-linear models more efficiently. Version 8.0 of LINGO is to be used as it is the only licensed version available for the project and allows for more variables than the limit of 150 variables in the more recent student versions.
4.2 The Problem

CDR utilises top-loading, circular melting furnaces. Such furnaces have removable domed lids which, when opened, allow for the charging of scrap by charge buckets with drop bottom type doors that are moved overhead and lowered into the furnaces by cranes (Top Loading Melting Furnace, 2011). Single bucket charges can be up to 23 tons depending on the scrap format.

Appendix A shows an updated schematic of the CDR facility layout as received from the Drawing department within Hulamin. Line 1 and the three buckets generally allocated to it are noted in green. Similarly, Line 2 and Line 3 are noted in blue and red respectively. The ASRS, scrap yard and pig storage area have also been marked on the plan. Each line comprises a melting furnace (MF), a holding furnace (HF) and a casting pit (DC).

5. Data Analysis

5.1 Melt Cycle Analysis

Hulamin has a specially designed Enterprise Resource Planning (ERP) system called BES or Business Execution System. BES stores data from the different production departments throughout the company. Sensors within the CDR furnaces register the movement of lids, tilt angles and heat cycles and record the relevant times along with cast number and other data into BES. Data from all furnace casts on both Line 1 and Line 2 from 2 January to 11 July, 2011, was extracted from the system and placed into a Microsoft Excel spreadsheet in a data dump including dwell, charging and cleaning times for each cast. Each of the two lines had around 2100 rows of data equal to about 700 casts.

The data did not show full melt cycle times as was required, but through manipulation and establishing the time difference between start times of sequential casts a full cycle time in minutes was established. Multiple pivot tables were created as they allow for swift data analysis with automatic summation of the different times per cast. The summed dwell, charging and cleaning times were subtracted from this total cycle time to establish a time value for the melt cycle of each cast. The data was scrutinized, with the aid of conditional formatting, to remove outlying data points where excessively large or small time values appeared. Such outliers could be due to scheduled or non-scheduled maintenance, aborts or a myriad of unreported delays but by incorporating them, one would be including further bias.
Line 3 is a new addition to CDR and, as of yet, working sensors have not been installed into the melting furnace. To obtain the required time data, a copy of the Visual Process Audit (VPA) sheet from the Line 3 control room was obtained. The VPA is a chart that breaks the process of melting in Line 3 into PVCs including Cleaning Furnace, Charging, Melting, Alloying and Transferring. PVCs are process variables that require controlling to ensure a specific outcome that they have been critically linked to. In this case, the time taken to complete the individual PVC tasks needs to be monitored and kept within the relevant “standard control limit” to ensure that the entire melt cycle time remains within the assigned overall control limits. The operators are tasked with manually writing a start and end time for each of the above mentioned PVCs for every cast. The cast number, date and alloy type are also recorded. Although such data is not as accurate as that from BES, due to the inconsistency of inputs by operators, it is assumed to be for the purpose of this project.

Individual data analyses were performed on each data set, e.g. Line 1 dwell times, using the “Descriptive Statistics” data analysis tool in Microsoft Excel. Each set followed a mostly normal distribution curve with some positive skewness. The skewness is due to the manner in which limits were set to decide which data values to keep and which to exclude. As the reasoning behind excessively large values is not available, more leeway toward including higher values was given causing the mean of the task time to increase and creating a small tolerance within the data. All data sets were assumed to have normal distributions for the purpose of the simulation.

<table>
<thead>
<tr>
<th></th>
<th>Charge</th>
<th>Melt &amp; Alloy</th>
<th>Clean</th>
<th>Dwell</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>Line 1</td>
<td>46.72</td>
<td>15.45</td>
<td>276.03</td>
<td>70.84</td>
</tr>
<tr>
<td>Line 2</td>
<td>37.90</td>
<td>12.75</td>
<td>210.60</td>
<td>57.57</td>
</tr>
<tr>
<td>Line 3</td>
<td>33.00</td>
<td>11.36</td>
<td>256.43</td>
<td>25.93</td>
</tr>
</tbody>
</table>

Table 1: Process mean time (µ) and standard deviation (σ) in minutes per line.
5.2 Scenario Simulation
A basic simulation of the Remelt facility was created in Arena with each furnace line as a separate “production line”. The model can be viewed in Appendix B. To keep the accuracy of the input data, the tasks are shown as individual processes with their own mean and standard deviation values as shown in Table 1, above. All three lines start with Charge and then Melt and Alloy processes before the introduction of a decision point as not every cast requires the cleaning of the melting furnace. Line 1, 2 and 3 were programmed to include the Clean process 25, 30 and 30 percent of the time, respectively, as was established from historical data. The Dwell process then occurs before the ending of the cycle. It is at this point that an end time attribute, equal to the ready-state time of the following cast, is allocated to each entity.

Each cast is assigned an attribute, Line Number, at the start associating it with the CDR line through which it is processed. A variable is used to note the Line Number attribute of the last cast to leave the system allowing the splitting of data on the basis of which line has just completed and which line finished immediately before that. The simulation was run for 6 months at full 24 hour production. Data was extracted to Microsoft Excel with the two relevant end times for every cast noted under each scenario. The time difference was established allowing for the determination of the frequency of each scenario occurrence over a 6 month period.

The mean charging time for each line was used as the cut-off for each scenario, i.e. if Line 1 ended followed by Line 2 all data was recorded and then in the analysis the data was separated into values above and below the mean charging time of Line 1 or 47 minutes. The frequency attributed to the scenario “Line 1 to Line 2” includes all casts with a time difference of less than 47 minutes and the rest are attributed to the scenario “Line 1” along with the outside values from the “Line 1 to Line 3” scenario. 2412 casts were completed within the 6 month simulation and Table 2, below, shows the results of the analysis.

The scenarios in Table 2 can be explained as:

Line 1: Line 1 will be ready for charge with no other line coming off within the expected charge time.

Line 2: Line 2 will be ready for charge with no other line coming off within the expected charge time.
Line 3: Line 3 will be ready for charge with no other line coming off within the expected charge time.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Count</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>653</td>
<td>0.2707</td>
</tr>
<tr>
<td>Line 2</td>
<td>630</td>
<td>0.2612</td>
</tr>
<tr>
<td>Line 3</td>
<td>565</td>
<td>0.2342</td>
</tr>
<tr>
<td>Line 1 to Line 2</td>
<td>105</td>
<td>0.0435</td>
</tr>
<tr>
<td>Line 1 to Line 3</td>
<td>79</td>
<td>0.0328</td>
</tr>
<tr>
<td>Line 2 to Line 1</td>
<td>111</td>
<td>0.0460</td>
</tr>
<tr>
<td>Line 2 to Line 3</td>
<td>89</td>
<td>0.0369</td>
</tr>
<tr>
<td>Line 3 to Line 1</td>
<td>101</td>
<td>0.0419</td>
</tr>
<tr>
<td>Line 3 to Line 2</td>
<td>79</td>
<td>0.0328</td>
</tr>
<tr>
<td>Total</td>
<td>2412</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: Probability of a scenario occurring within a 6 month period as established by simulation.

Line 1 to 2: Line 1 will be ready to charge and Line 2 could come off during the expected charge time of 47 minutes.

Line 1 to 3: Line 1 will be ready to charge and Line 3 could come off during the expected charge time of 47 minutes.

Line 2 to 1: Line 2 will be ready to charge and Line 1 could come off during the expected charge time of 38 minutes.

Line 2 to 3: Line 2 will be ready to charge and Line 3 could come off during the expected charge time of 38 minutes.

Line 3 to 1: Line 3 will be ready to charge and Line 1 could come off during the expected charge time of 33 minutes.

Line 3 to 2: Line 3 will be ready to charge and Line 2 could come off during the expected charge time of 33 minutes.
5.3 Additional Bucket Decision
There is an opportunity to save time in charging by filling an additional bucket over and above the number generally allocated to a particular line. Lines 1, 2 and 3 provisionally have 3, 3 and 2 buckets allocated although they require, on average, 5, 4 and 3 buckets, respectively. The “borrowing” of a bucket from an adjacent line is possible but can lead to an increase in time lost should the line that is to be charged stand for any reason. A delay in charging of the initial line would lead to the standing of the already loaded buckets, thus leaving a further bucket short for the charging of the other two lines.

Delay data was acquired regarding all recorded delays over the same period as was analysed for the melt cycle times. There were some discrepancies in the CDR data obtained from BES with regards to cast numbers of data included in the delay analysis that did not appear in the melt cycle time data and so the data was correlated by the identification and removal of the additional casts. There are five main types of delay namely Forced Maintenance Delay (FMD), Forced Production Delay (FPD), Management Delay (MD), Mould Maintenance Delay (MMD) and Planned Maintenance Delay (PMD). Each can be broken down further into classes.

Due to the nature of the data from BES that was used in the melt cycle time analysis, some delays were inherently included into the mean process times and so they were excluded from the delay analysis. The excluded delays were alloying and stirring, sample and skimming, cleaning and melting. All PMDs or Planned Maintenance Delays were also excluded for the fact that the operators would know of the planned downtime and therefore implement contingencies.

The intention was to use a decision tree with the only decision node being whether to utilise the allocated number or an extra bucket for the charging of a particular line and the individual types of delays as event nodes. However, a decision tree requires mutually exclusive events and, within the categories of delays, there are multiple delay classes that may or may not occur within the same cast. For this reason, decision trees could only be implemented once mutually exclusive events were established.

The delays from each of Lines 1 and 2 were analysed by class and the probability of occurrence was established by dividing the number of times a specific delay occurred by the total number of casts analysed for that line. Line 3 delays were similarly analysed but the occurrence was divided
by the total number of casts that had delays recorded, including those with “no delay recorded” as the class, as the delays and melt cycle time data were not from the same casts as with Lines 1 and 2. The time penalty was established by taking the average of the time lost values associated with each delay class for each line.

The risk of a delay occurring in each cast was therefore calculated as the probability of a risk and the associated time penalty or mean time lost due to the delay (Kaplan & Garrick, 1980). The results of the delay analysis and risk calculations can be viewed in Table 3.

Line 3 has an excessively high risk, but this is to be expected as it is newly commissioned. The data used in the Line 3 delay analysis would have included all of the initial startup delays. The line, itself, may not yet be running at optimal production levels. For this reason, as well as the fact that Line 3 has the smallest capacity, no additional bucket shall be utilised in the charging of Line 3.

All scenarios involving the direct follow on of a second furnace waiting to be charged that has the possibility of falling within the mean charging time of the initial furnace will not be considered for the filling of an additional bucket. The risk is substantially too high that a delay could cause further setbacks in production than the delay itself. This leaves “Line 1” and “Line 2” scenarios as the only two scenarios to be considered for the possibility of loading an additional bucket.

For Line 1 and 2, the respective risk time values were added to the mean charge times to establish limit values as cut-off points and then calculate the probability of a second furnace becoming ready for charging should the initial charge be delayed by the risk value. This produced cut-off time limits of 83.62 and 70.43 minutes for Line 1 and Line 2 respectively. Each cut-off time value was then used to separate the simulated finish scenario times. Of the 653 casts that fall in the “Line 1” scenario, 452 fall after the 83.62 minute difference. This equals a probability of 0.69219 that the next line to become ready for charging shall do so outside of the cut-off limit. Similarly, the “Line 2” scenario analysis established that 508 of the 630 casts fall outside of the 70.43 minute limit which equates to a probability of 0.806 that no additional delays will be caused.
<table>
<thead>
<tr>
<th>Line 1</th>
<th>Probability</th>
<th>Penalty</th>
<th>Line 2</th>
<th>Probability</th>
<th>Penalty</th>
<th>Line 3</th>
<th>Probability</th>
<th>Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td></td>
<td></td>
<td>A.C.D</td>
<td>0.004360465</td>
<td>63.33</td>
<td></td>
<td>0.003007519</td>
<td>67.5</td>
</tr>
<tr>
<td>ABORT</td>
<td>0.068313953</td>
<td>188.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BURNERS</td>
<td>0.001453488</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.F.F</td>
<td>0.010174419</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAST TOWER</td>
<td>0.001453488</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<td>CASTING</td>
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<td></td>
<td>0.315789474</td>
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<td></td>
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Table 3: Risk related to each line in terms of delay probability and associated penalty.
Using Microsoft Excel’s TreePlan add-in, a basic decision tree was drawn up to help make the decision regarding the utilisation of an additional bucket for both Line 1 and Line 2. Firstly, a time value was required to represent the expected outcome of each decision or event. The mean charging time was divided by the number of buckets to give an average charge time per bucket of 9.34 minutes for Line 1 and 9.48 minutes for Line 2. A general loading time of 20 minutes was used to account for the refilling of buckets and simple Gantt charts were constructed to calculate the average charge time of each line with both 3 and 4 buckets being loaded. The Gantt charts can be seen in Appendix C.

The results of the abovementioned Gantt charts or expected charge times were used as the expected positive or “No Delay” outcome of the decision. The expected “Delayed” outcome was calculated by summing the previously established risk value, the expected charge time as well as the extra time that would be added onto the charging time of the other line that would have to charge with one bucket short. The decision to use only the three buckets allocated to either line would cause the last value or additional wait time in the calculation above to be zero. The decision trees are shown in Figure 3 and Figure 4.

In both cases the decision to keep using only the 3 allocated buckets has a slightly lower expected value and so, seeing as the purpose of this project is to try to keep the charging time to a minimum, no additional buckets will be allocated for charging.

![Decision Tree](image_url)

**Figure 4: Decision tree regarding the number of buckets to be utilised in the charging of Line 1.**
6. Development of Solution
A model was designed to apply to the appropriate scenarios previously established during the data analysis phase. The purpose of the model is to generate a loading sequence and scrap breakdown that best handles the trade-off between load times and bucket charge times, where the current SOP fails to consider any aspect other than the direct charge time of each bucket. The objective function minimizes the idle time of each furnace or combination of furnaces. The idle or wait time is equal to the total charge time of each furnace (which is determined by the summation of the charge times of the individual loaded buckets) as well as any delay incurred by reloading buckets during the charge sequence.

A base model, considering the following assumptions, was designed and then run with only the relevant parts included for different scenarios. For the purpose of this model, scenario “Line 1 to Line 2” and “Line 2 to Line 3” would produce the same results and so have been run as one model, namely Model 4. Similarly, cases involving Line 1/Line 3 and Line 2/Line 3 have been merged to make Model 5 and Model 6, respectively. Models 1 through 3 cover the loading
sequence of scenarios which include the charging of only a single furnace, Line 1 through Line 3.

6.1 Assumptions

1) It is assumed that all required scrap is available as needed. Currently, multiple projects are being implemented within CDR to improve the layout and logistics of the scrap yard to provide for the aforementioned assumption. In reality, in the case of a shortage of required scrap, an alloy change will be made to the schedule if possible or a mandate must be obtained from the Planning Department to exceed the targeted level of pig used.

As all charges are prepared in the scrap yard outside and through the ASRS system, no set values were enforced on the “amount of scrap” variable, $x_{ijklm}$. 

2) For the purpose of this project, a general charge make-up for each melting line has been used as is most commonly applied, according to the lead ASRS operator. In reality, some alterations to scrap composition would need to be made depending on the alloy being cast.

The charge make-up to be used for each line is as follows:

Melting Furnace 1 (80 tons):

- 12 tons light scrap (mostly from ASRS and 3 or 4 tons from the yard)
- 10-20 tons pig
- 6-9 tons heavy scrap
- Rest medium scrap up to 65%

Melting Furnace 2 (65 tons):

- 2 buckets ASRS scrap of which about 12 tons 19% should be light scrap.
- 1 bucket floor scrap
- 1 bucket pig (23 tons)
Melting Furnace 3 (53 tons):

- 1 bucket pig (23 tons)
- 2 buckets floor scrap of which a maximum of 15% or around 6 or 7 tons can be light scrap

3) The mass associated with the carry capacity of each material handling method or each trip is an assigned general value as each scrap type could consist of any of the subtype scrap formats. Appendix D shows the scrap classification of each scrap subtype into the four scrap types of light-, medium-, heavy scrap and pig.

4) The maximum load capacity of a bucket is 23 tons, as mentioned previously. However, the format of the scrap that is loaded into each bucket may vary causing the capacity to be significantly less. For this reason, the model sets the capacity of each bucket as 19 tons.

5) Scrap ingots are often loaded into the furnace in place of a bucket of scrap. This is to be excluded from the model as it would take pressure off of a charge by decreasing the number of buckets required as well as the bucket loading time.

6) The model allows for only a single forklift truck (FLT) to load the buckets. There are often two FLTs used, however it cannot be guaranteed that both FLTs will be available for the loading of buckets when required. Also, all of the scrap bins that are loaded via FLT need to be loaded by an inverter FLT of which there is only one.

7) The model assumes that both the ASRS and FLT can load a bucket in the same time period. Although, in reality, the forklift truck would have to wait for the ASRS tippler to empty and move away. To compensate for this, the individual load times are added together making the modeled loading time longer, despite the simultaneous movement.

8) CDR has two cranes specifically assigned to loading the three furnaces, however there is a structural limitation in that the two cranes cannot be between the same two pillars at any one time which equates to a mandatory 12m distance between them at all times. This, as well as the issue of power trips with Crane 2, led to the decision that the model would be run using a single crane.

9) The order in which buckets are loaded is identical to the charging sequence.
6.2 The Model

Sets

There are several scrap variations that are classified as light, medium or heavy scrap as can be seen in Appendix D. These three scrap classifications along with a fourth, pig, make up the “scrap type” or $\bar{I}$ set in the model.

There are two material handling methods used to transport scrap into buckets, namely the ASRS and forklift trucks. These are represented by the ‘method’ or $\bar{J}$ set.

CDR’s eight available buckets constitute the ‘bucket’ or $\bar{K}$ set.

Line 1, Line 2 and Line 3 make up the ‘furnace’ or $\bar{M}$ set.

Six time periods were included in the ‘time period’ or $\bar{T}$ set to allow for the sequential loading and charging of buckets.

The $\bar{E}$ or ‘Equation’ set was established to link different if-then statements in terms of the relevant time periods they relate to, regardless of whether two or three time periods are considered in the equation itself.

\[
\bar{I} = \{1, 2, 3, 4\} \text{ with } 1 = \text{light scrap, } 2 = \text{medium scrap, } 3 = \text{heavy scrap and } 4 = \text{pig}. \\
\bar{J} = \{1, 2\} \text{ with } 1 = \text{ASRS and } 2 = \text{Forklift Trucks}. \\
\bar{K} = \{1, 2, \ldots, 8\} \text{ with } 1 = \text{bucket 1, } 2 = \text{bucket 2, } \ldots, 8 = \text{bucket 8}. \\
\bar{M} = \{1, 2, 3\} \text{ with } 1 = \text{Melt Line 1, } 2 = \text{Melt Line 2 and } 3 = \text{Melt Line 3}. \\
\bar{T} = \{1, 2, \ldots, 6\} \text{ with } 1 = \text{time period 1, } \ldots, 6 = \text{time period 6}. \\
\bar{E} = \{1, 2, 3, 4\} \text{ with } 1 = \text{regarding time periods two and three, } \\
2 = \text{regarding time periods three and four, } 3 = \text{regarding time periods four and five, and } \text{4 = regarding time periods five and six.}
\]

Decision Variables

$w_m \triangleq$ the calculated time taken (mins) to charge furnace $m \in \bar{M}$.

$y_{km} \triangleq 1$ if bucket $k \in \bar{K}$ is allocated to furnace $m \in \bar{M}$, 0 otherwise.

$p_{kmt} \triangleq 1$ if bucket $k \in \bar{K}$ is loaded for furnace $m \in \bar{M}$ in time period $t \in \bar{T}$, 0 otherwise.
\[ x_{ijkmt} \triangleq \text{amount (tons) of scrap } i \in I \text{ moved by method } j \in J \text{ into bucket } k \]
\[ \in \bar{R} \text{ for furnace } m \in \bar{M} \text{ in time period } t \in \bar{T}. \]
\[ d_{im} \triangleq \text{given demand (tons) for scrap type } i \in I \text{ by furnace } m \in \bar{M}. \]
\[ r_m \triangleq \text{the given required total scrap mass (tons) for furnace } m \in \bar{M}. \]
\[ n_{ijkmt} \triangleq \text{the calculated number of trips of scrap } i \in I \text{ moved by method } j \in J \text{ into bucket } k \]
\[ \in \bar{R} \text{ for furnace } m \in \bar{M} \text{ in time period } t \in \bar{T}. \]
\[ c_{ij} \triangleq \text{given capacity (tons) of method } j \in J \text{ to move scrap } i \in I. \]
\[ s_{kmt} \triangleq \text{calculated time (mins) taken to load bucket } k \in \bar{R} \text{ for furnace } m \in \bar{M} \text{ in time period } t \]
\[ \in \bar{T}. \]
\[ t_{ijk} \triangleq \text{given time (mins) taken to move 1 load of scrap } i \in I, \text{ using method } j \in J, \text{ to bucket } k \]
\[ \in \bar{R}. \]
\[ g_{km} \triangleq \text{the given time (mins) taken to charge bucket } k \in \bar{R} \text{ into furnace } m \in \bar{M}. \]
\[ u_{kme} \triangleq \text{the calculated additional delay (mins) before charging bucket } k \in \bar{R} \text{ into furnace } m \]
\[ \in \bar{M} \text{ due to reloading buckets as calculated in equation e } \in \bar{E}. \]

\[
\begin{align*}
\text{Min } z &= \sum_{m=1}^{3} W_m \\
\text{s.t.} \\
1a] & \sum_{k=1}^{8} y_{km} \leq 3 & \forall m \neq 3 \\
b] & \sum_{k=1}^{8} y_{k3} \leq 2 \\
2] & \sum_{k=1}^{8} p_{kmt} \leq 1 & \forall m \in \bar{M}, t \in \bar{T} \\
3] & \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{ijkmt} \geq d_{im} & \forall i \in I, m \in \bar{M} \\
4a] & \sum_{k=1}^{8} \sum_{t=1}^{6} x_{i1kt} \geq 7
\end{align*}
\]
b) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{jk1t} \leq 13.5 \]

c) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{jk2t} \leq 13 \]

d) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{jk3t} \leq 8 \]

5a) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{jk1t} \leq 0.65 \times \sum_{i=1}^{4} \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{ijk1t} \]

b) \[ \sum_{i=1}^{3} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{ik2t} \geq 34 \]

c) \[ \sum_{i=1}^{3} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{ik2t} \geq 17 \]

6a) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{3jk1t} \leq 9 \]

b) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{3jk2t} \leq 8 \]

c) \[ \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{3jk3t} \leq 8 \]

7a) \[ \sum_{k=1}^{8} \sum_{t=1}^{6} x_{32kmt} \leq 23 \quad \forall \ m \in \bar{M} \]

b) \[ \sum_{k=1}^{8} \sum_{t=1}^{6} x_{41kmt} = 0 \quad \forall \ m \in \bar{M} \]

8) \[ \sum_{i=1}^{4} \sum_{j=1}^{2} \sum_{k=1}^{8} \sum_{t=1}^{6} x_{ijkmt} \geq r_m \quad \forall \ m \in \bar{M} \]

9) \[ \sum_{i=1}^{4} \sum_{j=1}^{2} x_{ijkmt} \leq 19 \quad \forall \ k \in \bar{K}, m \in \bar{M}, t \in T \]
10] \[ n_{ijkmt} \geq \frac{x_{ijkmt}}{c_{ij}} \quad \forall i \in \bar{I}, j \in \bar{J}, k \in \bar{K}, m \in \bar{M}, t \in \bar{T} \\

11] \[ s_{kmt} = \sum_{i=1}^{4} \sum_{j=1}^{2} n_{ijkmt} \times t_{ijk} \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \bar{T} \\

12] \[ \sum_{i=1}^{4} \sum_{j=1}^{2} x_{ijkmt} \leq 100 \times p_{kmt} \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \bar{T} \\

13] \[ \sum_{i=1}^{4} \sum_{j=1}^{2} \sum_{t=1}^{6} x_{ijkmt} \leq 100 \times y_{km} \quad \forall k \in \bar{K}, m \in \bar{M} \\

14] \[ \sum_{i=1}^{4} \sum_{j=1}^{6} x_{i1kmt} = 0 \quad \forall k \in \{1,7,8\}, m \in \bar{M} \\

15] \[ W_{m} = \sum_{k=1}^{8} \sum_{t=1}^{6} g_{km} \times p_{kmt} + \sum_{k=1}^{8} \sum_{t=1}^{6} u_{kmt} \quad \forall m \in \bar{M} \\

16a] \[ s_{kmt+2} - u_{kmt} \leq 1000 \times f_{kmt} \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \{2,3,4\} \\
b] \[ p_{kmt+1} + p_{kmt+2} - 1 \leq 1000 \times (1 - f_{kmt}) \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \{2,3,4\} \\
c] \[ s_{k33} - u_{k31} \leq 1000 \times f_{k31} \quad \forall k \in \bar{K} \\
d] \[ p_{k32} + p_{k33} - 1 \leq 1000 \times (1 - f_{k31}) \quad \forall k \in \bar{K} \\

e] \[ a_{mt} - u_{kmt} \leq 1000 \times (h_{kmt}) \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \{3,4,5\} \\
f] \[ 2 - p_{kmt+1} - p_{kmt+2} \leq 1000 \times (1 - h_{kmt}) \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \{3,4,5\} \\
g] \[ a_{31} - u_{k31} \leq 1000 \times (h_{k31}) \quad \forall k \in \bar{K} \\
h] \[ 2 - p_{k32} - p_{k33} \leq 1000 \times (1 - h_{k31}) \quad \forall k \in \bar{K} \\

i] \[ \sum_{k=1}^{8} (s_{kmt+2} - g_{km} \times p_{kmt+1} - g_{km} \times p_{kmt}) - a_{mt} \leq 1000 \times b_{mt} \quad \forall m \in \{1,2\}, t \in \{2,3,4\} \\
j] \[ \sum_{k=1}^{8} (s_{kmt+2} - g_{km} \times p_{kmt+1} - g_{km} \times p_{kmt}) \leq 1000 \times (1 - b_{mt}) \quad \forall m \in \{1,2\}, t \in \{2,3,4\}
\[ k \sum_{k=1}^{9} (s_{k3,t+2} - g_{k3} \times p_{k3,t+1}) - a_{3t} \leq 1000 \times b_{3t} \quad \forall t \in \{1,2,3,4\} \]

\[ l \sum_{k=1}^{8} (s_{k3,t+2} - g_{k3} \times p_{k3,t+1}) \leq 1000 \times (1 - b_{3t}) \quad \forall t \in \{1,2,3,4\} \]

17] \[ \sum_{m=1}^{3} y_{km} \leq 1 \quad \forall k \in \bar{K} \]

18a] \[ p_{km1} + p_{km2} + p_{km3} \leq 1 \quad \forall k \in \bar{K}, m \neq 3 \]

b] \[ p_{k31} + p_{k32} \leq 1 \quad \forall k \in \bar{K} \]

19a] \[ \sum_{k=1}^{8} p_{km} \geq \sum_{k=1}^{8} p_{km,t+1} \quad \forall m \in \bar{M}, t \in \{3,4,5\} \]

b] \[ \sum_{k=1}^{8} p_{k32} \geq \sum_{k=1}^{8} p_{k33} \]

\[ x_{ijkm} \geq 0 \quad \forall i \in \bar{I}, j \in \bar{J}, k \in \bar{K}, m \in \bar{M}, t \in \bar{T} \]

\[ n_{ijkmt} \geq 0 \text{ and integer} \quad \forall i \in \bar{I}, j \in \bar{J}, k \in \bar{K}, m \in \bar{M}, t \in \bar{T} \]

\[ p_{km}, f_{km}, h_{km} \in \{0,1\} \quad \forall k \in \bar{K}, m \in \bar{M}, t \in \bar{T} \]

\[ b_{mt} \in \{0,1\} \quad \forall m \in \bar{M}, t \in \bar{T} \]

1) Maximum Bucket Allocation:
Earlier risk analyses regarding the number of buckets that should be loaded for each furnace confirmed that Line 1, Line 2 and Line 3 should be allocated a maximum of 3, 3, and 2 buckets respectively.

2) Limit Loading of Buckets per Period:
The loading of each bucket is limited to once per time period to establish a sequence of loading.

3) Meet Scrap Specific Demand:
For each furnace, a minimum demand exists for each of the four scrap types and must be met or exceeded over the loading of all buckets associated with said furnace.
4) **Light Scrap Specific Constraints:**
All three furnaces have a maximum amount of light scrap that may be incorporated into a charge.
4a models MF1’s ASRS specific light scrap demand of 7 tons.

5) **Medium Scrap Constraints:**
A charge for Line 1 can consist of up to a maximum of 65% medium scrap.
In charging Line 2, one bucket should be floor scrap or brought in with the FLT, while two buckets should be made up of ASRS scrap.

6) **Heavy Scrap Constraints:**
Each furnace has a max amount of heavy scrap that can be charged into the furnace as heavy scrap increases the melting time of a charge.

7) **Pig Constraints:**
7a) A maximum of 23 tons of pig (one full bucket) is imposed on each charge as any amount larger than that requires a mandate from the Planning Department.
7b) No pig is currently loaded into the ASRS and so the total amount of pig that can be loaded from the ASRS is 0. Pig is moved into a designated area on the shop floor from the pig store outside the Remelt as it is needed for subsequent charges. Pig is moved only by FLT.

8) **Total Required Mass:**
Each furnace has a different melting capacity. The total required mass of scrap that must be loaded for a furnace has been set at 0.5 tons less than said capacity.

9) **Max Bucket Mass:**
The assumed capacity of a bucket being charged into a furnace is 19 tons, see Assumptions above.

10) **Number of Trips:**
The number of trips is calculated by dividing the amount of specific scrap type ($x_{ijkmt}$) loaded into a bucket by the carrying capacity of the material handling method used to transport said scrap type. The value is rounded up to the closest integer as half the capacity moved would still take the same amount of time.

11) **Calculate Load Time:**
The load time of each bucket during each time period is calculated by multiplying the number of trips value calculated above by the time taken to move a single load of a particular scrap type using a certain method to a specific bucket ($t_{ijk}$).
12) **Whether a Bucket is Loaded:**
The binary variable $p_{kmt}$ is driven by the amount of scrap ($x_{ijkmt}$). If any amount of scrap is actually loaded into bucket $k$ in time period $t$, $p_{kmt}$ is 1. Conversely, if no amount of scrap is loaded the $p_{kmt}$ value is automatically 0.

13) **Whether a Bucket is Allocated:**
Similar to the $p_{kmt}$ variable, the $y_{km}$ variable is binary and equal to 1 if any scrap is loaded into bucket $k$ for furnace $m$ over any of the time periods.

14) **Non ASRS Buckets:**
The ASRS tippler is restricted by the track on which it runs and therefore cannot be used to fill scrap into buckets 1, 7 and 8.

15) **Total Charge Time of Furnace:**
The total charge time of a furnace includes the sum of the charge time of each loaded bucket as well as any delay incurred due to reloading or loading buckets outside of the initial “preload time zone” while the furnace in question is still occupied.

16) **Reload Delay Constraints:**
This constraint considers the time that elapses while a bucket is being loaded or reloaded during the charging of a furnace.

16 a-b) state that If: bucket $k$ is loaded both in time period $t$ as well as in time period $t+1$,
Then: the delay added to the charging time of the furnace in question is equal to the load time of the bucket loaded in time period $t+1$.

16 c-d) includes the relevant Line 3 delay regarding the loading of a bucket in time period 3 and the charging of a bucket loaded in time period 2.

16 e-f) state that If: bucket $k$ is not loaded twice in consecutive time periods,
Then: the potential delay added to the charging time of the furnace in question is represented by a variable $a_{mt}$.

16 g-h) includes the relevant Line 3 delay regarding the loading of a bucket in time period 3 and the charging of a bucket loaded in time period 2.
16 i-j) state that If: the load time of a bucket is larger than the sum of the charge times of the previous two buckets that were loaded,
Then: the difference is to be the added delay, $a_{mt}$.

16 k-l) Line three has a “slack” of only one bucket and so the delay would be dependent on the difference between the load time of a bucket in period $t+1$ and the charge time of the bucket loaded in the preceding time period, $t$.

17) **Bucket Allocated to a Single Furnace:**
Each bucket may only be allocated to one furnace for each modeled scenario.

18) **Preloading:**
Due to the nature of the process, each melting line has a long cycle time which allows for scrap preparation for subsequent casts. The model allows for the preloading of allocated buckets, but the needs to enforce that a bucket can only be loaded once in the scrap preparation time period as it cannot be charged into a furnace while that furnace is still occupied. The scrap preparation time is taken to be the same number of time periods number of buckets that can be allocated to a furnace.

19) **Sequential Loading:**
By enforcing that any bucket loaded in time period $t+1$ had to have been loaded in time period $t$, the model cannot bypass the associated delays based on the reloading or loading of buckets during the charging process. No such enforcement is set for the scrap preparation time periods to allow the model to decide whether filling all of the assigned buckets is the best option.

7. **Results**

The base model was run in Lingo with the relevant constraints included for each of the six models. The Lingo model as run for Model 1 can be seen in Appendix K. By “commenting out” irrelevant constraints and editing both the demand and the required scrap mass, the model can be run for any of the models as described below.
**Model 1**

Any scenario in which Line 1 finishes its cycle with no other Line becoming ready for charge within 47 minutes is covered by Model 1. The model rendered a loading sequence with an equivalent charge time of 42.23 minutes for Line 1 compared to the historical mean charging time of 46.72 minutes. The optimal loading sequence and scrap breakdown as extracted from Model 1 can be viewed in Appendix E. Interestingly, the model produced a solution in which only two of a possible three buckets were allocated, forfeiting the opportunity to prepare scrap into a third bucket during Line 1’s melt cycle. The optimal solution included alternating the loading and reloading of Bucket 6 and Bucket 5 over Time Periods 2 through 6.

![Figure 6: Lingo solver status summary at the end of Model 1.](image)

**Model 2**

Any scenario in which Line 2 finishes its cycle with no other Line becoming ready for charge within 38 minutes is covered by Model 2. The established charging time of Line 2 as determined
by Model 2 is 30.496 minutes compared to the historical mean charging time of 37.9 minutes. The optimal loading sequence and scrap breakdown for Model 2 can be seen in Appendix F.

Model 3

Any scenario in which Line 3 finishes its cycle with no other Line becoming ready for charge within 33 minutes is covered by Model 3. The model rendered a loading sequence with an equivalent charge time of 30.972 minutes for Line 3 compared to the historical mean charging time of 33 minutes. The optimal bucket loading sequence is shown in Table 4, below, as well as in Appendix G. Each solution has the furnace name at the top and the scrap breakdown for each allocated bucket in the optimal loading sequence in terms of the mass of the specific scrap type to be loaded by the ASRS and by FLT.

Table 4: Optimal bucket loading sequence and scrap breakdown for Model 3.

Model 4

Any scenario in which Line 1 finishes its cycle with Line 2 becoming ready for charge within 47 minutes or in which Line 2 finishes its cycle followed within 38 minutes by Line 1 is covered by Model 4. The model considers the optimal loading sequence of buckets to meet the demands of both Line 1 and Line 2. The loading sequences of Line 1 and Line 2, as generated by Model 4,
equate to charging times of 42.47 and 30.92 minutes respectively. The solution to Model 4 can be seen in Appendix H. Model 4 is the first model that considers the loading of two furnaces within the same time periods and therefore the bucket allocation decision becomes more complicated. The charge time for a furnace in a scenario with a second furnace will generally be higher than or possibly equal to the optimal charge time associated with the furnace itself, in an earlier model. This is because a bucket can only be allocated to a single furnace and the model is designed to find the lowest value of the sum of the two furnace charge times.

**Model 5**

Any scenario in which Line 1 finishes its cycle with Line 3 becoming ready for charge within 47 minutes or, similarly, a scenario in which Line 3 finishes its cycle followed by Line 1 within 33 minutes is covered by Model 5. Loading sequences for Line 1 and Line 3, as rendered by the model, equate to charging times of 43.342 and 30.972 minutes respectively. The resulting optimal loading sequence and scrap breakdown for Model 5 is shown in Appendix I.

Line 3 is predominantly filled by Bucket 7 and Bucket 8 at the moment due to their close proximity to the furnace but, in the case of Model 5’s solution, it is suggested that Bucket 5 be charged twice and Bucket 8 once to meet Line 3’s requirements with the shortest possible charge time. Although Bucket 5 has a higher charge time when travelling to Line 3, this is compensated for by the lower load times of all scrap types and its ability to receive ASRS scrap.

**Model 6**

Any scenario in which Line 2 finishes its cycle with Line 3 becoming ready for charge within 38 minutes or, similarly, a scenario in which Line 3 finishes its cycle followed by Line 2 within 33 minutes is covered by Model 6. The loading sequences of Line 2 and Line 3, as generated by Model 6, equate to charging times of 30.86 and 31.096 minutes respectively. The optimal solution for the loading sequence and scrap breakdowns for Line 2 and Line 3 together is shown in Appendix J.
8. Observations

Standard Operating Procedure

The standard operating procedure (SOP) currently employed within CDR states that the three closest buckets to a furnace should generally be allocated to that particular furnace, but this fails to take into consideration the extended load times that are linked with buckets stationed further away from the scrap store and ASRS outlets. As well as this, there is the problem of enforcement in that the SOP logic has been established but is not implemented. Each of the ASRS operators has their own preferences and there is considerable variability in the charge time of furnaces. Understandably, when unforeseen circumstances such as aborts or breakdowns occur, ASRS operators need to be able to use their discretion and experience in accommodating the limitations set on the charge.

Communication

There is a definite need for better communication protocols within CDR. It is currently not uncommon for aborts to occur without notifying the ASRS operator. For example: In a case where an abort occurs after 200mm has been cast, there would be insufficient metal to cast all five ingots and so one of the moulds would be blocked off and four ingots would be cast. This could leave up to 10 tons of additional metal in the holding furnace which would soon be joined by the full capacity of the melting furnace containing the following molten cast. As one cannot charge scrap into molten aluminium due to safety protocol, the ASRS operator needs to be informed to compensate for the additional metal and stop the further inundation of metal in the system.

Radios are already utilised by operators and shift leaders although vital information is not always relayed in a timely manner and sometimes not at all. Estimated melt cycle finish times should be reported and updated to the ASRS operator for the correct charging scenario to be considered and implemented. Immediate reports should be logged over radio on any major delay for the ASRS operator to accurately plan around aborts and excessive delays.
The Value of a Minute

The value of a minute is calculated by taking the resulting profit that is earned from a single cast of a furnace and dividing it by the total cycle time of that furnace.

- Line 1 produces 5 slabs of 15 tons per cast. The total cycle time is 354.09 minutes.
- Line 2 produces 4 slabs of 15 tons per cast. The total cycle time is 273.76 minutes.
- Line 3 produces 3 slabs of 15 tons per cast. The total cycle time is 306.10 minutes.

The profit earned per cast can be calculated using the following formula:

\[
\text{Number of slabs} \times 15 \text{ tons} \times 65\% \text{ sales ton yield} \times \$5000 \text{ profit per sales ton} \times \text{
R7.97 exchange rate}
\]

Profits yielded from a single cast are: R 1 942 687.5 for Line 1, R 1 554 150 for Line 2 and R 1 165 612.5 for Line 3.

Therefore the value of a minute lost on each of the melting lines is:

\[
\text{Line 1: } R 1 942 687.5 \div 354.09 = R 5 486.42 \text{ per minute}
\]

\[
\text{Line 2: } R 1 554 150 \div 273.76 = R 5 640.52 \text{ per minute}
\]

\[
\text{Line 3: } R 1 165 612.5 \div 306.10 = R 3 807.95 \text{ per minute}
\]

Bucket Hooking Delays

During the time study regarding flow of scrap between the scrap stores, ASRS, buckets and furnaces; it was observed that multiple delays were incurred while the crane operator waited for another operator to align the smaller lifting hook on the ground level in order to lift a bucket for charging. Over the documented period (which was just short of three 8-hour shifts), 25.35 minutes of delay were recorded that were directly caused by the crane standing and waiting for an operator. With three shifts per day, and the general consensus that there is even less discipline
on night shifts as supervision is slightly less, CDR is losing almost half an hour a day due to a single type of avoidable delay.

As a cautious estimate, let one assume that 20 minutes are lost due to bucket hooking delays, and let that be calculated over a conservative 300 days of production. That leads to a lost time of 6000 minutes in a year. The total average melt cycle times of Line 1, Line 2 and Line 3 are 354.09, 273.76 and 306.10 minutes respectively. This lost time could theoretically be turned into 16.94 casts on Line 1 or 1200 (16 casts of 5 ingots of 15 tons) additional tons of metal in the system; or 21.92 casts on Line 2 or 1260 (21 casts of 4 ingots of 15 tons) tons additional metal in the system; or 19.60 casts on Line 3 which equates to 855 (19 casts of 3 ingots of 15 tons) tons additional metal in the system; or any combination of the above.

Hulamin achieves an output of 65% of the start mass as sales and their average sales equate to about $5,000 profit per sales ton. Taking the lowest value calculated above, 855 tons additional rolling slab into the system renders 555.75 sales tons. At the above mentioned profit margin, $2,778,750 profit could be realized and with the current U.S. Dollar exchange rate as on 8 October, 2011, at R7.97, this translates into a profit of R22,146,375.

**Lid Cranes**

The charging crane regularly has to wait for a lid crane to open as the process is relatively slow and often initiated too late. It is the responsibility of the crane driver to initiate the opening and closing of the furnace lid cranes and any delay experienced due to error or absentmindedness can be directly translated to lost time for additional melting. The operator cannot simply leave the lid open as the time between charging each bucket is used for the preheating of the furnace. A manner in which to establish the ideal ‘initiate opening’ moment or reminder system needs to be looked into or the importance of lost time needs to be stressed and fully comprehended by operators to prevent future losses in precious production time. Delays due to waiting for lid cranes to open amounted to 15.57 minutes over the time study period which if calculated in a similar manner to the bucket hooking delays equates to 4500 lost minutes of production. 430 sales tons are theoretically wasted amounting to a lost profit value of R17,135,760.37.
Operating Staff

A team of international consultants performing a benchmarking project on Hulamin in January 2011 established that Hulamin is operating with a workforce of around 30% more staff than international equivalents and so, although the potential profit values justify the hiring of an additional operator on each shift, other avenues may need to be explored. Some departments have restructured or are in the process of doing so to ensure better utilisation of staff as well as to move excess staff to positions where they could be more effective. It is proposed that one such additional staff member be added as a CDR furnace operator on every shift. If the delays could be reduced or eliminated without incurring the cost of an extra operator, Hulamin would be in an even better position.

The operators on the shop floor are of the opinion that an additional operator is needed for the effective carrying out of the team’s responsibilities. The team on shift control: the FLT movement of scrap into the bucket loading area; the ASRS out-feed and planning; the overhead cranes; the holding furnaces including skimming and sampling; the charging of all furnaces and the loading of buckets. There are times where the charging of a furnace waits for up to 5 minutes at a time due to the lack of an operator to help hook a bucket, but at the same time there are
points where the utilisation of team members seems too low to justify an additional member. It seems as if, at times, the operators are intentionally on a go-slow to prove their point.

Either a change in mindset and motivation levels needs to be achieved or an additional operator needs to be hired or transferred into CDR to help prevent the delays that are causing excessive time losses and ultimately damaging the production levels of Hulamin.

**Training**

The maintenance function is a centralized unit that performs tasks as needed across the Remelt facility and an artisan or electrician is not always close-at-hand when required. The time spent waiting on maintenance personnel could easily be reduced by the training of crane operators and ASRS operators in the handling of simpler and more common problems. A tripped crane often needs only for the main switch at the breaker to be flipped and the crane operator is within meters of the offending switch, but the operator has to wait for someone to climb four floors, cross the upper walkway to the crane’s position, walk across the length of the crane and do exactly that – assuming that the maintenance worker is able to come immediately. It was also noted that ASRS operators are highly frustrated by the delay times that could be avoided by simple maintenance training in common occurrences such as replacing slipped chains on the ASRS tippler.

**Crane Utilisation**

As previously mentioned, there are two cranes used to load CDR melting furnaces. Crane 2 is designated to Line 3 and Crane 1 covers Line 1 and Line 2. Due to the fact that Line 1 and Line 2 share a single lid crane, they cannot be charged at the same time as only one furnace can be open at any one time. The loading of Line 1 and Line 3 simultaneously is tricky in that Bucket 7 is less than 12m away from the point of entry for the loading of Line 1. Therefore, if Crane 1 is in the process of lowering a bucket into Line 1, Crane 2 cannot access Bucket 7 or, in fact, any bucket other than Bucket 8. It is possible to raise Bucket 7 or another bucket further away from Line 3
and move toward the furnace while Crane 1 hooks a different bucket, but impeccable timing would be required as Crane 2 is decidedly slower than Crane 1.

Charging of Line 2 and Line 3 at the same time is practical and could significantly reduce the idle time of the combination of furnaces as long as the 12m gap is maintained. That means that if Line 3 utilises Bucket 6, Line 2 is limited to using only Buckets 1 to 3, as the distance between Bucket 4 and Bucket 6 is approximately 10.8m from center to center.

Almost all of the operators are trained and capable of operating the cranes, but due to other duties being performed, there is no one on hand to drive the second crane and so charging times are significantly increased when Line 2 and Line 3 come off together. This is projected to occur 6.97% of the time.

While studying the procedures in and about CDR, it was observed that Crane 2 has occasional electrical problems in the form of the power tripping. This could also prove to be hazardous should one attempt to charge Line 1 and Line 3 simultaneously as a stationary Crane 2 within 12m of Line 1 would halt the charging of both Line 1 and Line 3. Operators have to wait on electrical maintenance staff to reboot the crane, which can take a considerable amount of time despite the often simple nature of the problem.

9. Conclusions and Recommendations

Every solution rendered by the models described and demonstrated in this report was an optimal loading sequence for a specific furnace or combination of furnaces. In every modeled scenario, the charge time calculated was less than the historical mean charge time (from 2011 production data). The most significant time saving was seen in Model 2 with a potential saving of 7.404 minutes. Results like these in conjunction with a (sometimes surprising) change in loading sequence shows that the load time of different scraps into the various buckets can affect the overall charge time of a furnace and should be considered in the allocation of buckets for charging each furnace as these convert directly into financial savings.
Due to the position Hulamin is in with the fact that any additional mass produced by CDR is able to be processed and sold, as well as the high profit-per-ton value of processed aluminium, every minute saved within CDR is valuable. A minimum of R3807.95 was calculated and can be saved for every minute not lost.

It is clearly essential to eliminate the delays regarding both lid cranes and the hooking of buckets for charging. While the focus of this project was to establish whether a few minutes could be saved in the charging process through optimal allocation, it has allowed for the exposure of additional costly delays. These delays should be focused on and eliminated immediately to prevent further losses in production time and improve profits. These can easily be rectified which would lead to significant increases in output for the Remelt facility.

According to results and observations discussed in this report, it is recommended that an additional labourer be hired to aid in the running of the CDR shop floor specifically for the bucket hooking delay. The cost of hiring an additional person is insignificant in comparison to the potential savings. An additional operator on each shift will also better enable both cranes to be utilised simultaneously in charging Line 2 and Line 3 furnaces, saving further time in 6.97% of charging scenarios.

Although the decision trees, used in the decision model regarding the number of buckets allocated for charging, produced an answer that no extra buckets should be allocated, the two cases were very close in terms of expected outcomes. In cases where additional scrap is required from the ASRS, the ASRS operators should be allowed to use their discretion in allocating an additional bucket to the charging of a furnace line especially as it can take well over 30 minutes to fill a bucket through this method. In all other cases, ASRS operators need to follow a more structured procedure of loading buckets to reduce charge times.

A more specific loading sequence could be established for every type of alloy that is cast in CDR to make the resulting instructions even more accurate. The scope of such an undertaking was too large for this project but, from the gleaned results, it seems that the reduction in charge time variability that would arise from such an undertaking would justify the effort required to implement it.
10. Reference List


CDR Logistics and Technical. (2011). *Bucket Charging SOP.*


Appendix

A: Schematic of CDR Facility
B: Arena Simulation Model for Scenario Establishment

Part 1:

Links to Part 2 here
Part 2:

Links to Part 1 here
C: Gantt Charts for Bucket Loading

**Legend**
- Charge Bucket into Furnace
- Load Bucket with Scrap

**Line 1** charge and load with 2 buckets
- Bucket 1: 9.34
- Bucket 2: 9.34

**Line 1** charge and load with 3 buckets
- Bucket 1: 9.34
- Bucket 2: 9.34
- Bucket 3: 9.34

**Line 1** charge and load with 4 buckets
- Bucket 1: 9.34
- Bucket 2: 9.34
- Bucket 3: 9.34
- Bucket 4: 9.34

**Line 2** charge and load with 2 buckets
- Bucket 1: 9.48
- Bucket 2: 9.48

**Line 2** charge and load with 3 buckets
- Bucket 1: 9.48
- Bucket 2: 9.48
- Bucket 3: 9.48

**Line 2** charge and load with 4 buckets
- Bucket 1: 9.48
- Bucket 2: 9.48
- Bucket 3: 9.48
- Bucket 4: 9.48

Total time: 68.02
D: Scrap Classification

HEAVY SCRAP

INGOTS

BUTT-ENDS

HOTMILL CROPS

SOWS

PLATES

DROSS SOWS
PLATE OFF CUTS

MEDIUM SCRAP

PRESSED PUP-COILS

THIN TRIMS – Finishing Mill

THICK TRIMS

FULL COILS
LIGHT SCRAP

BALED FOIL

SWARF

PUP-COILS

BALL TRIMS

THIN TRIMS

CARCOUSTIC BALES
### MF1

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G: Model 3 Solution

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### H: Model 4 Solution

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## J: Model 6 Solution

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K: Model 1 Lingo Code

**Model:**

**Sets:**
- ScrapType/s1,s2,s3,s4/;
- Method/M1,M2/;
- Bucket/b1,b2,b3,b4,b5,b6,b7,b8/;
- TimePeriod/t1,t2,t3,t4,t5,t6/;
- Furnace/F1,F2,F3/: ChargeFurnace, RequiredMass;
- Equation/e1,e2,e3,e4/;
- BucketPerEquation (Bucket, Equation): a,b,h,u;
- MoveScrap (ScrapType, Method): carry_capacity;
- All (ScrapType, Method, Bucket, TimePeriod);
- ScrapPerBucket (ScrapType, Method, Bucket): Movement_Time;
- BucketPerTime (Bucket, TimePeriod);
- MethodBucketTime (Method, Bucket, TimePeriod);
- ScrapBucketTime (ScrapType, Bucket, TimePeriod);
- ScrapTypePerFurnace (ScrapType, Furnace): Demand;
- BucketPerFurnace (Bucket, Furnace): allocation, ChargeBucket, eqn,f;
- BucketTimeFurnace (Bucket, Furnace, TimePeriod): Load_Time, Loaded;
- AllFurnace (ScrapType, Method, Bucket, Furnace, TimePeriod):

**Objective**

Min = @sum(Furnace (m): ChargeFurnace (m));

@For (Furnace (m)|m#LE#2:[Maximum_Bkt_Allocation]

@Sum (Bucket (k): allocation (k, m)) <= 3;

@FOR (TimePerFurnace (m, t):[Bucket_Loaded_per_Period_Limit]

@Sum (Bucket (k): Loaded(k, m, t)) <= 1;

@For (ScrapTypePerFurnace (i, m): [Meet_demand]

@Sum (MethodBucketTime (j, k, t): Amount_Scrap (i, j, k, m, t)) >= demand(i, m));

[Light_Scrap_ASRS] @sum (BucketPerTime (k, t): Amount_Scrap(1, 1, k, 1, t)) >= 7;

@sum (BucketPerTime (k, t): Amount_Scrap(1, 1, k, 2, t)) >= 9;

[Light_Scrap_Total1] @sum (MethodBucketTime (j, k, t): Amount_Scrap (1, j, k, 1, t)) <= 13.5;

[Light_Scrap_Total2] @sum (MethodBucketTime (j, k, t): Amount_Scrap (1, j, k, 2, t)) <= 13;

[Light_Scrap_Total3] @sum (MethodBucketTime (j, k, t): Amount_Scrap (1, j, k, 3, t)) <= 8;

@for (Furnace (m):[Pig_FLT]

@sum (BucketPerTime (k, t): Amount_Scrap(4, 2, k, m, t)) <= 23;

@for (Furnace (m):[No_Pig_ASRS]

@sum (BucketPerTime (k, t): Amount_Scrap(4, 1, k, m, t)) = 0;

[Heavy_scrap_limit1] @sum (MethodBucketTime (j, k, t): Amount_Scrap (3, j, k, 1, t)) <= 9;

[Heavy_scrap_limit2] @sum (MethodBucketTime (j, k, t): Amount_Scrap (3, j, k, 2, t)) <= 8;
![Heavy_scrap_limit3]@\text{sum} (\text{MethodBucketTime} (j, k, t): \text{Amount_Scrap} (3, j, k, 3, t)) \leq 8; \\
@\text{for}(\text{ScrapType} (i));
@\text{for} (\text{BucketTimeFurnace} (k, m, t): [\text{linkTripsToLoaded}]
\@\text{sum}(\text{Method} (j): \text{Number_Trips} (i, j, k, m, t)) \leq 20*\text{Loaded}(k, m, t));

\text{mf2} \text{ must have 1 bucket of floor scrap;}
![MF2ASRS] @\text{sum} (\text{BucketPerTime} (k, t):
@\text{sum}(\text{ScrapType} (i) | i\#NE\#4: \text{Amount_Scrap} (i, 1, k, 2, t)) \geq 34;
![MF2FLT] @\text{sum} (\text{BucketPerTime} (k, t):
@\text{sum}(\text{ScrapType} (i) | i\#NE\#4: \text{Amount_Scrap} (i, 2, k, 2, t)) \geq 17;

\text{additional load time for objective function;}
\text{a if statements;}

@\text{for}(\text{Bucket} (k):
@\text{for}(\text{Furnace} (m) | m\#LE\#2: 
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, m, 4) - \text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 2) - 
\text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 3)) - a(k, m, 1) \leq 1000*b(k, m, 1);
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, m, 4) - \text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 2) - 
\text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 3)) \leq 1000*(1-b(k, m, 1));
);)
)
@\text{for}(\text{Bucket} (k):
@\text{for}(\text{Furnace} (m) | m\#LE\#2: 
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, m, 5) - \text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 3) - 
\text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 4)) - a(k, m, 2) \leq 1000*b(k, m, 2);
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, m, 5) - \text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 3) - 
\text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 4)) \leq 1000*(1-b(k, m, 2));
);)
)
@\text{for}(\text{Bucket} (k):
@\text{for}(\text{Furnace} (m) | m\#LE\#2: 
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, m, 6) - \text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 4) - 
\text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 5)) - a(k, m, 3) \leq 1000*b(k, m, 3);
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, m, 6) - \text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 4) - 
\text{ChargeBucket} (k, m) * \text{Loaded}(k, m, 5)) \leq 1000*(1-b(k, m, 3));
);)
);
@\text{for}(\text{Bucket} (k):
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, 3, 3) - \text{ChargeBucket} (k, 3) * \text{Loaded}(k, 3, 2)) - a(k, 3, 4) \leq 1000*b(k, 3, 4);
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, 3, 3) - \text{ChargeBucket} (k, 3) * \text{Loaded}(k, 3, 2)) \leq 1000*(1-b(k, 3, 4));
);
@\text{for}(\text{Bucket} (k):
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, 3, 4) - \text{ChargeBucket} (k, 3) * \text{Loaded}(k, 3, 3)) - a(k, 3, 1) \leq 1000*b(k, 3, 1);
\@\text{sum}(\text{Bucket} (k): \text{Load_Time} (k, 3, 4) - \text{ChargeBucket} (k, 3) * \text{Loaded}(k, 3, 3)) \leq 1000*(1-b(k, 3, 1));
);)
@for (Bucket (k):
    @sum (Bucket (k): Load_Time (k,3,5) - ChargeBucket (k,3) * Loaded (k,3,4)) - a (k,3,2) <= 1000 * b (k,3,2);
    @sum (Bucket (k): Load_Time (k,3,5) - ChargeBucket (k,3) * Loaded (k,3,4)) <= 1000 * (1 - b (k,3,2));
);
@for (Bucket (k):
    Load_Time (k,3,5) - a (k,3,3) <= 1000 * b (k,3,3);
    Load_Time (k,3,5) - a (k,3,3) <= 1000 * (1 - b (k,3,3));
);
!
!u (k,m,e) if statements;

@for (BucketPerFurnace (k,m):
    Load_Time (k,m,4) - u (k,m,1) <= 1000 * f (k,m);
    Loaded (k,m,3) + Loaded (k,m,4) - 1 <= 1000 * (1 - f (k,m));
);
@for (BucketPerFurnace (k,m):
    Load_Time (k,m,5) - u (k,m,2) <= 1000 * f (k,m);
    Loaded (k,m,3) + Loaded (k,m,5) - 1 <= 1000 * (1 - f (k,m));
);
@for (BucketPerFurnace (k,m):
    Load_Time (k,m,6) - u (k,m,3) <= 1000 * f (k,m);
    Loaded (k,m,3) + Loaded (k,m,6) - 1 <= 1000 * (1 - f (k,m));
);
@for (Bucket (k):
    Load_Time (k,3,3) - u (k,3,4) <= 1000 * f (k,3);
    Loaded (k,3,2) + Loaded (k,3,3) - 1 <= 1000 * (1 - f (k,3));
);

!else;
@for (Bucket (k):
    a (k,3,4) - u (k,3,4) <= 1000 * h (k,3,4);
    2 - Loaded (k,3,2) - Loaded (k,3,3) <= 1000 * (1 - h (k,3,4));
);
@for (BucketPerFurnace (k,m):
    a (k,m,1) - u (k,m,1) <= 1000 * h (k,m,1);
    2 - Loaded (k,m,3) - Loaded (k,m,4) <= 1000 * (1 - h (k,m,1));
);
@for (BucketPerFurnace (k,m):
    a (k,m,2) - u (k,m,2) <= 1000 * h (k,m,2);
    2 - Loaded (k,m,4) - Loaded (k,m,5) <= 1000 * (1 - h (k,m,2));
);
!@for (BucketPerFurnace (k,m):
    a (k,m,3) - u (k,m,3) <= 1000 * h (k,m,3);
    ! 2 - Loaded (k,m,5) - Loaded (k,m,6) <= 1000 * (1 - h (k,m,3));
!);

@for (BucketPerFurnace (k,m): eqn (k,m) = @sum (Equation (e): u (k,m,e)));
@for (Furnace (m):
    @for (Equation (e): [binary_b]
        @Bin (b (k, m, e))));

@for (Bucket (k):
    @for (Furnace (m): [binary_f]
        @Bin (f (k, m))));

@for (Bucket (k):
    @for (Furnace (m):
        @for (Equation (e): [binary_h]
            @Bin (h (k, m, e))));

@For (AllFurnace(i,j,k,m,t): Amount_scarep(i,j,k,m,t) >= 0.5*
    Number_Trips(i,j,k,m,t));

[Med_percentage_of_All] @sum (MethodBucketTime (j, k, t): Amount_Scrap (2, j, k, 1, t)) <= 0.65*@
    sum (All (i, j, k, t): Amount_Scrap (i, j, k, 1, t));
@for (Furnace (m): [Total_scrap_required]
    @sum (All (i, j, k, t): Amount_Scrap (i, j, k, m, t)) >= RequiredMass
    (m));
@FOR (BucketTimeFurnace (k, m, t): [bucket_mass_limit]
    @sum (MoveScrap (i, j): Amount_Scrap (i, j, k, m, t)) <= 19);
@for (AllFurnace (i, j, k, m, t): [set_number_of_trips]
    Number_Trips (i, j, k, m, t) >= (Amount_Scrap (i, j, k, m, t))/(carry_capacity (i, j)));
@for (BucketTimeFurnace (k, m, t): [CalcLoadTime]
    Load_Time(k, m, t) = @sum (MoveScrap (i, j): (Number_Trips (i, j, k, m, t)) * (Movement_Time (i, j, k, m, t)));
@for (BucketTimeFurnace (k, m, t): [WhetherLoaded]
    @sum (MoveScrap (i, j): Amount_Scrap (i, j, k, m, t)) <= 100*(Loaded(k,m, t));
@for (BucketPerFurnace (k, m): [WhetherAllocated]
    @sum (ScrapMethodTime (i, j, t): Amount_Scrap (i, j, k, m, t)) <= 100*(allocation (k, m));
@for (Furnace (m):
    @for (Bucket (k)|k#NE#2#AND#k#NE#3#AND#k#NE#4#AND#k#NE#5#AND#k#NE#6:
        [NonASRSBucket]
            @sum (ScrapPerTime (i, t): Amount_Scrap (i, 1, k, m, t)) = 0);
@for (Furnace (m):
    ChargeFurnace (m) = @sum (BucketPerTime (k, t): ChargeBucket(k, m) *
        Loaded(k,m,t)) + @sum (Bucket(k):eqn(k,m)));
@For (Bucket (k):
    @sum (Furnace (m): allocation (k, m)) <= 1);

@for (Bucket (k): Loaded (k, 1, 1) + Loaded (k, 1, 2) + Loaded (k, 1, 3) <= 1);
@for (Bucket (k): Loaded (k, 2, 1) + Loaded (k, 2, 2) + Loaded (k, 2, 3) <= 1);
!@for (Bucket (k): Loaded (k, 3, 1) + Loaded (k, 3, 2) <= 1);
@For (Furnace (m): [LoadSequentially1]
    @sum (Bucket (k): Loaded(k,m,3) - Loaded(k,m,4)) >= 0);
@For (Furnace (m): [LoadSequentially2]
    @sum (Bucket (k): Loaded(k,m,4) - Loaded(k,m,5)) >= 0);
@For(Furnace (m): [LoadSequentially3]
@sum(Bucket (k): Loaded(k,m,5) - Loaded(k,m,6)) >= 0);
!@sum(Bucket (k): Loaded(k,3,2) -Loaded(k,3,3)) >= 0;

@for( BucketTimeFurnace (k,m,t): Loaded(k,m,t) <= allocation(k,m));
@for (ScrapType (i):
@for (Method (j):
@for (Bucket (k):
@for (Furnace (m):
@for (TimePeriod (t):[amount_scrap_positive]
  Amount_Scrap (i, j, k, m, t) >=0))));

@for (ScrapType (i):
@for (Method (j):
@for (Bucket (k):
@for (Furnace (m):
@for (TimePeriod (t):[General_Int_number] @Gin (Number_Trips (i, j, k, m, t))));)

@for (Bucket (k):
@for (Furnace (m):[Binary_allocation] @Bin (allocation (k,m)));
@for (Bucket (k):
  @for (Furnace (m):
    @for (TimePeriod (t): [binary_loaded]
      @Bin (Loaded (k, m, t))));)

DATA:
Demand = 11, 0, 0,
15, 0, 0,
6, 0, 0,
10, 0, 0;
carry_capacity = 1.2, 1.2,
1.6, 3,
3.5, 4,
0.1, 4;
Movement_Time = 20, 3.34, 2.95, 2.46, 2.13, 2.13, 20, 20,
0.903, 0.953, 1.047, 1.285, 1.316, 1.346, 1.968, 2.008,
20, 3.34, 2.95, 2.46, 2.13, 2.13, 20, 20,
2.5, 2.556, 3.308, 3.404, 3.456, 3.656, 3.88, 4.03,
20, 3.34, 2.95, 2.46, 2.13, 2.13, 20, 20,
2.75, 3.325, 3.363, 3.409, 3.629, 3.829, 4.034, 4.127,
20, 20, 20, 20, 20, 20, 20, 20,
2.667, 2.645, 2.678, 2.727, 2.816, 3.066, 3.3, 3.463;
ChargeBucket = 9.11, 8.047, 20,
8.94, 7.723, 20,
8.659, 7.615, 20,
8.542, 7.579, 10.727,
8.482, 7.978, 10.54,
8.422, 8.318, 10.352,
8.985, 20, 9.065,
9.19, 20, 8.87;
RequiredMass = 79.5, 0, 0;
Enddata
End