Estimating and Optimizing Throughput in an Aluminum Rolling Mill Using Capacity Modeling and Optimization Techniques

by

Scott Hungerford
B.S. Civil Engineering, California State Polytechnic University, Pomona (2016)

Submitted to the MIT Sloan School of Management
and
Department of Civil and Environmental Engineering
in partial fulfillment of the requirements for the degrees of
Master of Business Administration
and
Master of Science in Civil and Environmental Engineering
in conjunction with the Leaders for Global Operations program at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2023

Signature of
Author……………………………………………………………………………………………
MIT Sloan School of Management
and
Department of Civil and Environmental Engineering
May 12, 2023

Certified by:
……………………………………………………………………………………………………
Dr. David Simchi-Levi
Professor of Engineering Systems and Civil & Environmental Engineering, Thesis Supervisor

Certified by:
……………………………………………………………………………………………………
Sean Willems
Visiting Professor in Operations Management, Thesis Supervisor

Accepted by: ………………………………………………………………………………
Maura Herson
Assistant Dean, MBA Program, MIT Sloan School of Management

Accepted by: ………………………………………………………………………………
Colette L. Heald
Professor of Civil and Environmental Engineering Chair, Graduate Program Committee

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Abstract

The aluminum industry has sustained continuous growth since 1975 and expects to continue this trend with the increased popularity of electric vehicles. With these forecasts in place and the current market conditions, Commonwealth Rolled Products (CRP) is in a unique position to meet the increased market demand and supply auto and industrial product manufacturers with aluminum rolled products. In order for CRP to be able to meet the increased demand, they first must understand the full complexities of their operations and confidently estimate future volumetric capacity they are able to sell.

The objective of the internship program with CRP is to provide a quantitative analysis on the current state and future state throughput of the complex continuous line (CCL). The analysis includes a heuristic model to determine the throughput and identify key performance indicators (KPIs) that impact throughput improvement the greatest. This model will recommend a roadmap to achieve a sustainable operations plan and sales forecast that will enable increased manufacturing capabilities.

In addition to the heuristic model, a mixed integer program (MIP) will be developed to optimally schedule the product mix to reduce production hours lost to product changeover time. The scheduling of a CCL is considered a single machine scheduling problem (SMSP), and the introduction of transition coils is considered a sequence-dependent setup times (SDSTs) problem. This last portion of the paper will focus on the MIP application to optimally schedule the CCL to reduce transition coils.

Acknowledgements

I would like to start by thanking AIP and the Commonwealth Rolled Product team for their support throughout the internship. It was an honor to become a member of the team and learn about the aluminum industry. A special thanks to Kaitlyn Nealon, Derek Leck, Bill Dunlay, and Ashley Spencer for being great mentors and friends. To the CCL Steering Committee, thanks for always giving me a chance to share my ideas and research with the team.

To the LGO program for welcoming me to the LGO family and for the continuous support these past two years.

I would like to thank my thesis advisors David Simchi-Levi and Sean Willems for guiding my project and shaping the thesis with their knowledge and expertise.

A special thanks to my wife Christine for the motivation and support to apply to the MIT LGO program. I wouldn’t have been able to achieve this without you.

To my parents, thank you for giving me every chance to grow and succeed and always emphasizing the importance of education.

To my brother Vince, thanks for always being there for me when I needed your support, and for being the greatest best man at my wedding.

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1 Introduction

1.1 Project Motivation

The aluminum industry has sustained continuous growth since 1975 and expects to continue this trend with the increased popularity of electric vehicles. (Ducker Frontier) Since 2015, the annual average aluminum weight increase per vehicle in North America has been 69 lbs. This is due to aluminum's lightweight properties compared to steel and the auto industry's desire to improve their vehicle's mile per gallon (mpg) metric. All factors equal, cars designed with aluminum accelerate quicker, brake in shorter distances and handle corners better than their heavier, less-efficient counterparts. The aluminum industry is confident that auto manufacturers will continue to replace traditionally steel components with advanced aluminum products to improve the weight, mpg, and overall performance of their vehicles.

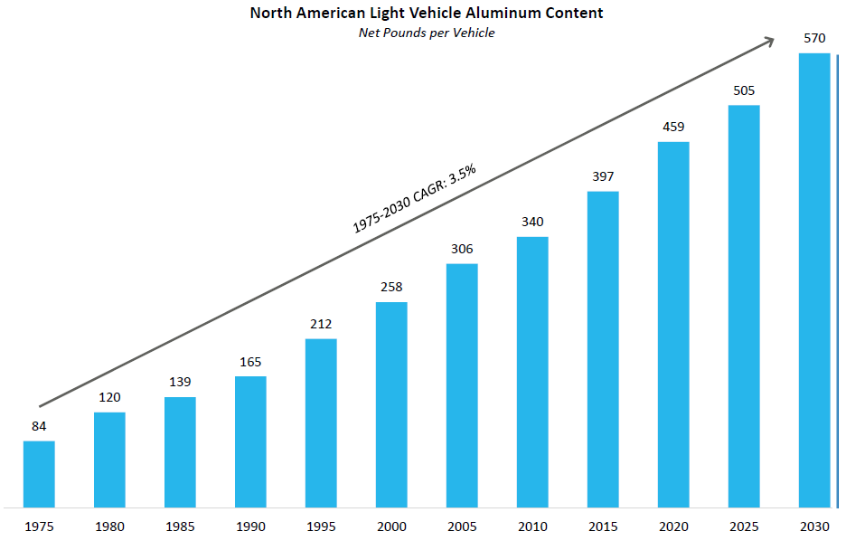

FIGURE 1: ALUMINUM GROWTH IN LIGHT VEHICLES FOR NORTH AMERICA (DUCKER WORLDWIDE)

With these forecasts in place and the current market conditions, Commonwealth Rolled Products (CRP) is in a unique position to meet the increased market demand and supply auto manufacturers with aluminum rolled products. In order for CRP to be able to meet the increased demand, they first must understand the full complexities of their operations and confidently estimate future volumetric capacity they are able to sell.

In his book Operations Rules, Dr. David Simchi-Levi emphasizes that the most valuable aspect of a company's value proposition is "the customer's perceived value of the entire relationship with a company." (Simchi-Levi) In my perspective, CRP agrees with this point of view and is convinced that understanding their operations and future capabilities will improve existing relationships with their customers, and give them the confidence to establish new partnerships with emerging players in the automotive and industrial sectors.

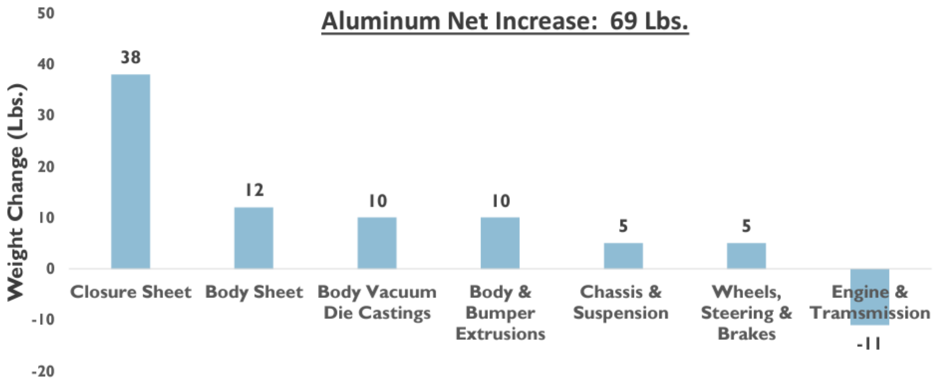

FIGURE 2: ALUMINUM COMPONENT WEIGHT CHANGES FROM 2015 TO 2020 (ABEY ABRAHAM)

1.2 Problem Statement

CRP aims to increase their automotive volumes significantly over the next three years and needs to understand the current state and future state throughput for their complex continuous lines (CCLs), which is comprised of two separate production lines (CCL 1 and CCL 2).

The CCLs are the at the tail end of the plant process and is a required step for most aluminum coils specified for the automotive industry. CCL operations and throughput significantly depends on a multiple array of factors including: 1) physical characteristics of incoming aluminum coils (gauge, width, length, alloy); 2) CCL furnace and pre-treatment recipe; 3) difference in physical characteristics and CCL recipes between the current coil being processed and the next in line to be processed; and 4) material recovery including reducing entire whole-unit-losses (WULs). The thesis will focus on providing CRP with a methodical process to determine current CCL throughput, identify key areas of improvement, and determining their maximum CCL throughput to assist in CRP's strategic and business planning.

The output will be a heuristic capacity model that will determine the current and future CCL capacity with key performance metrics identified. The capacity model will be compared to historic metrics to determine if the predicted throughput is representative of current operations. The scheduling portion of the capacity model will also be analyzed using a mixed integer program (MIP) method to further estimate how schedule optimization could improve CRP throughput.

2 Background

2.1 Commonwealth Rolled Products

Commonwealth Rolled Products (CRP) is a leader in the manufacture and sale of aluminum rolled products. CRP is an aluminum rolling mill that manufactures finished aluminum coils to the industrial and automotive sectors. CRP employs ~1100 employees at its primary manufacturing site in Lewisport, KY. The CRP facility houses over 53 acres of manufacturing area and sits on ~1300 acres of land. Nineteen different aluminum alloys are produced at the facility with widths ranging from 4" to 92" and rolled gauges of 0.5mm to 4mm. (Commonwealth Rolled Products)

FIGURE 3: ALUMINUM COILS MIDWAY THROUGH THEIR PROCESS, AWAITING FINISHING PROCESSING

3 Aluminum Rolling Process

Rolling aluminum is an industry standard method of converting aluminum slab produced from smelters into a usable industrial form, coils and flat sheets. Aluminum rolling has a short history of about 200 years but the technology and process has matured and stabilized significantly over the past two decades, with sophisticated methods resulting in a higher quality end product. (Mallesham) The aluminum rolling process makes it possible to reduce a primary aluminum ingot, weighing up to 20 tons, to thick plate gauges (typically 250 mm to 6 mm), sheet gauges (typically 6 mm to 250 µm), and ultimately foil gauges (typically 250 µm to 6 µm). The rolling process has enabled around 50% of all aluminum use to be in the flat rolled product form. (Mallesham) The following sections will further explain in detail the rolling process from ingot to final rolled product.

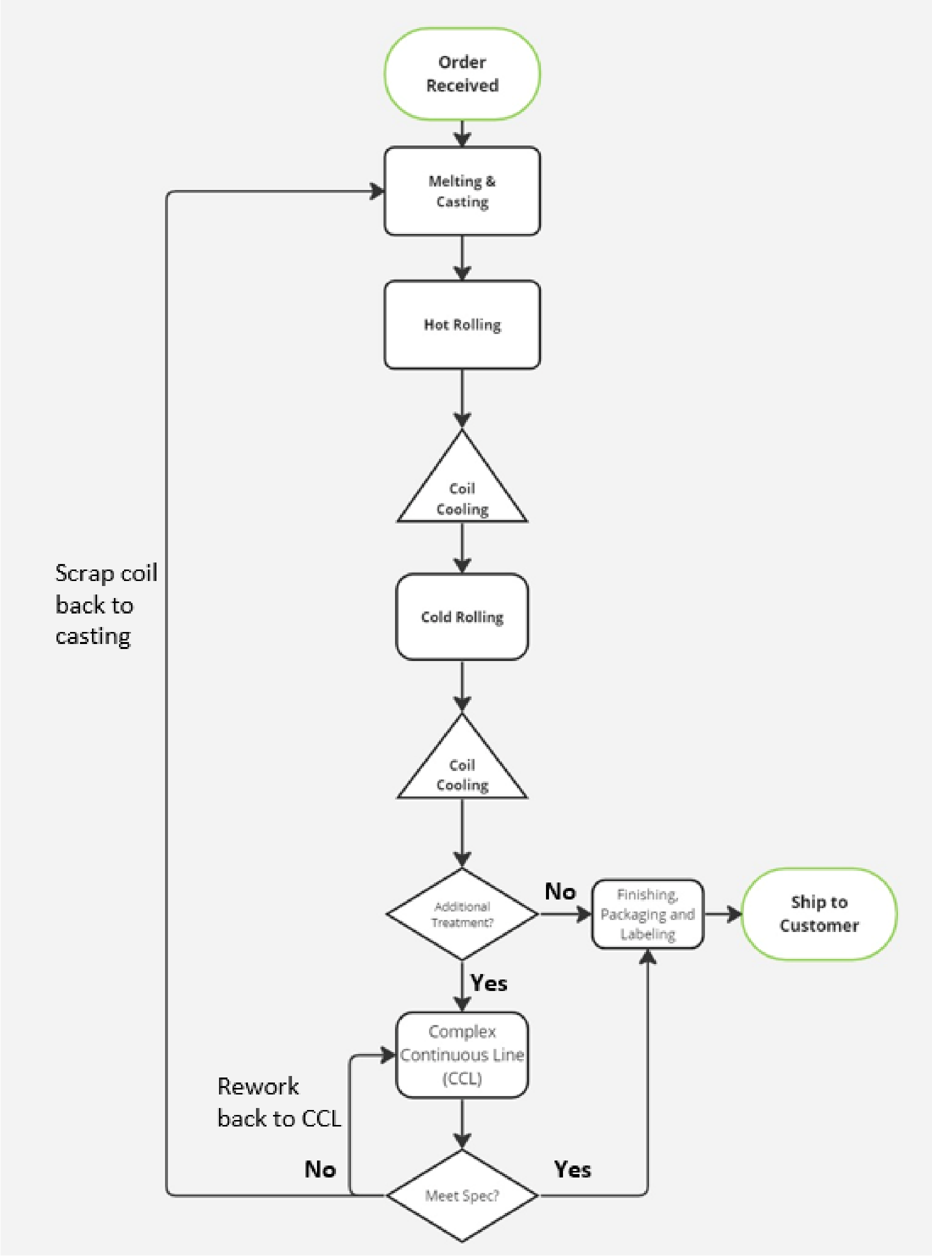

FIGURE 4: ALUMINUM ROLLING PROCESS

3.1 Melting and Casting

At CRP's casting operation, prime ingot, which is purchased from outside vendors, and scrap metal produced during the rolling process, are melted and converted into molten aluminum and then recast into ingot molds and baked within the melting furnaces. Hardeners and additives are included in the mix to meet certain customer specifications and to ensure the final product has certain physical, chemical, and metallurgical properties. Once CRP has created slabs, the slabs are then heated in the pit furnaces and tunnel furnaces to ensure optimal uniformity of metal temperature prior to hot rolling. Each pit and tunnel furnace can typically hold around 10-20 slabs at any given time, and the furnace temperatures can be controlled in various different zones.

FIGURE 5: MELTING & CASTING PROCEDURE (CHEMISTRY DEPENDENCE OF CONSTITUTIVE MODELS)

3.2 Hot Rolling

During hot rolling the microstructure and mechanical properties of the material change with its thermomechanical state, determined by composition, percent reduction, strip thickness, strip speed, and heat transfer. Although hot rolling for steel is conducted around 850-1200 degrees Celsius aluminum hot rolling is conducted around 350-500 degrees Celsius. (K.H. Jürgen Buschow) The hot rolling process passes the aluminum slab back and forth through special rollers that operate at high temperature regimes.

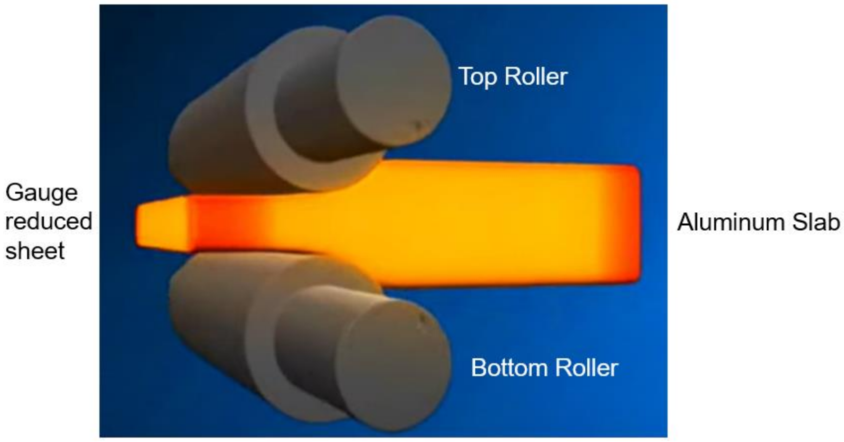

FIGURE 6: METAL SLAB PROCESSED THROUGH HOT ROLLERS (WILLIAMSON)

3.3 Cold Rolling

After an aluminum coil has been processed through the hot rolling procedure and has cooled to room temperature, the aluminum can be processed through the cold rolling mill line. The coil is passed several times between a series of rollers until the aluminum sheet has reached the desired gauge. Each pass generates heat and required the coil to sit idle for a certain time period to allow the metal to reach room temperature once again. The number of passes is determined by the type of alloy and the incoming and outgoing gauge specifications. The metal is processed below its re-crystallization temperature and increases the strength of the aluminum by up to 20%, allowing for the aluminum to serve a wide variety of end uses. (Mallesham)

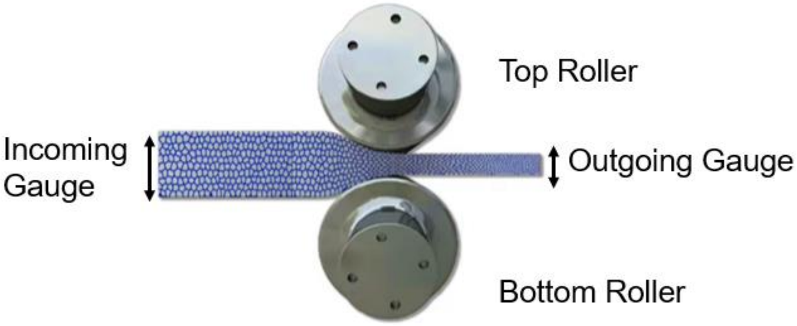

FIGURE 7: COLD MILL ROLLING ALUMINUM INTO THE DESIRED GAUGE (MALLESHAM)

3.4 Complex Continuous Line (CCL)

The Complex Continuous Line (CCL) process is the primary focus of this paper and the most complex process in the plant’s operation, involving multiple distinct sub processes to produce a finished aluminum coil. The CCL processes aluminum alloys that arrive from the cold rolling mills, and is capable of processing mill finish and electric discharge texture (EDT) surfaces. The CCL process combines the two historically separate processes into a single, fully automated line: heat treatment and surface treatment. (Andritz)

3.4.1 Stitching and Leveling

The first step in the CCL process is the mechanical stitching and leveling process. The mechanical stitcher physically attaches the incoming coil to the current coil being processed allowing for a continuous process. As seen in Figure 8, the mechanical stitcher has to consider the physical properties of both coils and bonds them together so the CCL machines perceive the two sheets as one body.

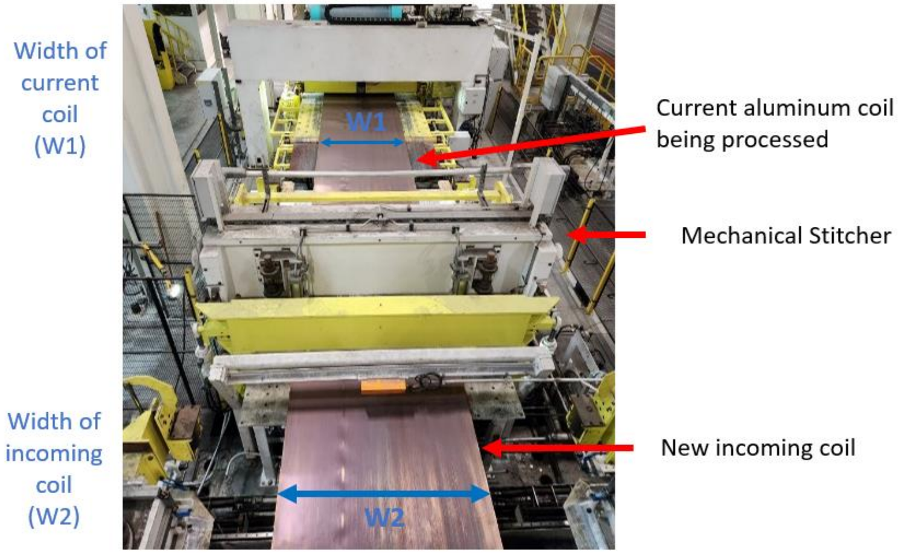

Figure 8: CCL Mechanical Stitcher

The mechanical stitcher is a critical component and also introduces a physical limitation to the scheduling process, which will be discussed in the later sections of this paper.

The leveler ensures that the incoming coil is on the correct trajectory and that the sheet has the correct curvature. The leveler also removes stresses from the sheet and makes the material lay flat through processing.

FIGURE 9: MECHANICAL STITCH PHYSICALLY CONNECTING TWO SEPARATE COILS IN THE CCL PROCESS (ANDRITZ)

3.4.2 Chemical Treatment

Automotive sheet requires cleaning (degreasing), pickling (de-oxidizing), and conversion (passivation). All of these processes are integrated into the CCL and react with high flexibility to the changing line speeds determined by the heat treatment furnace. (Andritz)

Before pickling, the aluminum coils are thoroughly degreased and cleaned in the first rinse cycle. This is an important step since pickling of greasy parts is not possible because it would prevent a uniform surface structure. Pickling occurs to restore the aluminum's appearance and corrosion-resistant properties after processing. Passivation occurs to apply an oxide coating to further prevent oxidation and corrosion. These steps are important for the end product because it improves the product's usability and ensures the customer has a long-lasting quality product. This is specifically important in the automotive industry due to the nature of vehicles being a high-cost personal item and the cost of repairing defects and external damage are expensive.

3.4.3 Heat Treatment

Heat treatment of aluminum alloys, annealing or solution heat treatment, requires high temperatures above 500 degrees Celsius, close to the melting point of aluminum alloys. The heat treatment is critical because it establishes and locks in the metallurgical properties of the aluminum products. The aluminum strip is heat treated through the CCL furnace. The heat treatment process of the CCL is very sensitive to product changes and requires in-depth technical analysis to understand the speed at which each product should be processed at. If CRP desired to increase the processing speed of any of their existing product lineup, then the engineering team would need to understand how an increased speed impacts the movement of metal during the heat treatment cycle.

Aluminum products have different incoming properties (gauge, width, and hardness) that make the aluminum sheets behave differently during heat treatment. By being able to set the heat treatment for every combination of the three incoming parameters, the company is able to maximize recovery chances and production speed. If the aluminum does not process correctly or begins to oscillate due to incorrect processing speed or adverse reaction to other operating parameters, then this increases the risk that the product will be damaged during the heat treatment process. One of the most common quality issues is a “furnace scratch”. This happens when the top or bottom portion of the aluminum sheet touches either the end of the furnace, creating a long scratch or streak on the aluminum sheet. This quality issue usually results in a whole-unit-loss, which makes the entire coil unsaleable and requires CRP to scrap the coil and re-melt it back in the casting process. For this reason, both the processing speed, heat treatment time, and operating controls are critical components when the engineering team designs the CCL process for each product. The paper will discuss the importance in more detail in section 6.2.5.

3.5 Finishing

The last step in the rolling process prior to shipping the product to the customer is finishing. Finishing ensures the product is blemish free, meets customer specifications, and was processed correctly through the rolling process. This is also a critical step in the quality control process, allowing CRP to thoroughly review the finished coil and occasionally scrap portions of the coil if it doesn’t meet customer specifications. This process can either be performed in-house or subcontracted out to a specialist.

4 Literature Review

4.1.1 Scheduling Optimization

There has been various works aimed at single machine scheduling problems (SMSP). The first literature found on SMSP was authored by Lenstra Balas. (Balas) Balas researched an SMSP with release dates, delivery times, and delayed precedence constraints. Balas identified the problem as a relaxation of the job-shop scheduling problem (JSP) which is tighter than the standard SMSP relaxation. The results showed that the SMSP could consistently achieve better solutions for all classes of JSPs compared to other algorithms, but sacrificed computational power to achieve the better results. Luckily in modern times, computational power has enabled SMPSs to achieve great results with commonly owned computational power.

Another research paper authored by Finta and Liu examined an SMSP with delayed precedence constraints, with the goal of minimizing the makespan. (Z. and L.) Finta and Liu identified that this problem was NP-hard in the strong sense when the delay and execution times are integers, and it is polynomically solvable with an $O(n^2)$ optimal algorithm.

5 Data Sources

5.1 Data from Stakeholder Engagements

5.1.1 Operational Data

Data was collected through a variety of different method, but the primary operational data source originated from the CCLs' propriety software and data storage system. The data was stored in an oracle database which allowed for easy SQL extraction and Python and Excel manipulation.

5.1.2 Sales Forecast

In addition to the operational data, customer forecast data was the main driver in determining future demand for the CCLs. The demand data was compiled by the Sales team and was generated through multiple conversations with both existing and new customers. The sales forecast informed the heuristic model on how much weight was demanded for each SKU.

6 Exploratory Analysis

6.1 Product offerings

CRP produces aluminum rolled products for a wide variety of industries using a broad range of alloys and processing techniques to meet any customer specification. The industries CRP currently services include: automotive, building and construction, commercial transportation, consumers goods, and industrial products. (Commonwealth Rolled Products)

Focusing on CRP’s automotive offerings, CRP is a leading supplier in the automotive industry and can manufacture light weight solutions for a sustainable vehicle approach. (Commonwealth Rolled Products) . As shown in Figure 10, the end products for CRP’s automotive aluminum products range from being converted into a car hood, a body side panel, trunk lid, or the roof of the vehicle. Each portion of the car has a unique metallurgic and physical property requirement that CRP must meet.

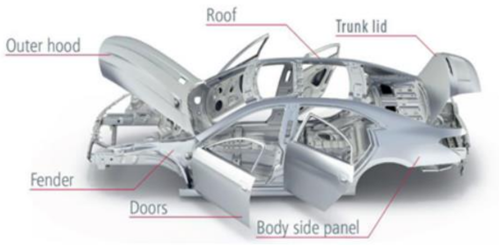

FIGURE 10: ALUMINUM END USES (COMMONWEALTH ROLLED PRODUCTS)

6.2 Product Variation

6.2.1 Product Gauge

As seen in Figure 11, CRP offers a wide variety of ranges for their products to meet the needs of their customers.

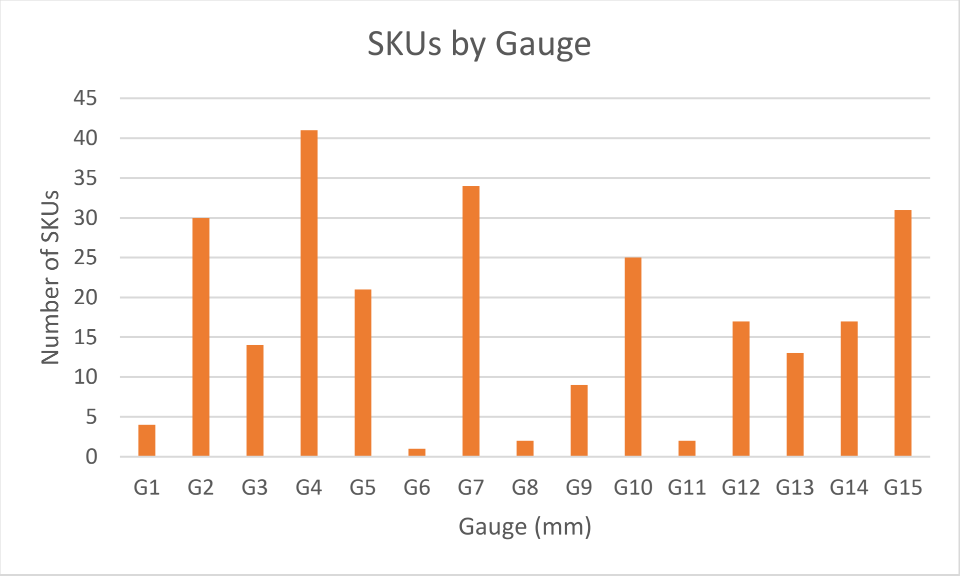

FIGURE 11: ACTIVE PRODUCT OFFERINGS BY GAUGE

6.2.2 Product Widths

As seen in, Figure 12 CRP offers a wide variety of widths for their products to meet the needs of their customers.

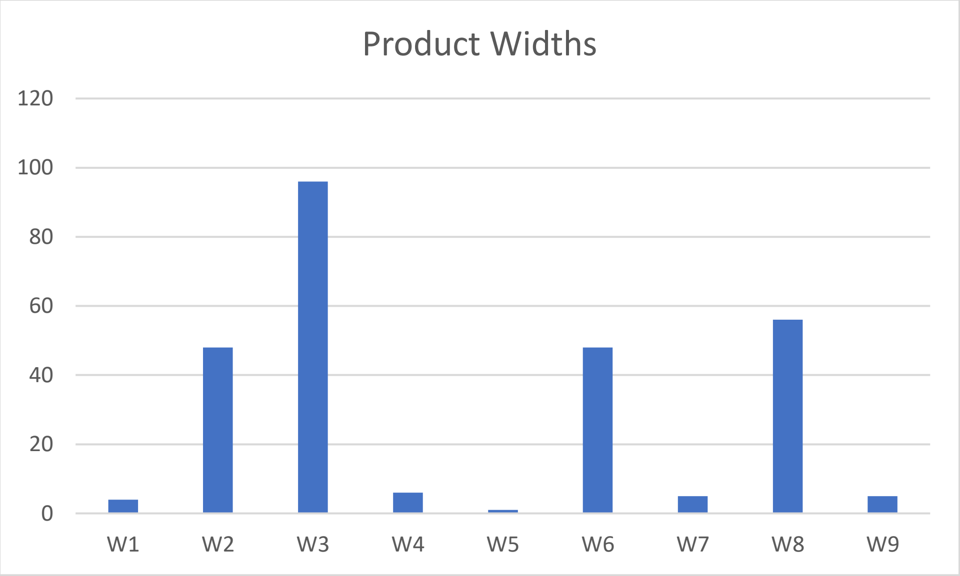

FIGURE 12: WIDTHS OF ACTIVE PRODUCTS

6.2.3 CCL Recipes

Looking at just one of the CCL machines, we see that there exists many unique CCL recipes that are processed on Machine 1. Each recipe contains unique product offerings that will be used by different customers for different end uses. For example, looking at Figure 13: Active Product Offerings per CCL Recipe, there are many different SKUs that use the same CCL Recipe ID 10. However, their end uses may differ greatly. One product may be used to create an external automobile rear end, while another product utilizing the same CCL Recipe ID may be used to create a door handle for a different manufacturer.

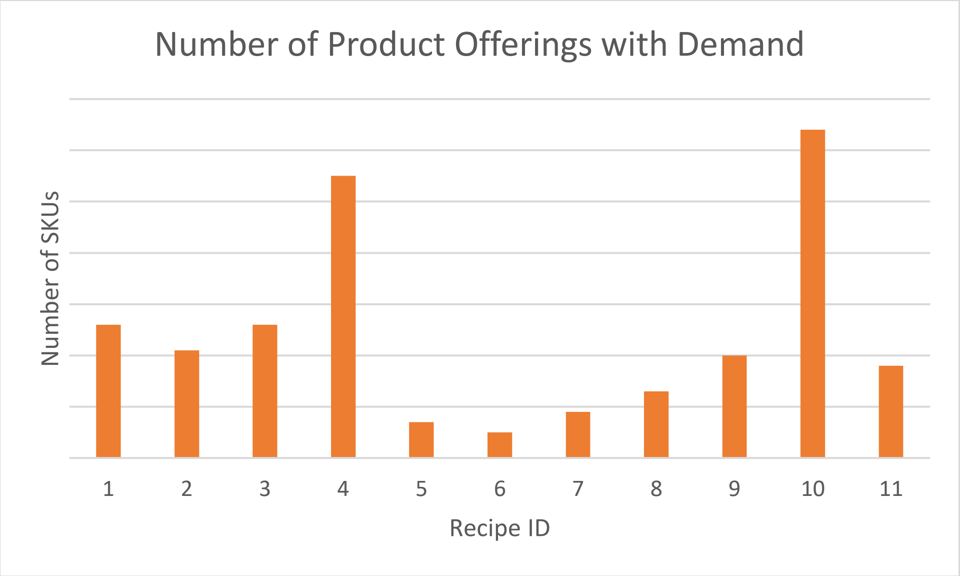

FIGURE 13: ACTIVE PRODUCT OFFERINGS PER CCL RECIPE

6.2.4 Chemical Processing

Different end uses requires different chemical treatments to prevent corrosion and oxidation. The customer sets the chemical treatment requirements for each product.

6.2.5 CCL Transition Rules

As with most production lines, product changeover is a major consideration for production planning. The CCLs have a set of product changeover rules that they describe as “transition rules.” These transition rules trigger a “transition coil”, which allows the necessary setup time required to allow for processing a product with different physical, metallurgical, and chemical characteristics. The specific transition rules are proprietary information, but they are related to the cross section, metallurgical properties, and chemical and temperature requirements for a given coil. If one of the aforementioned tolerances are exceeded, then a transition coil is scheduled to prepare the CCL to process the following coil.

7 Heuristic Capacity Model

7.1 Motivation and Challenges

This heuristic model was motivated by the following:

- Conversations with the company’s subject matter experts, which include management, production supervisors, supply chain professionals, and technical engineers
- A desire for the company to be able to comprehend model results and compare the results and iterations with current tracked operational performance metrics
- The need for the company to have a tool that they were able to use for their monthly Integrated Sales, Inventory and Operations Planning (SIOP)
- An expedited request to complete the model within the company’s timeline of securing future business

The major challenge to develop this model was a lack of domain knowledge and extracting useful information from the data available. It took time to understand the entire rolling process and to narrow down the unique manufacturing capabilities of both the plant and the CCLs. Understanding which data sources were useful in the analysis was difficult because it was challenging to differentiate specific instances in the process that should be included in the study.

For example, overall unit recovery is not the same as length recovery because unit recovery includes width in the calculation. When comparing historical data of a certain product to inspect the trends of material recovery, it is imperative that the original ingot width is known to make an accurate estimate of unit recovery. If a wider than normal ingot was used to make a certain product, than the width will affect the weight of the product at different stages. However, when the product has completed the rolling process and is trimmed to the final width, the unit recovery is negatively impacted because only increased weight due to length improves the product yield. This is why many rolling professionals state that “width is free” when discussing metal rolled products. This concept was difficult to grasp initially and caused historical data analysis efforts to be redone.

7.2 Approach

In this strategy, we apply a simple heuristic that specifies production metrics to match how the company currently tracks their operational performance. Thus, our objective is to quantify the CCL’s current state and future state throughput and identify key performance indicators that were most impactful to throughput.

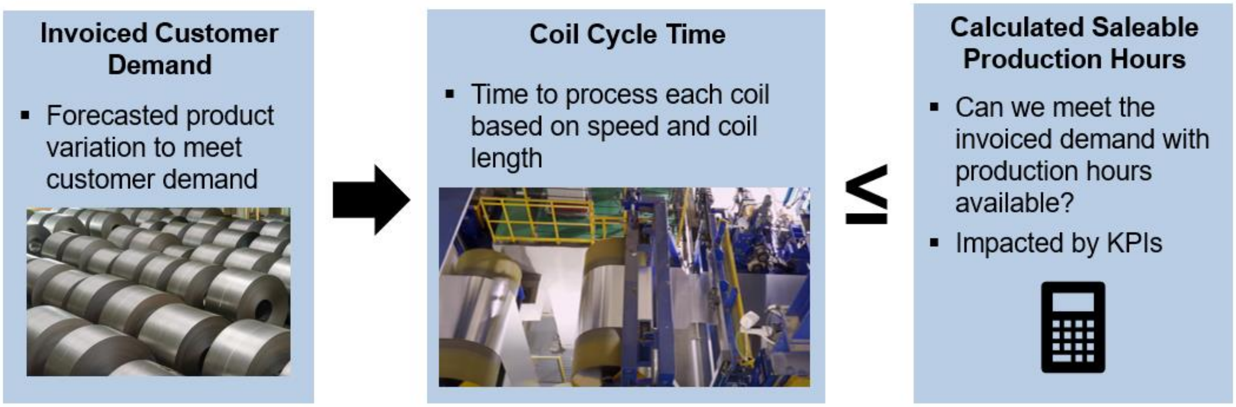

FIGURE 14: APPROACH TO CCL HEURISTIC MODEL

7.3 Invoiced Customer Demand

The aluminum rolling product world works in two separate but related measuring units, weight and coils. In the case of CRP, weight is the pounds of aluminum sold to the customer, and coils are the number of aluminum coils shipped to the customer. Although they are closely related, the weight per unit coil can greatly impact the overall operations of the plant.

The heuristic model begins with the conversion of the customer's forecast of each SKU, which is in lbs., and converts that to the required number of coils to fulfill the monthly forecasted volume. Fortunately, the customers understand that each coil does not weigh exactly the same, therefore the customer allows under/overage tolerance for the weight delivered to them.

$$\# \ of \ Coils \ Deliverd \ to \ Customer = \frac{Customer \ Invoiced \ Demand \ Weight \ (Lbs)}{Average \ Coil \ Weight \ for \ that \ product \ (\frac{Lbs}{coil})} \tag{1}$$

CRP uses a pull-based supply chain approach, where their production and distribution are demand driven and coordinated with true customer demand rather than internal forecast demand. (Simchi-Levi) This approach makes sense because of the type of product CRP manufactures and the make-to-specification nature of the aluminum products. For example, if CRP were to implement a push approach and incorrectly made too much product for Customer A, there is a risk that Customer A no longer needs the product and the finished coils that have been manufactured would have to be scrapped. The coils would need to be scrapped because each SKU is manufactured exactly to customer specifications and are unlikely to be sold for another use.

7.4 Key Performance Indicators (KPIs) and Operating Metrics

7.4.1 Time Metrics

Gaining a better understanding of the time metrics involved in the CCL production required a thorough analysis of KPIs that are tracked by the company and time metrics that impact throughput. Starting from the top line on Table 1, the breakdown shows every time metric that impacts CCL operations and calculates the available hours the CCL can process saleable aluminum coils, called Calculated Saleable Production Hours.

Table 1: Time metrics for CCL operations[1]

Calendar Hours in Month	744
(-) Scheduled Downtime	10
(-) Holdback	0
Available Calendar Hours	734
(-) No Manning Downtime	0
(-) No Metal Downtime	15
Available Production Hours	719
(-) Unscheduled Downtime	55
Calculated Available Production Hours	664
(-) Transition Hours	10
(-) WUL Hours	10
(-) Rework Hours	10
Calculated Saleable Production Hours + Trials	634
(-) Non-Saleable Trial Hours	20
Calculated Saleable Production Hours	**614**

We begin the breakdown by identifying the month of the year, and calculating how many hours are possible for production if the machine ran 24/7.

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[1] All values are arbitrary and do not represent CRP operations. Values were included in the table for illustrative purposes only

$$\textbf{Calendar Hours in Month} = \textbf{Number of Days in Month x 24 Hours} \tag{2}$$

Scheduled Downtime is a metric to represent time required for preventative maintenance and planned outages. The company has a preventative maintenance and outage schedule for the entire calendar year.

$$\textbf{Scheduled Downtime} = \textsc{Preventative Maintenance Hours} + \textsc{Planned Outage Hours in a Month} \tag{3}$$

Holdback is a metric the company uses to introduce a buffer stock and allow time for the CCLs to process aluminum coils that were either not scheduled for the month or had to be re-processed due to a quality or upstream issue. This analysis did not include a holdback value because the model attempted to calculate the maximum throughput of the CCLs.

The company used the term Available Calendar Hours as a representation of the absolute maximum available production hours if production was perfect.

$$\textbf{Available Calendar Hours} = \text{Calendar Hours in Month} - \text{Scheduled Downtime} - \text{Holdback} \tag{4}$$

No Manning Downtime represents the event in which the CCLs were unable to operate due to insufficient staffing. The company is able to track this event by inputting a specific code into the Oracle database from the beginning of the No Manning time until the CCLs are able to begin production. The company has indicated that No Manning has not been a significant contributor to production loss in recent events, however the heuristic model enables the user to estimate the potential No Manning hours in any given month. This is important because labor issues arise sporadically, as seen in manufacturing plants across the world during the COVID-19 Pandemic.

$$\textbf{No Manning Downtime} = \text{Production Hours lost due to staffing} \tag{5}$$

No Metal Downtime represents the event in which CCLs were unable to operate due to insufficient metal ready to be processed at the CCLs. This metric is a very interesting and complex metric to fully understand and forecast because it is a result of 1) all upstream processing issues throughout the entire rolling process; 2) product seasonality demand; and 3) poor forecasting and planning from any of the proceeding steps (casting, hot rolling, cold rolling, etc.). CRP has adopted the culture of “keeping the CCLs fed” by communicating more with the different area managers and emphasizing the CCLs upstream inventory with the plant schedulers.

An example of upstream issues would be the event that the cold mill malfunctioned and was out of service for a few days. This independent event would prevent the CCLs from receiving products and would stop the CCLs from processing coils, generating No Metal hours.

$$\textbf{No Metal Downtime} = \text{Production Hours lost due to no metal available to process} \tag{6}$$

Available Production Hours is the term CRP uses to describe the production hours available to process coils when considering events within the CCL team’s control. Looking at Table 1, we can see that scheduled downtime is a function of the preventative maintenance schedule, holdback is a planning buffer, and no manning and no metal downtime is outside of the CCL team’s control. They cannot impact upstream processing issues and they are unable to forecast when a labor strike or labor issue will arise. Therefore, the Available Production Hours term can be considered the maximum hours available to process coils without considering outside impacts.

$$\textbf{Available Production Hours} = \text{Calendar Hours in Month} - \text{Scheduled Downtime} - \text{Holdback} - \text{No Manning} - \text{No Metal} \tag{7}$$

Unscheduled Downtime describes the time the CCL machines are down due to unforeseen mechanical or machine performance issues. This time does not include time already categorized as scheduled downtime, no metal or no manning downtime. An example of this event would be a shutdown due a certain process within CCL failing, like the passivation or pickling features. This metrics is important to the CCL engineering team because it measures reliability and gives the team goals to achieve in the future.

$$\textbf{Unscheduled Downtime} = \text{Any downtime due to mechanical or machine failure} \tag{8}$$

$$\textbf{Calculated Available Production Hours} = \text{Available Production Hours} - \text{Unscheduled Downtime} \tag{9}$$

Uptime with Transitions is a metric CRP tracks that represents the CCL is running either a production coil or a transition coil. This metric is really a function of Unscheduled Downtime, so it measures the machines reliability.

$$\textbf{Uptime with Transitions} = \frac{\text{Calculated Available Production Hours}}{\mathit{Available\ Production\ Hours}} \tag{10}$$

Transition hours represents the time lost due to required product changeover, in CRP’s case this represents the time to process transition coils within a given month. As described in section 6.2.5, product changeover, or here known as transition coils, is a function of product variability on a given machine. The time spent to process transition coils impacts the available hours to product saleable coils since transition coils can be viewed as a waste product.

$$\textbf{Transition Hours} = \text{Time lost due to processing transition coils}$$

(11)

Whole-unit-loss (WUL) hours describes the production time lost due to processing a coil that was later determined to be unsaleable and classified as scrap. CRP placed a large emphasis on the reduction of WUL coils because of the following reasons:

- Scrap coils that were processed on the CCL and later scrapped occupied valuable production hours;
- If a coil was scrapped after the CCL, that means the coil went through the entire rolling processing only to be classified as scrap. This leads to increased manufacturing costs, energy costs, and capacity loss at every step in the plant
- Delinquent delivery to customers increases because the product might need to be restarted back at the casting phase, which could push out the delivery date multiple days.

For the reasons listed above, a major emphasis on both quality prevention and imperfection detection was in place at CRP and is included as an operational lever described in later sections.

$$\textbf{WUL Hours} = \text{Time lost due to processing scrap coils}$$

(12)

Rework hours describes the time CCL dedicates for reprocessing coils due to a failure in the previous processing attempt. An example of this would be that the previous coil was supposed to get a layer of finishing oil but the CCL machine did not perform this action. Instead of scrapping the coil, the coil can go through the CCL once again for the oil application. The rework time eats up throughput because a CCL machine is only able to process a single coil at a time, regardless if it is a rework coil or regular saleable coil.

$$\begin{aligned}&\textbf{Rework Hours}\\&= \text{Time lost due to reprocessing finished coils on CCL due to a missed or failed step}\end{aligned}$$

(13)

Non-Saleable Trial Hours records the time required to test out new products on the CCL machines. This is an important step is product management and is necessary before a SKU goes into production. Achieving the correct line speed and recipe formulation is critical to ensuring quality and reducing WULs. This monthly estimate was provided by the CRP Product team.

$$\textbf{Non} - \textbf{Saleable Trial Hours} = \text{Time lost due to perfoming tests on new products for CCL} \tag{14}$$

We can see in Figure 15 how the different KPIs or time metrics ultimately affect the hours available to produce saleable aluminum coils.

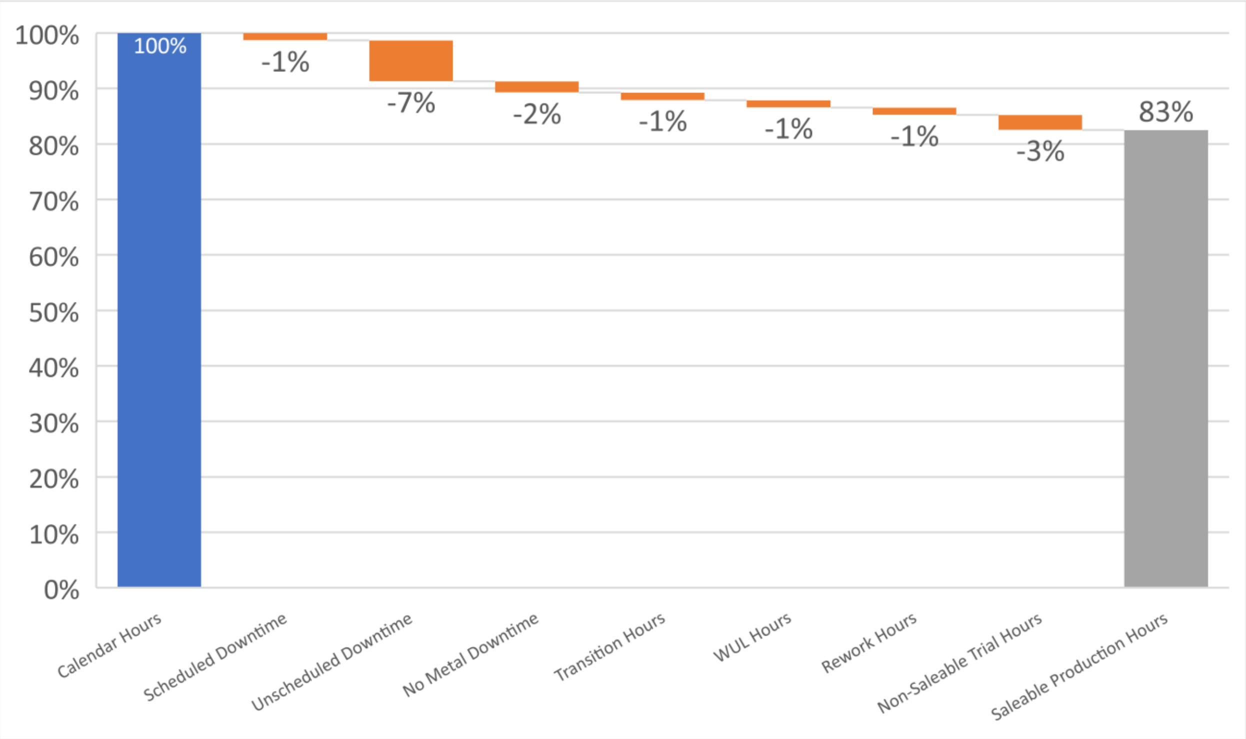

FIGURE 15: OPERATIONAL EVENTS IMPACT TO AVAILABLE HOURS TO PRODUCE SALEABLE PRODUCTION COILS

7.4.2 Transition Coil Estimate

The heuristic model uses a combined code to determine how many transition coils will be processed in any given month. The combined code is a representation of the transition rules listed earlier, and is a unique indicator of each aluminum product's properties. An example and explanation of the combined code are listed below:

TABLE 2: DESCRIPTION OF THE COMBINED CODE TO ESTIMATE PRODUCT CHANGEOVER (TRANSITION COILS) ON CCL

Combined Code: **Recipe_Rounded Gauge (mm)_Rounded Width at CCL (in)_ Passivation (0 or 1)_Oil (0 or 1)_ CCL 1 or 2**
Example aluminum product: 1_1.5_60_ 0_1_ 1 • The product utilizes CCL **recipe 1** • The approximate finished gauge is 1.5mm • The approximate width at the CCL is 60 inches • The product does not require passivation • The product does require an application of oil • The product will be processed on Machine 1 (CCL 1)

The combined codes are summarized in an Excel Pivot Table, which estimates how many unique combined codes exist in any given month. The heuristic model calculates transition coils based on the number of low runners, mid runners, and high runners are forecasted in a given month. Low runners are combined codes with less than M coils in that month, mid runners are combined codes with more than M but less than N, and high runners are combined codes with volumes greater than N. See Table 3 for more details on the volumetric classification.

TABLE 3: VOLUME CLASSIFICATION FOR TRANSITION COIL CALCULATIONS

Classification	**Threshold**
Low Runner	Low Runner < M
Mid Runner	M < Mid Runner < N
High Runner	High Runner > N

For low runners, the transition coils are calculated by the count of unique combined codes in a given month. We assume that every combined code with less than M coils would require a transition coil to be processed on the CCL. Each transition coils specified for low runners is indicated by β_L.

For mid runners, which make up the largest calculated transition coils estimate (see Figure 16), the heuristic model mimics current CRP scheduling practices by spreading the monthly demand into weekly demand and batching the weekly demand into scheduling batches for mid runners, β_M. Each β_M created equates to a single transition coil. The weekly scheduling is performed to optimally fill the pit furnaces during the melting and casting phase, as described in section 3.1. However, these weekly scheduling practices impact the CCLs because of the systematic process the coils undergo.

Transition coils for high runners are calculated in a similar method, however the weekly spread doesn't meaningfully impact the transition coil estimate due to the nature of the high runners making up the majority of the customer demand. Each batch dedicated for high runners is indicated by β_H

$$Estimated\ Transition\ Coils\ in\ a\ month = \beta_L + \beta_M + \beta_H \tag{15}$$

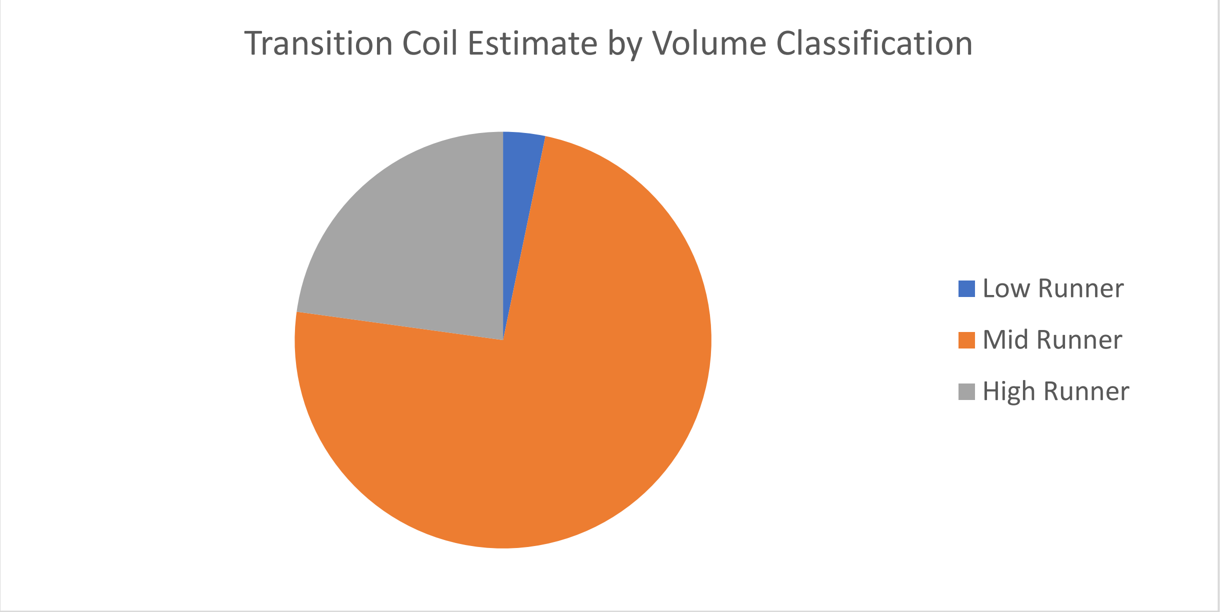

FIGURE 16: HEURISTIC MODEL TRANSITION COILS ESTIMATE BY VOLUMETRIC CHARACTERIZATION OF PRODUCTS ON THE CCL

7.4.3 KPI Levers

The heuristic model includes operational levers that the company can toggle to inspect the throughput impact of each lever. This strategically informs the company on which operational efforts should be prioritized and the financial, throughput, and resource impact each KPI improvement will result in.

7.4.3.1 Line Speed

The specified line speed of each product, per CCL recipe, determines the CCL processing speed required to completely process each coil. As noted in section 3.4.3, there are other engineering parameters that need to be considered when determining if a line speed increase is feasible. However, with that consideration in mind, this model lever shows the impact of increasing the speed of any given SKU.

$$CCL\ Processing\ Time\ for\ Coil_x = \frac{Coil\ Length\ (ft)}{Line\ Speed\ per\ CCL\ Recipe\ for\ Coil\ X(ft/s)} \tag{16}$$

Since increasing the line speed for any given SKU requires an in-depth engineering analysis, understanding the overall throughput impact for such an effort was important. CRP used this analysis to prioritize the line speed analysis for certain SKUs based on the overall throughput impact the speed increase would have.

7.4.3.2 Unit Recovery

The sale of aluminum coils is priced per unit weight. Every section of coil that is determined to be scrapped due to quality issues is lost revenue to the company. For this reason, recovery is specified as:

$$Unit\ Recovery = \frac{Starting\ slab\ weight}{Finished\ coil\ weight} * 100\% \tag{17}$$

Recovery losses can occur at every stage of the process, but the largest weight loss usually occurs during the hot rolling step. One key point to recovery is the difference between length recover and width recovery. The only method to increase width recovery is to start the rolling process with a thinner slab, whereas length recovery can be improved through a variety of different methods including; quality control, length optimization, and pass reductions on the cold mills. For the purposes of the heuristic model, length recovery increased the unit weight of each finished coil, which reduced the total number of coils required to meet the customer demand in any given month.

Table 4 is an example to further explain this concept, which considers a customer demand of SKU #1 is 100,000 lbs. in a given month. If the historic average weight of a finished coil within that SKU is 20,000 lbs., then CRP would need to process five ingots to meet the customer's demand. However, if the recovery improved for that specific SKU due to process improvements and less scrap loss, and the average finished coil weight improved from 20,000 lbs. to 25,000 lbs., then the number of ingots required to meet customer demand would reduce from five to four. Although the final cumulative shipped to customer weight is equivalent, CRP is able to reduce the coils shipped to the customer by one, further decreasing operational, shipping, and logistic costs.

TABLE 4: EXAMPLE OF IMPROVED RECOVERY AND THE IMPACT TO COIL REDUCTION

SKU	**Customer Demand in a month (lbs.)**	**Average Finished Coil Weight (lbs.)**	**Number of Coils Required meet customer demand**
1	100,000	20,000	5
1	100,000	25,000	4

7.4.3.3 Whole-Unit-Losses (WUL)

The WUL metric is tracked on a monthly basis and includes reasons for each WUL experienced. Figure 17 is an example of the downward trend of WUL as the year progressed, indicating that CRP improved their quality control and their quality efforts were in fact impactful. The combination of conversations with CRP's quality control engineering, evaluation of quality projects in the pipeline, and a simple linear forecast was sufficient in determining future WULs for throughput analysis.

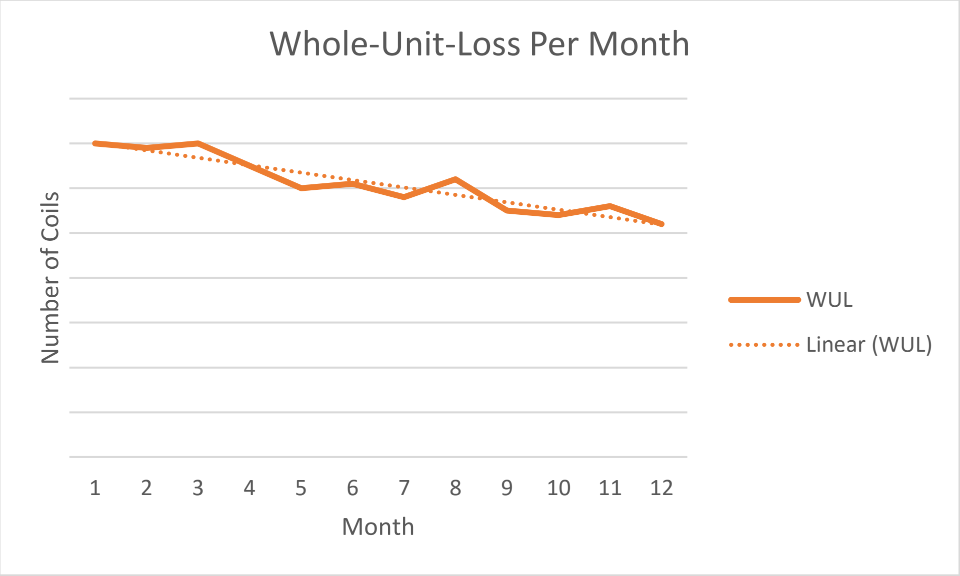

FIGURE 17 : EXAMPLE OF WUL TRACKING PER MONTH[2]

7.5 Results

The CCL heuristic model led to a 4-year operational and throughput roadmap that CRP is using for their Sales, Inventory, and Operations Planning (SIOP). The model set goals for WULs, no metal hours, recovery, and line speed increases. These goals also led to CRP establishing unique improvement projects for each identified KPI since they were deemed to be impactful to throughput. When comparing the heuristic model to historic performance, the model was within 5% of the processed metal weight and 10% of total transition coils for a given month. Since product changeover could be improved by improved scheduling practices, the author decided to investigate whether a mixed integer program could reduce the number of transition coils by optimizing monthly schedules using the transition rules as constraints.

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[2] The WUL values shown in the chart are for illustrative purposes only and do not represent actual production metrics.

8 Capacity Model - Mixed Integer Program for Transition Coils

Scheduling optimization for aluminum rolling is the process of determining the most efficient schedule for producing aluminum products using rolling mills. This can include determining the order in which jobs are completed, the amount of time allocated for each job, and the allocation of resources such as personnel and equipment.

Scheduling orders for a single machine, a production line, an entire manufacturing system, or a manufacturing system with a bottleneck station are an example of the single machine scheduling problem (SMSP). The scheduling of a CCL is considered a SMSP, and the introduction of transition coils is considered a sequence-dependent setup times (SDSTs) problem. This portion of the paper will focus on the MIP application to optimally schedule the CCL to reduce transition coils.

The SDST constraint occurs when the setup times of jobs depend on their immediate predecessors. We can apply this constraint to the transition coil rules highlighted in section 6.2.5.

8.1 Motivation and Methodology

Although the author and company are confident with the above results from the heuristic model and believe it represents real-time operations, this section investigates how transition coils could be reduced if the following were true:

- Instead of scheduling on a weekly basis, look at the entire month and plan scheduling on that view
- Allow for monthly SKU batching and process the entire allotment of coils within each SKU
- Relax the transition coil rules such that lubrication and oiling changes does not trigger a transition coil

8.2 Equation Formulation

8.2.1 Objective Function

No	Equation	Description
8-1	Minimize C_{max}	denotes the scheduling objective is to minimize the makespan, which is representative of the processing time for both the production coils and the transition coils.

8.2.2 Assumptions

The following assumptions are made to calculate the minimum makespan by optimally scheduling coils to reduce transition coils:

- Each coil (job) is assumed to be immediately available for processing.
- Only one coil can be processed at any given time.
- Each job is independent of each other, and the processing time is a known and fixed time.
- The CCL (machine) is available throughout the entire planning period, unscheduled downtime and breakdowns are not addressed in this analysis.
- There is enough storage buffer for coils to await processing and to be stored after CCL processing.
- All times (processing, setup times, lags) are considered to be zero or positive.

8.2.3 Variables

Indices	**Description**
j, i	Job tags, j = 1, 2, ….., n; i = 0, 1, …..,n, where 0 is a dummy job
A	Set of delayed precedence constraints of all jobs
Parameters	**Description**
n	Number of jobs (coils)
b_j	Starting time of job j (coil)

s_{ij}	Sequence-dependent setup times required for the processing of job j after job i
d_{ij}	Delay time needed for the processing of job j after job i. This is to represent the transition coil time required for CCL to process the next coil
p_j	Processing time of job j
M	Sufficiently large positive number

8.2.4 Decision Variables

Parameters	**Description**
x_{ij}	Binary variable, x_{ij} = {1, if job j is processed immediately after job i; 0 otherwise.
c_i	Completion time of job *i*
c_j	Completion time of job *j*

8.2.5 Constraints

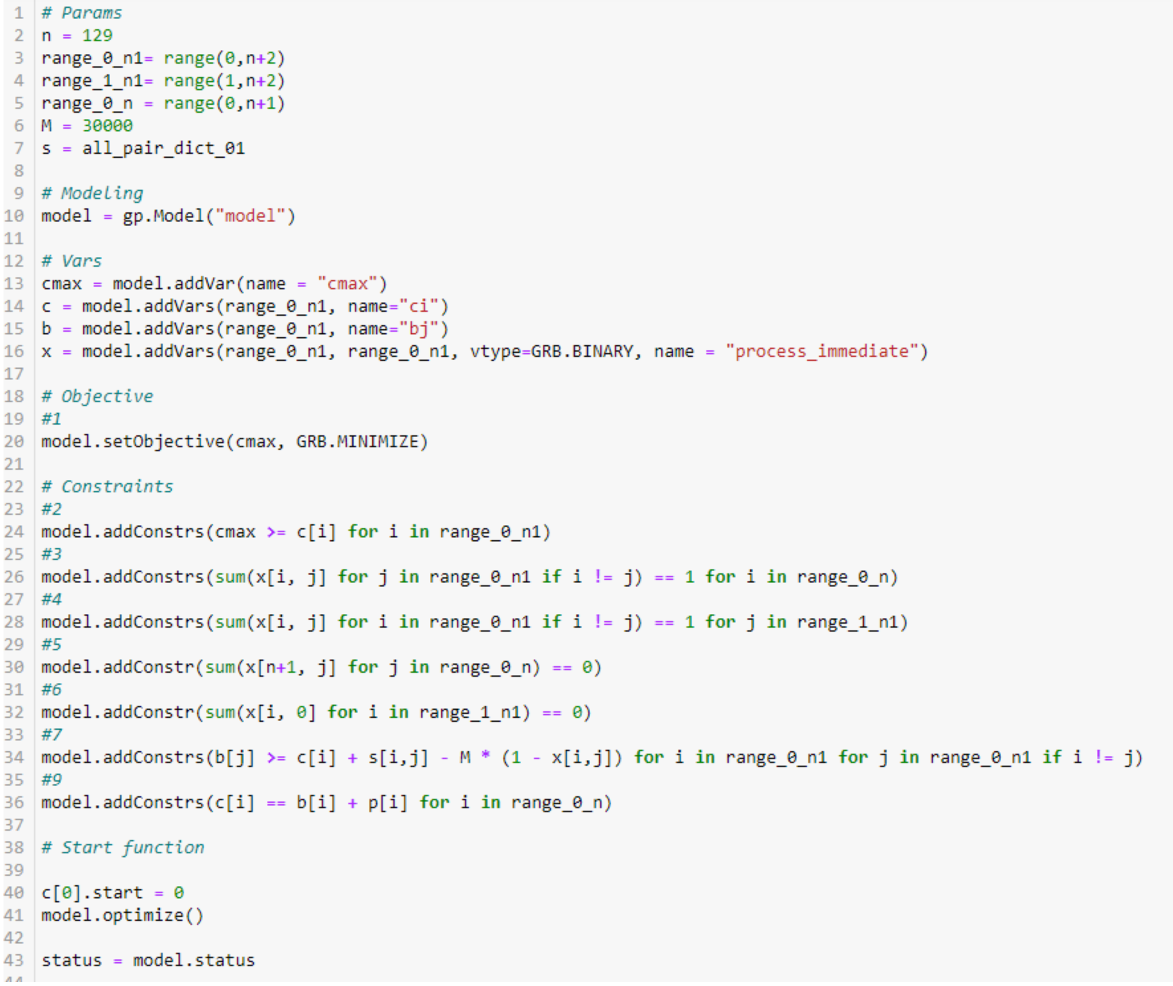
No	**Equation**	**Description**
8-2	$C_{\max} \geq c_j$; j = 1,2,…, n,	Calculates the makespan
8-3	$\sum_{j=1}^{n+1} x_{ij} = 1; i = 0,1,\dots,n\ (i \neq j)$	Ensures each job (coil) is dispatched to only one position in the scheduling sequence
8-4	$\sum_{i=0}^{n} x_{ij} = 1; j = 0,1,\dots,n+1\ (i \neq j)$	Ensures each job (coil) is dispatched to only one position in the scheduling sequence
8-5	$\sum_{j=0}^{n} x_{ij} = 0;\ i = n+1$	Ensures that job n + 1 is a dummy job and it is the last job and succeeded immediately by no job.
8-6	$\sum_{i=1}^{n+1} x_{ij} = 0;\ j = 0$	Ensures that job 0 is a dummy job and that it is the first job and preceded immediately by no job
8-7	$b_j \geq\ (c_i +\ s_{ij}) - M(1 - x_{ij})$ $j = 0,1,\dots,n+1$ $i = 0,1,\dots,n+1$ $(i \neq j)$	Ensures that the time interval between the starting time of job j and the completion time of job i is greater than the setup time between job i and j, if job j is preceded immediately by job i, where M is a sufficiently large number.
8-8	$b_j \geq\ c_i +\ d_{ij};$ $\forall(\mathrm{i},\mathrm{j}) \in \mathrm{A}$	Ensure that the time interval between the starting time of job j and the completion time of job i is greater

		than the delay time between job i and j, if the pair of jobs (i, j) ∈ A.
8-9	$c_i = b_i + p_i;$ $i = 1,2, \dots, n;$	Completion time of job is the starting time plus the processing time
8-10	$x_{ij} \in \{0,1\};$ $i = 0,1,2, \dots, n;$ $j = 0,1,2, \dots, n;$	Defines the ranges of the decision variable x_{ij}

8.2.6 MIP Modeling with Gurobi

The author decided to use the Gurobi optimizer to complete the MIP for scheduling the transition coils. The first requirement was gathering a list of all job combinations that would result in a transition coil. This was completed by evaluating each job j and comparing the gauge, width, and recipe code with the rest of the data set. The final product was a dictionary that included a tuple as the key and the delay or transition coil time as the value, indicates as all_pair_dict_01 in Figure 18.

Using Equations 8-1 through 8-10 as variables, parameters, and the objective function, the MIP was able to calculate the optimal makespan to process all the jobs. This makespan calculation is discussed further the next section.



```
# Params
n = 129
range_0_n1= range(0,n+2)
range_1_n1= range(1,n+2)
range_0_n = range(0,n+1)
M = 30000
s = all_pair_dict_01

# Modeling
model = gp.Model("model")

# Vars
cmax = model.addVar(name = "cmax")
c = model.addVars(range_0_n1, name="ci")
b = model.addVars(range_0_n1, name="bj")
x = model.addVars(range_0_n1, range_0_n1, vtype=GRB.BINARY, name = "process_immediate")

# Objective
#1
model.setObjective(cmax, GRB.MINIMIZE)

# Constraints
#2
model.addConstrs(cmax >= c[i] for i in range_0_n1)
#3
model.addConstrs(sum(x[i, j] for j in range_0_n1 if i != j) == 1 for i in range_0_n)
#4
model.addConstrs(sum(x[i, j] for i in range_0_n1 if i != j) == 1 for j in range_1_n1)
#5
model.addConstr(sum(x[n+1, j] for j in range_0_n) == 0)
#6
model.addConstr(sum(x[i, 0] for i in range_1_n1) == 0)
#7
model.addConstrs(b[j] >= c[i] + s[i,j] - M * (1 - x[i,j]) for i in range_0_n1 for j in range_0_n1 if i != j)
#9
model.addConstrs(c[i] == b[i] + p[i] for i in range_0_n)

# Start function

c[0].start = 0
model.optimize()

status = model.status
```

FIGURE 18: GUROBI PROGRAMMING FOR THE MIP MODEL TO MINIMIZE THE MAKESPAN BY OPTIMALLY SCHEDULING THE CCL

8.2.7 Makespan Calculation

The MIP model seeks to find the optimal job sequence to reduce transition coils and ultimately minimize the makespan. The makespan calculation was inspired by the works of Kuo, Chen, and Yeh and their paper titled “Single machine scheduling with sequence-dependent setup times and delayed precedence constraints”. The makespan was calculated used the following equations and variables:

No	Equation	Description
8-11	$\pi(\mathrm{r}) = k$	$\pi(\mathrm{r})$ indicates the job sequence r and $\pi(\mathrm{r}) = k$ implies the r-th job to be processed is job k
8-12	es_j	Indicates the earliest time job j can be processed
8-13	$c_{\pi(r)} = b_{\pi(r)} + p_{\pi(r)}$	Completion time for the job with sequence r is the addition of the start time of job r and the processing time of job r
8-14	$s_{\pi(r-1),\pi(r)}$	Sequence time between two jobs, r and r-1

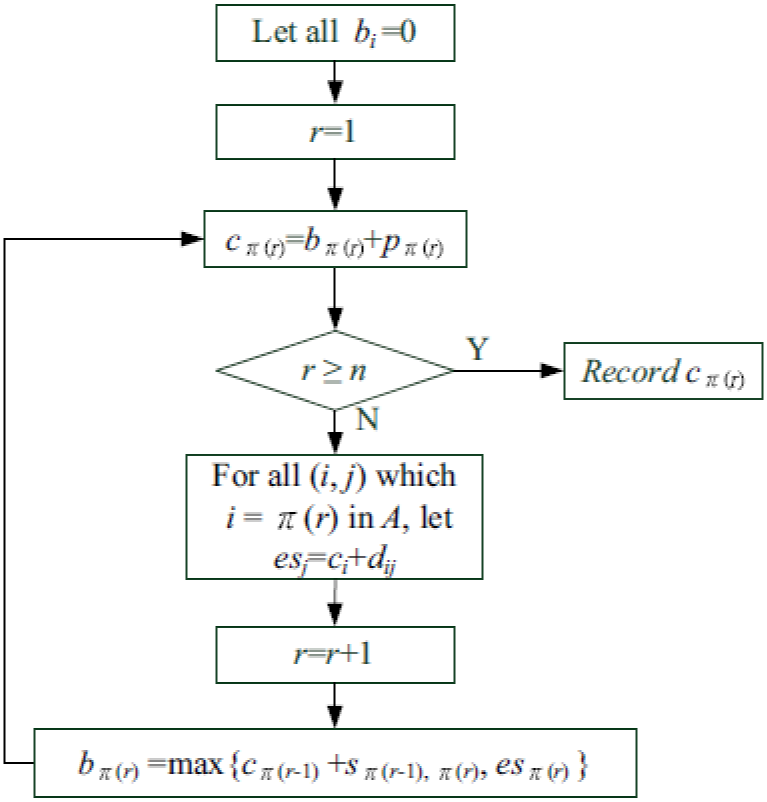


FIGURE 19: MAKESPAN CALCULATION FOR THE MIP MODEL (KUO, CHEN AND YEH)

The makespan of the job sequence is the completion time of the last job processed through the model.

8.3 MIP Results and Heuristic Model Comparison

After 22.25 hours of computation, the MIP determined the optimal number of transition coils to process all the required coils in a given month. Using a random assortment of demand for a given month, the heuristic model predicted that N transition coils would be needed to complete the entire month’s demand. Again, the heuristic model uses a weekly scheduling forecast and estimates transition coils based on the combined code logic explained in section 7. Using the same random assortment of product mix demanded in a single month, the MIP model calculated a 60% reduction in transition coils required to process the same product mix. However, one significant difference between the two approaches was the scheduling window allowed. The heuristic model was subject to a weekly scheduling mix when scheduling the mid runners and high runners, forming smaller batches of SKUs to meet the product demand, while the MIP model allowed for all demanded coils for a given SKU to be processed in a single batch. This reduced the overall variability of product mix for the machines.

The number of transition coils for a given month was 60% less than the value the heuristic model calculated. This result suggests two major findings:

1. The value of batching scheduling at the monthly lens versus the weekly lens translates to significantly less product changeovers.
2. Intelligently scheduling aluminum coils through the CCLs using a MIP model can greatly improve overall throughput and reduce time spent processing transition coils.

Since the original data source and the transition rules are proprietary information, this paper is only able to discuss the percent difference in transition coils calculations and is unable to quantify the throughput and monetary value this scheduling practice would have on operations. However, the findings from the MIP suggest that aluminum rolling scheduling would benefit from using advanced scheduling practices.

9 Conclusions and Future Work

The results from both models suggests significant improvement in aluminum rolling throughput is possible when focused on key performance indicator improvements and advanced scheduling practices. The MIP model showed the advantage of increasing batch sizes by changing from weekly batches to monthly batches. The increase in batch sizing and the intelligent scheduling practices optimally reduced the number of transition coils by 60%.

The metal rolling process is a highly advanced process and this study only evaluated one portion of the rolling process, the CCLs. To truly determine the optimal scheduling practices for the entire plant, additional analysis and constraints would need to be included in the MIP to evaluate how the schedule impacts the hot rolling, cold rolling, and cooling steps.

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