Recycling production designs: the value of coordination and flexibility in aluminum recycling operations

by

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Abstract

The growing motivation for aluminum recycling has prompted interest in recycling alternative and more challenging secondary materials. The nature of these alternative secondary materials necessitates the development of an intermediate recycling facility that can reprocess the secondary materials into a liquid product. Two downstream aluminum remelters will incorporate the liquid products into their aluminum alloy production schedules. Energy and environmental benefits result from delivering the products as liquid but coordination challenges persist because of the energy cost to maintain the liquid. Further coordination challenges result from the necessity to establish a long term recycling production plan in the presence of long term downstream aluminum remelter production uncertainty and inherent variation in the daily order schedule of the downstream aluminum remelters. In this context a fundamental question arises, considering the metallurgical complexities of dross reprocessing, what is the value of operating a coordinated set of by-product reprocessing plants and remelting cast houses?

A methodology is presented to calculate the optimal recycling center production parameters including 1) the number of recycled products, 2) the volume of recycled products, 3) allocation of recycled materials across recycled products, 4) allocation of recycled products across finished alloys, 4) the level of flexibility for the recycling center to operate. The methods implemented include, 1) an optimization model to describe the long term operations of the recycling center, 2) an uncertainty simulation tool, 3) a simulation optimization method, 4) a dynamic simulation tool with four embedded daily production optimization models of varying degrees of flexibility. This methodology is used to quantify the performance of several recycling center production designs of varying levels of coordination and flexibility. This analysis allowed the identification of the optimal recycling center production design based on maximizing liquid recycled product incorporation and minimizing cast sows.

The long term production optimization model was used to evaluate the theoretical viability of the proposed two stage scrap and aluminum dross reprocessing operation including the impact of reducing coordination on model performance. Reducing the coordination between the recycling center and downstream remelters by reducing the number of recycled products from ten to five resulted in only 1.3% less secondary

material incorporated into downstream production. The dynamic simulation tool was used to evaluate the performance of the calculated recycling center production plan when resolved on a daily timeframe for varying levels of operational flexibility. The dynamic simulation revealed the optimal performance corresponded to the fixed recipe with flexible production daily optimization model formulation. Calculating recycled product characteristics using the proposed simulation optimization method increased profitability in cases of uncertain downstream remelter production and expensive aluminum dross and post-consumed secondary materials.

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Chapter 1. Introduction

1.1 Advantages of aluminum recycling

As the material needs of the world's population continue to grow, strategies that promote production efficiency and mitigate environmental impact become increasingly important. The growing consumption of aluminum is of particular importance because aluminum is used extensively in many ubiquitous products including transportation, packaging, and construction applications that are expected to increase (Gesing and Wolanski 2001). Global aluminum consumption is enormous; 40.5 million tons of aluminum were consumed in 2003 (Boin and Bertram 2005). Aluminum demand is projected to continue to increase dramatically in the coming future as demonstrated in Figure 1 which plots the historical and projected proportion of aluminum metal produced from recycled material and the proportion produced from primary material (IAI 2009). Recycling secondary materials to produce aluminum for industrial applications is one strategy that can meet growing aluminum demand while minimizing environmental impact.

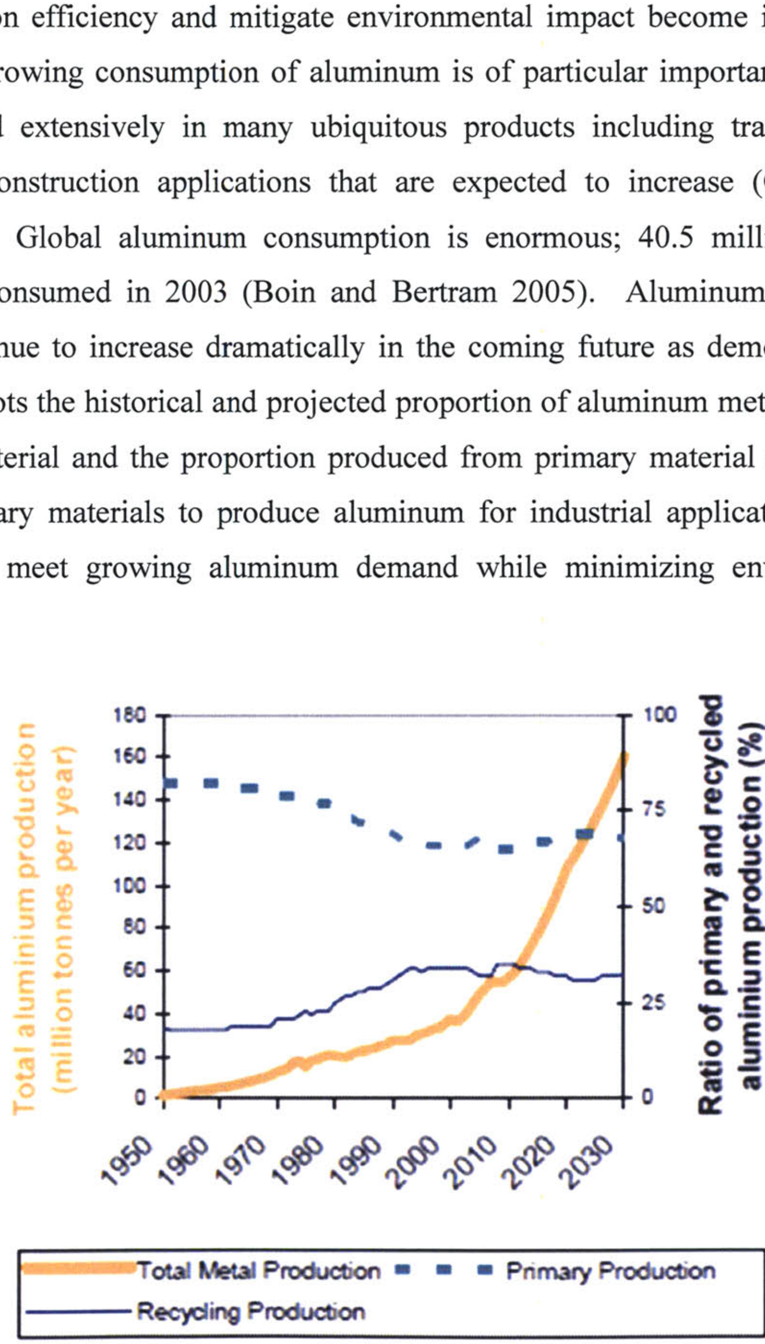

Figure 1. Historical aggregate aluminum production and amount of aluminum produced from recycled and primary sources (IAI 2009).

The significant energy savings resulting from recycling secondary aluminum materials over using primary materials to produce aluminum products incentivizes industrial remelters to identify strategies to increase secondary material utilization. The energy requirement to produce a finished aluminum alloy from recycled secondary materials is approximately 2.8 kWh/kg or 5% of the energy requirement to produce the alloy from bauxite (Green 2007). Producing aluminum alloys by recycling secondary materials also has a smaller carbon footprint than producing aluminum from primary materials. When using secondary materials approximately 0.6 kilograms of CO_2 is released per kilogram of aluminum alloy produced which is 95% smaller than the roughly 12 kilograms of CO_2 released per kilogram of aluminum alloy produced when using primary materials (Choate and Green 2004). However, the kilograms of CO_2 released per aluminum alloy produced depends on the electricity grid and the technology used to produce the primary aluminum (McMillan and Keoleian 2009). For example, in 2005 the associated carbon footprint of primary aluminum production in China was 21.9 (±3.0) kilograms of CO_2 per kilogram of primary metal produced while in Latin America the associated carbon footprint was 7.07 (±0.69) kilograms of CO_2 produced per kilogram of primary metal (McMillan and Keoleian 2009). The large energy savings associated with aluminum recycling are especially impressive when compared to the energy savings associated with recycling other metals. For example, producing austenitic stainless steel from secondary material uses 67% less energy and emits 70% less CO_2 than producing austenitic stainless steel from primary materials (Johnson, Reck et al. 2008). The relatively large energy savings associated with aluminum recycling results from the large change in Gibbs free energy resulting from aluminum oxidation compared to the change in Gibbs free energy associated with the oxidation of other metals. Figure 2 provides an Ellingham diagram that includes the change in Gibbs free energy associated with the oxidation of several other metals (Birks, Meier et al. 2006). Although significant motivation to promote aluminum recycling exists, including economic and environmental benefits, significant opportunities to improve the global aluminum recycling rate persist.

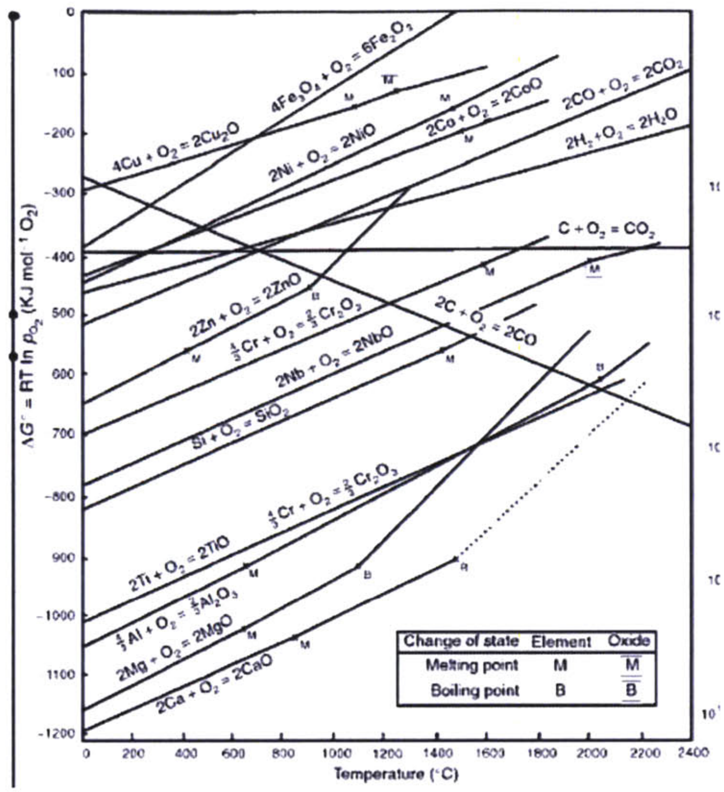

Figure 2. Ellingham diagram demonstrating the change in Gibbs free energy for oxidation as a function of temperature for several materials (Birks, Meier et al. 2006).

The opportunity for improvement in the global aluminum recycling rate can be identified by examining existing material flows in the aluminum industry. Figure 3 maps the relative flows of aluminum across sources to final aluminum products as estimated by the International Aluminum Institute (IAI 2009). To produce the 75.1 million metric tons of aluminum ingot produced in 2009, 36.7 million metric tons of primary aluminum and 38.5 tons of remelted aluminum were consumed (IAI 2009). To better identify opportunities for improvement in aluminum recycling, it is important to differentiate between new scrap and old scrap as labeled in the diagram. New scrap or prompt scrap is secondary aluminum that was produced during aluminum remelting operations, but has not been used by a consumer; included in the diagram as traded new scrap and fabricator scrap. Post-consumed aluminum scrap or old scrap is aluminum that has been used by consumers and collected by a recycler for resale. It is important to differentiate prompt scrap from post-consumed scrap because prompt scrap is much easier to recycle with recycling rates that approach 100% (Xiao, Reuter et al. 2005). As a result of these high recycling rates, there is limited room for improvement in the prompt scrap recycling rate. To better understand the underlying reasons for the modest post-consumed scrap recycling rate, the recycling efficiency is applied to analyze the aluminum mass flow model prepared by (IAI 2009).

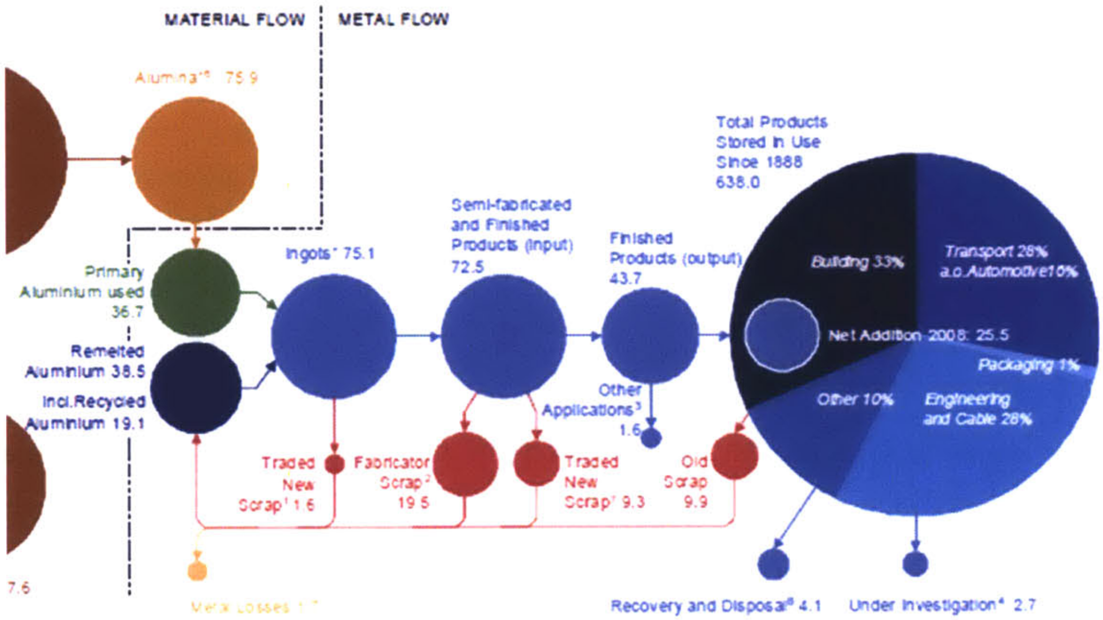

Figure 3. Aluminum material flow diagram mapping indicating the weight in millions of metric tons of the metal source and destination (IAI 2009) using a mass balance model developed by (Boin and Bertram 2005)

Recycling efficiency is a measure of the ability of post-consumed scrap material to be incorporated into new products. Eq. 1 provides a formula for recycling efficiency which divides the weight of old scrap remelted to produce aluminum ingot by the total weight of old scrap that is no longer being used or stored: including recycled old scrap, landfilled scrap, unaccounted for scrap, and scrap that is lost due to chemical reactions or other processing events. An efficiency of 54% was calculated using the weights reported in Figure 3 (IAI 2009). This moderate recycling efficiency demonstrates that there is more potential to improve the post-consumed secondary material recycling rate than in the prompt scrap recycling rate. Another opportunity for improving the post-consumed recycling rate is reducing the material losses that occur during prompt and post-consumed secondary material recycling and remelting operations which the IAI estimates to be 1.7 million metric tons per year (IAI 2009). The opportunities for improving the recycling efficiency and reducing material losses that occur during aluminum recycling and remelting result from several systematic and technical challenges in the aluminum metals market.

$$\text{recycling efficiency} = \frac{\text{old scrap}}{\text{old scrap} + \text{recovery and disposal} + \text{under investigation} + \text{metal losses}}$$

Equation 1

1.2 Challenges to broadening aluminum recycling

Despite the economic and environmental advantages of aluminum recycling, there are many systemic and technological challenges limiting the recycling efficiency and leading to material losses during recycling. Examples of systemic factors restricting the aluminum recycling efficiency include: modest consumer participation (Morgan and Hughes 2006),(Saphores, Nixon et al. 2006) (Watts, Jones et al. 1999), uncertain scrap quality and composition (Gaustad, Li et al. 2007), availability (Toto 2004), costly collection methods (Porter 2002), (Calcott and Walls 2005), and insufficient products that are readily able to incorporate recycled materials such as aluminum alloys with wide compositional specifications (Das 2006). Technological challenges limiting the recycling efficiency include inefficiencies and limited availability of industrial shredding and sorting operations and inadequate optimization of the recycling process (Das 2006).

The value of technological tools that can compositionally differentiate secondary materials such as shredding and sorting operations to increase the aluminum recycling efficiency can be better determined by examining aluminum alloy compositional specifications and the compositional characteristics of the secondary materials. The higher elemental concentration of alloying elements in post-consumed secondary materials limits their incorporation into aluminum alloys which have typically have more narrow compositional specifications. Cast alloys commonly have higher maximum specifications of alloying elements and can incorporate larger proportions of recycled materials than wrought alloys which commonly have smaller maximum compositional specifications (Gesing 2004). The tighter compositional specifications of wrought alloys result from material property requirements including sufficient mechanical strength to withstand intensive fabrication processes such as rolling, forging, and extrusion without mechanical failure (Gesing and Wolanski 2001). Table I lists an example aluminum alloy specifications retrieved from the Aluminum Association for each of the alloy series 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, 7xxx, and 8xxx (Association 2009). Example secondary material compositions retrieved from (Velasco and Nino 2011) are included in Table II below. Comparing the sample secondary material compositions in Table II with the aluminum alloy compositional specifications in Table I demonstrates the challenge of incorporating post-consumed secondary materials with relatively high alloying element concentrations into finished alloy products with relatively narrow alloying element specifications. Particularly small elemental tolerances in the alloys and large elemental compositions in the scrap compositions are highlighted in bold to emphasize the difference. For example, UBC cover (AA5182) scrap is 4.5% magnesium while the upper magnesium concentration limit for alloy 6101 is 0.03% (Association 2009; Velasco and Nino 2011). As a result of this significant magnesium composition difference, it would be challenging to produce alloy 6101 from UBC cover (AA5182) scrap. Compositional constraints resulting from alloys with narrow compositional specifications are especially difficult for increasing post-consumed secondary material content in aluminum production compared to other metals because of the limited opportunities to use thermodynamic reactions to alter the alloying element concentrations.

Table I. Example Aluminum Alloy Specifications (wt-%) According to the Aluminum Association (Association 2009).

No.	Si	Fe	Cu	Mn	Mg	Zn
1050	0.25	0.40	**0.05**	**0.05**	**0.05**	**0.05**
2010	0.5	0.5	0.7-1.3	0.1-0.4	0.4-1.0	0.3
3002	**0.08**	**0.1**	0.15	0.05-0.25	**0.05-0.2**	**0.05**
4004	9.0-10.5	0.8	0.25	0.10	1.0-2.0	0.20
5005	**0.30**	0.7	0.20	0.20	0.50-1.1	0.25
6101	0.30-0.7	0.50	0.10	**0.03**	0.35-0.8	**0.10**
7016	**0.10**	0.12	0.45-1.0	**0.03**	0.8-1.4	4.0-5.0
8017	0.10	0.55-0.8	0.10-0.20	...	**0.01-0.05**	**0.05**

Table II. Example Aluminum Scrap Types and Compositions (wt-%) Following the International Alloy Designation System (Velasco and Nino 2011).

Raw material	Si	Fe	Cu	Mn	Mg	Zn
Wrought	0.51	0.59	0.11	0.21	0.82	0.45
Cast	**5.18**	0.75	**2.5**	0.26	0.58	**1.27**
Mixed W&C	**4.5**	0.8	**2.3**	0.2	0.5	1.2
Transmission	**10.3**	**0.9**	**3.79**	0.28	0.21	**2.17**
UBC body (AA3104)	0.6	0.8	0.15	**1.1**	**1**	0.25
UBC cover (AA5182)	0.2	0.35	0.15	0.35	**4.5**	0.25
UBC seal (AA5182)	0.2	0.35	0.15	0.35	**4.5**	0.25
6061 Al frames	0.6	0.6	0.25	0.13	**1**	0.2

The relatively large aluminum oxidation potential compared to the oxidation potential of alloying elements presents a technical challenge to aluminum recycling that is less pronounced in recycling other metals. One of the principal characteristics of post-consumed aluminum scrap that limits recycling into aluminum alloys is the tendency to have higher compositions of secondary alloying elements than products, largely resulting from material accumulation during its lifecycle. The Ellingham diagram in Figure 1 shows that aluminum has a larger oxidation potential than the majority of its secondary alloying elements including silicon, iron, copper, manganese, and zinc but a lower oxidation potential than magnesium (Birks, Meier et al. 2006). As a result of preferential aluminum oxidation during remelting, accumulating alloying elements during the lifecycle of the secondary materials is particularly challenging because these alloying elements cannot be removed from the melt by oxidation during aluminum remelting operations which does occur in other metal systems. For example, aluminum is commonly added during steel production because the large oxidation potential promotes the formation of lower density aluminum oxide which quickly rises to the surface of the melt, providing a protective cover to the melt. Thus, the relative Gibbs free energy change associated with elemental oxidation during metal production can influence the recyclability of the host metal. (Castro, Remmerswaal et al. 2004) developed a method based on system thermodynamics to determine the value of various material combinations including aluminum alloy systems, in the context of recycling. For example, the authors recommended separating wrought aluminum from cast aluminum, copper, platinum group alloys, steel and expressed the necessity of separating lead, magnesium, and zinc based on thermodynamic considerations (Castro, Remmerswaal et al. 2004). The limited ability to use thermodynamic reactions to alter secondary material composition during aluminum recycling and remelting operations emphasizes the importance of compositional quality in increasing post-consumed secondary material content for finished aluminum alloy products.

1.2.1 Secondary material quality

In addition to higher alloying element concentrations, compositional uncertainty also limits the inclusion of secondary materials into aluminum alloys during remelting. The complexity associated with satisfying the aluminum alloy specifications when using a blend of primary, alloying elements, and secondary materials of varying composition limits the willingness of aluminum remelters to incorporate post-consumed secondary materials. Post-consumed secondary materials have accumulated more elemental additions over their lifecycle than prompt scrap materials increasing compositional uncertainty to varying degrees depending on the application (Gesing and Harbeck 2008). As recycling operations continue over multiple product lifecycles, it is expected that accumulation will cause average compositions of certain elements such as iron and magnesium to increase over time (Das 2006; Gaustad, Olivetti et al. 2012). One example of material accumulation in aluminum production, is iron accumulation caused by shredding and sorting operations using steel equipment (Das 2006). Figure 4 demonstrates the compositional variation characterizing post-consumed secondary materials found from taking aluminum siding scrap compositional measurements (Peterson 1999), (Gaustad, Li et al. 2007). Secondary material compositional uncertainty further exacerbates the challenge of meeting compositional specifications of alloy products when including recycled materials (Gaustad, Peterson et al. 2008), (Gaustad, Li et al. 2006). Prompt scrap is characterized by less compositional uncertainty than post-consumed secondary materials which further promotes higher recycling rates. Frequently, remelters store prompt scrap generated during production and integrate the recovered scrap into the same alloy type later in production, a procedure that further limits opportunities to increase compositional uncertainty (Gesing and Harbeck 2008).

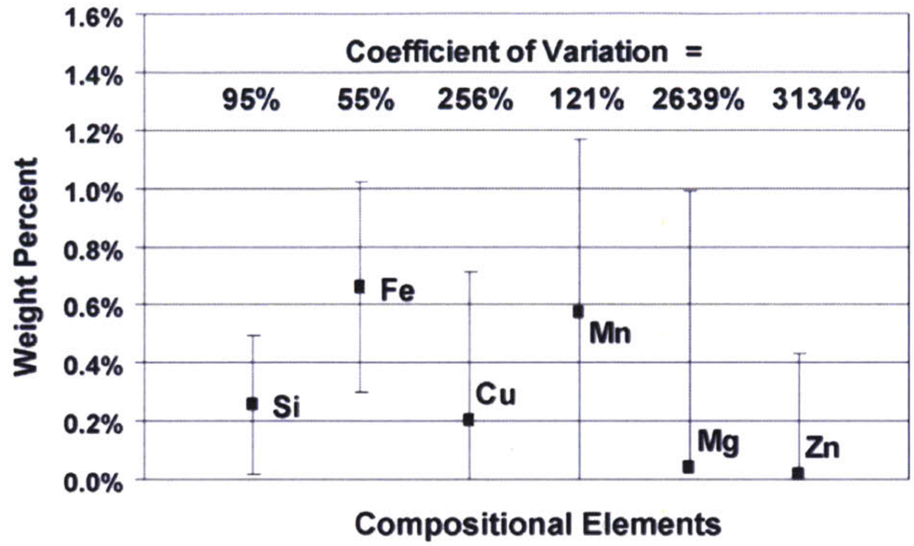

Figure 4. Aluminum siding scrap compositional measurements taken over a one year period (Peterson 1999) , (Gaustad, Li et al. 2007).

Additional negative effects on secondary material quality and value can result from material yield effects. Material yield refers to the relative amount of metal that is output after processing compared to the total material input prior to processing. Non-unity aluminum material yields result from the separation of oxide and low density non-metallic content initially present in the scrap during production as well as aluminum and magnesium oxidation reactions that occur during remelting. Secondary material quality (Xiao, Reuter et al. 2005) and remelting conditions such as oxygen pressure in furnace, temperature, and residual moisture in the scrap can influence material yield (Zhou, Yang et al. 2006). A few examples of the relative compositions of aluminum metal, oxide metal, and other materials present in aluminum scrap are given in Table III below adapted from (Boin and Bertram 2005) (Krone 2000). As seen in Table III, secondary materials with coatings tend to have a lower associated material yield because the lower density coatings separate and rise to the surface of the melt reducing the total metal output (Boin and Bertram 2005). For example, used beverage cans which are a type of painted scrap, tend to have material yields lower than 85% after remelting (Gesing and Harbeck 2008). Material characteristics such as composition, compositional uncertainty, and material yield strongly influence the value of secondary materials on the metals market. Aluminum secondary market effects and economics influence the willingness of aluminum remelters to incorporate secondary materials and the overall aluminum industry recycling efficiency.

Table III. Example Scrap Compositions Taken from European Aluminum Scrap Standard (EN 13920) (Krone 2000) as Collected by (Boin and Bertram 2005).

Scrap Type	Aluminum Metal Content (%)	Oxide Metal Content (%)	Other Material Content (%)
Wire and cable (new scrap)	98.7	1.3	-
Wire and cable (old scrap)	97.7	1.8	0.5
One single wrought alloy	97.2	1.0	1.8
Castings	83.4	6.2	10.4
Shredded and density separated scrap	84.5	5.4	10.1
Used beverage cans	94.0	0.8	5.2
Turnings, one single alloy	95.3	3.7	1.0
Packaging (coated)	71.5	3.8	24.7
Packaging (de-coated)	86.1	12.9	1.0
Dross	55.7	44.3	-

1.2.2 Secondary material economics

Amidst the economic advantages of secondary material recycling, several economic and regulatory factors present challenges to increasing both global and local aluminum recycling rates. To promote and incentivize aluminum recycling, many countries have implemented policies such as tax policies to reward recycling and penalties for landfill disposal (Blomberg and Söderholm 2009). However, the specifics of the recycling regulations vary geographically causing profitability disparities which results in asymmetries in the effectiveness of the policies to promote recycling (Gesing 2004). Additionally, (Blomberg and Söderholm 2009) assert that the success of regulatory policies depends on aluminum market factors such as price elasticity. Differences in regional health and safety regulations in Asia versus Europe and North America provides an example of disparate governmental policies that make recycling operations more profitable in Asia than in Europe or North America (Gesing 2004). Another example of a regional economic advantage is the 15% value added tax refund provided by the Chinese government to Chinese recyclers that allows aluminum recyclers to pay more for secondary materials than their North American and European counterparts while maintaining the same profitability (Gesing 2004). In addition to China, Mexico, Turkey, and India are also willing to pay a premium for secondary materials (Gesing and Harbeck 2008). The tax refund provided by the Chinese government and the price premium other nations are willing to pay for secondary materials has constrained secondary material availability and increased secondary material prices in the United States and Europe (Gesing 2004). The significant impact of the 15% value added tax to Chinese recyclers on the aluminum market is demonstrated by the sharp increase in Chinese scrap consumption to approximately 2,500,000 tons in 2003 from 500,000 tons in 1992 (Bijlhouwer 2005). In addition to affecting secondary material availability, regulatory policies promoting aluminum recycling also impact secondary material price.

The purchasing price of secondary materials is a crucial factor in promoting aluminum recycling and increasing recycling efficiency. Although the alloying elements in aluminum scrap in pure form can be more valuable than pure aluminum, such as silicon alloying material; manufacturers sell scrap to brokers at a discount proportional to the alloying material content (Gesing and Harbeck 2008). However, because the scrap supply is limited, scrap brokers are frequently able to sell the scrap materials to smelters according to primary metal prices (Gesing and Harbeck 2008). Expensive secondary materials reduce the profitability of aluminum recycling operations and can deter aluminum remelters from incorporating secondary materials in addition to the existing deterrent of managing the associated process complexity. At present, secondary material economics present a challenge to increasing aluminum recycling and further strategies must be explored to improve the global aluminum recycling efficiency.

1.3 Approaches to increase aluminum recycling

1.3.1 Operation and technical approaches to increase aluminum recycling

There are several operational and technical strategies that can be implemented to promote aluminum recycling. One common strategy to increase post-consumed secondary materials content in remelting charges given the challenge of high alloying element concentration and compositional uncertainty is to modestly incorporate the secondary materials and dilute with more compositionally certain and expensive primary aluminum (Das 2006). A more long term approach to promoting aluminum recycling is to produce alloys with compositional specifications engineered to increase allowable secondary material content (Gaustad 2009), (Gaustad, Olivetti et al. 2010). (Gaustad, Olivetti et al. 2010) have developed a methodology to characterize an alloy's ability to incorporate recycled materials and identify the most impactful compositional specification modifications to increase recycled material content. (Das 2011) has also offered several suggestions to improve the recyclability of aluminum alloys commonly used in industry including; reducing the number of alloying elements included in the compositional specifications and reducing total number of globally used aluminum alloys to 15. Another proposed method to reduce compositional variation in the scrap material stream is to develop an alloy or a "unialloy" that can be used to produce various components in the automotive industry that are presently produced using several aluminum alloys with distinct compositional specifications (Das, Green et al. 2010). Although re-engineering aluminum alloy compositional specifications has tremendous potential to improve the global aluminum recycling efficiency, such an effort would require significant cooperation between regulatory bodies and aluminum remelting companies that may not be presently realizable.

Another operational approach to increasing aluminum recycling is colloquially referred to as landfill mining and refers to recovering disposed aluminum materials from landfills (Das 2011). The main allure of landfill mining is the enormous potential volume of material to recover that is presently stored in landfills. (Das 2011) estimates that there are between 20 and 30 million tons of used aluminum beverage containers presently in American landfills. Reclaiming this aluminum is challenging because of health and occupational safety concerns of the reclamation workers and the uncertain quality of the used aluminum beverage cans after remaining in landfills for a significant period of time. As a result, landfill mining operations may be delayed until further research has addressed these concerns. In the more near term, there are several technological strategies that can improve the value of post-consumed secondary aluminum materials.

Technological methods that increase the value of secondary materials and improve industrial recycling profitability are also effective at promoting aluminum recycling. Examples of such technological strategies include computational optimization of the recycling process (Gaustad, Li et al. 2007), melt separation techniques (Das 2006), and sorting secondary materials by composition (Gesing 2004). (Gaustad, Olivetti et al. 2012) provide a thorough survey on the advantages and disadvantages of melt separation, sorting, inclusion removal, and hydrogen removal in the context of aluminum recycling. Magnesium can be separated in the melt to produce higher purity aluminum using chlorination (Gesing and Wolanski 2001). However, treating post-consumed secondary aluminum materials with chlorination processes presents other environmental concerns because of the health hazards associated with the required chemicals (Gesing and Wolanski 2001). Sorting co-mingled secondary materials provides economic value by separating the materials into groups with narrower compositional ranges. For example, eddy current coil sensors have been implemented to sort nonmetallic content from metallic content and dual energy x-ray transmission sensors have been implemented to sort low density metals from high density metals at municipal recycling facilities (Gesing and Harbeck 2008). Another promising sorting technique uses laser induced breakdown spectroscopy or (LIBS) which can calculate secondary material composition with minimal damage to the material properties (Gesing, Stewart et al. 2000). Compositional sorting can also be performed at lower cost using hand-held chemical analyzers (Das, Green et al. 2010). Presently, the most prevalent sorting technology is hand sorting performed by low income laborers in China (Spencer 2005). Sorting is a promising technique to increase the value of secondary aluminum materials but increasing industrial implementation is limited by economic factors.

The slow implementation rates of sorting technology at scrap yards results from insufficient economic incentives because of the relatively expensive price scrap brokers can sell secondary materials for on the market (Gesing and Harbeck 2008). Economic advantages of sorting have been demonstrated by (Li, Dahmus et al. 2011) but further technological improvements must be made to promote wide scale implementation of sorting operations. There are inherent compositional limitations to sorting post-consumed secondary materials to increase their value, because ultimately the post-consumed secondary materials would be the most valuable if co-mingling had never occurred. Research in reprocessing byproducts produced during aluminum remelting operations may provide an alternative secondary material source with reduced compositional uncertainty and alloying element accumulation.

1.3.2 Novel secondary material feedstocks

Increasing economic pressure to identify inexpensive secondary materials has motivated research on strategies to recycle aluminum dross byproducts for the production of high quality aluminum alloys. The complex economic and regulatory factors outlined previously characterizing the present state of the aluminum industry have motivated the pursuit of less expensive secondary materials with sufficient material properties to be included into aluminum remelting and recycling operations. Aluminum dross is formed as a byproduct during aluminum alloy production and contains a significant quantity of valuable metallic aluminum. Aluminum dross could serve as an alternative secondary material feedstock for aluminum remelters, provided economic recovery of the entrapped metal content and material management costs.

The production factors used in recycling and remelting operations determine the volume, value, and other characteristics of aluminum dross byproduct produced. The entrapped metal content in the aluminum dross determines the economic value to industrial remelters. The bulk of aluminum dross is composed of aluminum oxide which is created as a result of the large oxidation potential of aluminum at the temperatures used during aluminum remelting. As a result of the large aluminum oxide content, aluminum dross has a lower density than liquid aluminum metal causing it to accumulate at the melt surface with the other low density materials formerly in the melt. The density of cooled aluminum dross byproduct is approximately 880 kg/m^3 (Amer 2010) compared to the density of liquid aluminum at its melting point, 2,375 kg/m^3. To avoid deteriorating the material properties of the aluminum alloy product, the aluminum dross byproduct is removed from the melt at the end of the remelting operation in a process called tapping or skimming (Xiao, Reuter et al. 2005). Liquid aluminum becomes entrapped in the aluminum dross as a result of imperfect tapping or skimming practices performed at the interface between the aluminum melt and the aluminum dross (Manfredi, Wuth et al.

1997). Metal entrapment in the aluminum dross due to imperfect interfacial practices causes more aluminum material losses than aluminum oxidation (Manfredi, Wuth et al. 1997). The photograph of aluminum dross byproduct in Figure 5 shows the physical appearance of the material and the large volumetric proportion of aluminum oxide relative to entrapped metal (Urbach 2010). The relative metal and oxide content can vary depending on the remelting production parameters with average entrapped metal content on the order of 50% (Ünlü and Drouet 2002). Ultimately, the generation of aluminum dross byproduct represents an inefficiency in aluminum remelting and recycling operations because it is a significant source of aluminum losses; aggregating the total weight of aluminum in metal, oxide, and nitride form can amount to as high as 75-wt% of the dross (Yan 2008). The value of aluminum dross is determined differently by aluminum remelters and dross reprocessors. A remelter aims to minimize the total volume of aluminum dross and entrapped liquid metal during remelting to maximize profitability. However, the resale value of the dross byproduct increases with the entrapped aluminum metal content to the dross reprocessor. In addition to determining the economic value of aluminum dross byproduct generation and reprocessing, the material properties also determine its environmental impact.

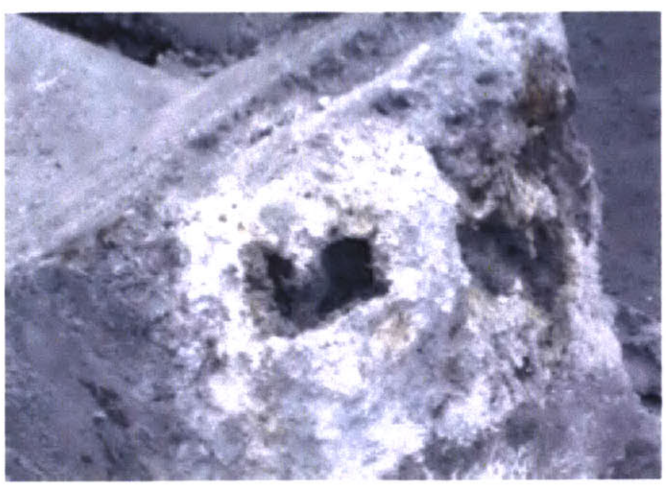

Figure 5. A photograph of aluminum dross byproduct (Urbach 2010).

The environmental concerns associated with the production and disposal of aluminum dross byproduct also motivate research on recycling methods. The large volumes generated make the production of aluminum dross byproduct an important environmental issue; global generation is estimated to be 250,000 tonnes per year (Yan

2008). This tonnage is considered waste by most aluminum remelters and extra cost results from having to treat this material prior to disposal because most member states in the European Union prohibit landfill disposal of aluminum dross byproduct (Prillhofer, Prillhofer et al. 2009), (Union 1999). Regulations restricting landfilling aluminum dross originate from concerns about potentially harmful water soluble compounds and other components within the aluminum dross that will react with water to form dangerous compounds such as odorous, poisonous, and explosive gases (Xiao, Reuter et al. 2005). Examples of hazardous gases emanating from landfilled aluminum dross exposed to rainwater include ammonia, acetylene, (Manfredi, Wuth et al. 1997), methane, and phosphine (Xiao, Reuter et al. 2005). Treating and reprocessing aluminum dross prior to landfill disposal limits creating these environmentally harmful byproducts (Xiao, Reuter et al. 2005). The majority of aluminum dross generated from aluminum production in geographic regions without environmental regulations on aluminum dross disposal is landfilled and not recycled because of the process complexity increase and economic costs required for aluminum dross recycling (Hermsmeyer, Diekmann et al. 2002). Due to the uncertain and variable characteristics of aluminum dross byproduct, contamination risks also limit the willingness of industrial remelters to import dross byproduct generated from other facilities. Reprocessing aluminum dross byproduct to extract the entrapped metal from the non-metallic content generates a material commonly called salt cake which poses many of the same environmental hazards as aluminum dross when landfilled without proper treatment (Ünlü and Drouet 2002). Several researchers have explored alternative applications for the non-metallic salt cake including concrete blocks (Shinzato and Hypolito 2005), a cover material for steel production (Ueda, Tsukamoto et al. 2005), refractory materials (Ueda, Tsukamoto et al. 2005), and soil substitutes for covering landfilled mining residue (Hermsmeyer, Diekmann et al. 2002). Recovering salt flux from the salt cake is also a potentially valuable endeavor because potassium chloride can be recovered and converted into potash to be sold as fertilizer (Hermsmeyer, Diekmann et al. 2002). Alternatively, aluminum can be recovered in the form of aluminum sulfate which has applications including: dying, sizing, water purification, tanning, insulation, and fire-proofing applications (Amer 2010). However, aluminum sulfate is not as valuable as metallic aluminum. Despite the associated challenges, industrial interest in reprocessing aluminum dross to reclaim entrapped metal has increased because of the potential environmental and economic benefits associated with an economically viable aluminum dross reprocessing operation (Prillhofer, Prillhofer et al. 2009).

The economic and environmental motivation for aluminum recycling has motivated the pursuit of secondary materials that have sufficient material quality and cost. Excessively expensive scrap costs and limited availabilities have motivated interest in pursuing technical scrap upgrading approaches to increase the value of secondary materials such as shredding and shorting operations. Although these upgrading technologies demonstrate significant potential to promote recycling, at present, significant start up and equipment costs are limiting widespread industrial adoption. One relatively new strategy to increase the global aluminum recycling efficiency is reprocessing aluminum dross byproduct from industrial remelting operations to recover entrapped metal. There are many challenges associated with reprocessing aluminum dross byproduct into a viable alternative secondary material. For example, the large non-metallic content in aluminum dross necessitates reprocessing large tonnages of this material to ensure economic viability. Industrial scale aluminum dross reprocessing operations also require expensive equipment such as rotary furnaces to manage the significant non-metallic content in the dross. The high temperatures required in aluminum dross reprocessing to melt the entrapped metal introduce additional process complexity because of energy efficiency concerns. For example, the non-metallic content contains significant heat after reprocessing and frequently dross reprocessors choose to keep a portion of this material in the rotary furnace to reduce the heat requirement for reprocessing the subsequent batch. Another source of process complexity resulting from energy efficiency concerns is the option of incorporating the reprocessed aluminum dross as liquid metal since it is removed from the furnace in this state. Delivering the reprocessed aluminum dross as liquid metal reduces the aluminum recycler's energy costs and time requirement to melt the reprocessed material. This thesis will explore a specific industrial aluminum dross reprocessing operation and quantify the effects of process complexity on performance.

The economic and environmental advantages of recycling post-consumed secondary materials and aluminum dross byproduct has motivated interest in the development of a recycling center that can deliver recycled materials in a form that can be used as raw material feedstocks by aluminum remelting facilities. The issues surrounding secondary material quality and reprocessing requirements have motivated the creation of a separate recycling center to reprocess the post-consumed secondary materials and aluminum dross byproduct rather than introduce these materials directly to the remelting facilities without prior refinement. Quantifying the industrial challenges associated with the development and implementation of a recycling center is crucial to promoting and ensuring the economic viability of the aluminum dross byproduct and post-consumed secondary material recycling operation.

1.4 Industrial Challenges

1.4.1 Dynamic downstream production schedule

Inherent variation in the downstream remelter production schedules challenges formulating a long term production plan that coordinates the operations of the recycling center with the downstream remelter production. The industrial interest in establishing a long term recycling center production plan is motivated by the desire to provide simplicity to the recycling center operators. The recycling center must decide the optimal level of flexibility to deviate from the long term production plan and adjust its production to the daily demands of the downstream remelting facilities without creating too much complexity for the recycling center operators which could reduce production efficiency. The recycling center aims to establish a set of production guidelines to apply to daily operations based on knowledge of the long term production trends of the downstream aluminum remelters.

Long term production constraints necessitate establishing recycling center production guidelines but the dynamic character of downstream remelter production introduces risk to ensuring the optimality of these guidelines. The economic viability of the recycling center requires reprocessing large tonnages of recycled materials. In order to supply the large tonnages, the recycling center must procure the aluminum dross and post-consumed secondary materials well in advance. Procuring aluminum dross and post-consumed secondary materials is challenging because of limited availability and a poorly defined market. The aluminum dross market is immature because the vendors are predominately internal customers with few competitors. Purchasing contracts for technically unlimited amounts of aluminum dross are risky because of expensive storage costs. For example, to preserve the material properties of aluminum dross and prevent hazardous reactions it is necessary to provide indoor storage to prevent water exposure. The dynamic nature of the downstream remelter production schedule makes quantifying the optimal tonnages of aluminum dross and post-consumed secondary materials to purchase in advance of realized downstream production, challenging and risky. For example, a calculation of the optimal recycling material purchasing and allocation volumes based on historical downstream remelter production mean volume can be rendered sub-optimal if production orders in the subsequent year differ from the previous year. The realized downstream remelter production volumes are influenced by a number of external factors including macroeconomic conditions and specific market factors such as building construction demand. As a result of these external factors, it is difficult to precisely quantify in advance the long term production needs of the downstream remelters.

1.4.2 Economies of scale associated with aluminum dross reprocessing

The large energy and machinery requirement for aluminum dross and post-consumed secondary material reprocessing provides economies of scale benefits. The large energy requirement for heating aluminum dross and post-consumed secondary materials to a temperature that allows the oxide content to separate from the liquid metal makes reprocessing large volumes of aluminum dross more economical than reprocessing smaller volumes. The substantial equipment costs also challenges the intuitive solution to purchase additional rotary furnaces to increase the reprocessing capacity at the recycling center. In order to maximize energy efficiency, the rotary furnaces at the recycling center must be operated at maximum capacity. As a result of this efficiency requirement, there is a mismatch between the output volume of recycled material from the recycling center and the recycled material input volume desired by the downstream remelters. In other words, it is not economically feasible for the recycling center to produce the exact volume of recycled product desired by the downstream remelters at any given time and instead the recycling center must produce a volume of recycled product that maximizes the rotary furnace capacity. Delivering the desired recycled product volume to the downstream remelting facilities and storing the left over recycled products as cast sows at the recycling center presents economic penalties.

The large amount of energy and time required to melt aluminum translates significant economic benefits to delivering the recycled products produced at the recycling center to the downstream remelting facilities as liquid metal as opposed to cast solid metal. Delivering the recycled products as liquid provides economic benefits by relieving the downstream facilities from the burden of remelting the recycled products. Besides cost and environmental advantages, avoiding a time delay in production resulting from remelting the metal at the downstream remelting facilities provides economic benefits that are difficult to quantify. Melting aluminum requires significant time and providing new quantities of liquid metal is a key merit of the recycling center. Without these liquid metal shipments, the downstream remelters can purchase primary liquid aluminum and alloying metal to ensure the total remelter production volume is unaffected, but at greater cost. Although the economic benefits of delivering liquid metal are difficult to quantify; liquid metal shipments is an important attribute from the perspective of the downstream customer plants. The practical limitations and constraints characterizing industrial production will inevitably cause a portion of the liquid recycled product to be cast and stored as solid metal at the recycling center. Quantifying the relationship between the recycling center production design and the amount of recycled material delivered as liquid to the downstream aluminum remelters is essential to determining the economic viability of the proposed recycling center. The industrial challenges presented by operating two separate sets of aluminum production plants creates a tension between providing flexibility for daily recycling center operations and coordinating recycling center production with downstream remelting production.

In this context, a fundamental question that emerges is whether an aluminum dross and post-consumed secondary material reprocessor could increase recycled material consumption by directing his / her reprocessing operations with knowledge of the characteristics of the finished aluminum alloys the recycled materials will be used to produce in subsequent remelting. This work intends to develop computational models to explore the effect of recycling center design strategies improves the ability to use post-consumed scrap and aluminum dross in finished alloy products.

1.4 Description of thesis- the value of coordination and flexibility in aluminum recycling

This thesis will explore following question-

1) Considering the metallurgical complexities of aluminum dross reprocessing, what is the value of operating a coordinated set of aluminum dross and post-consumed secondary material reprocessing recycling centers and aluminum remelting plants?

A mathematical modeling framework to describe the operation of the recycling center and the downstream aluminum remelting plants is developed to answer this research question. . Figure 6 represents the recycling operation that is being described mathematically and indicates the direction of material flow through the system. The performance of the proposed recycling center production design is estimated by performing a production simulation using historical downstream remelting plant production data. A successful implementation of the recycling center to deliver liquid recycled products to two downstream remelting plants requires the recycling center to determine production designs that meet the needs of the downstream remelting plants. The liquid recycled products from the recycling center are combined with primary, alloying material, and process scrap at the downstream remelters to produce finished alloys. The recycling center must decide the optimal combinations of aluminum dross and post-consumed scrap materials to reprocess into recycled products that maximize recycled material content and minimize primary and alloying material additions in downstream remelter production.

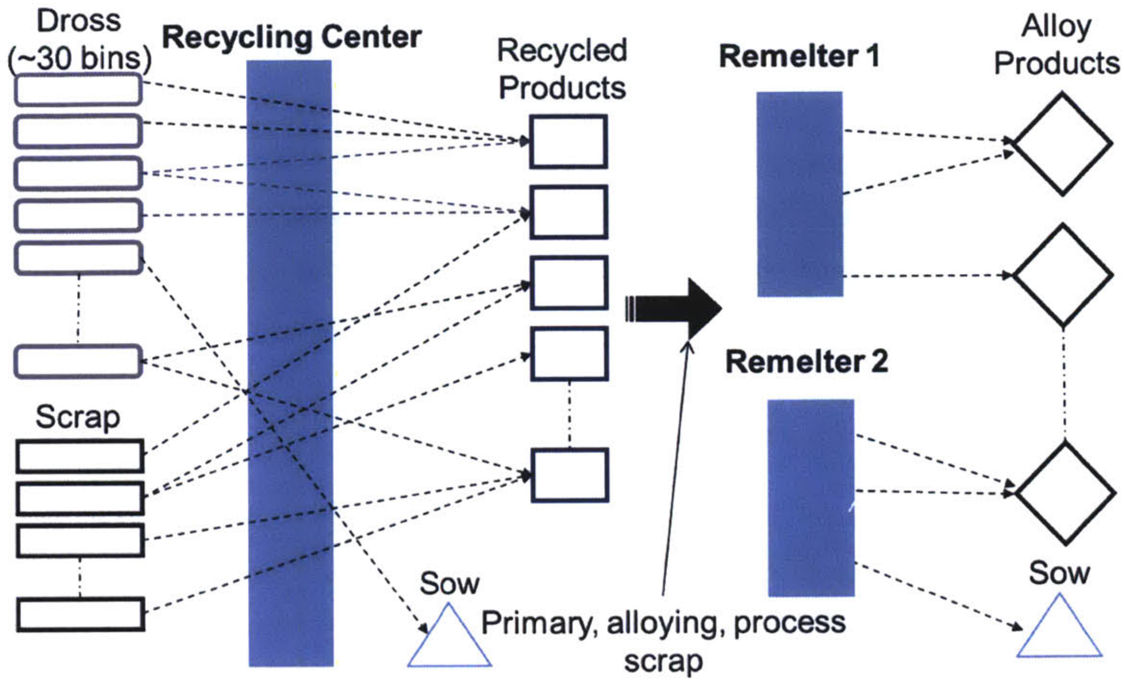

Figure 6. Material flow from dross and scrap raw materials to finished alloy products.

Accurate determination of the optimal recycling production plan requires modeling the coordination between the recycling center and the downstream remelting plants. The aluminum dross and post-consumed scrap materials available to the recycling center have a diverse set of compositional and material yield characteristics. Recycling center materials with extreme characteristics motivate the use of mathematical modeling techniques to ensure proper allocation in the alloy products produced at the downstream remelters. In addition, the physical complexities of operating a set of aluminum production facilities also motivates the use of mathematical modeling to quantify the impact of varying the level of coordination and the impact of the number of recycled products produced at the recycling center on performance. The long term versus daily benefits of coordinating the production of the recycling center with the downstream facilities must be balanced with the benefits of daily operational flexibility by the manager of the recycling center. The performance criterion and analyses that will be presented in this thesis to answer the proposed research question are outlined in Figure 7 below. The key performance metrics to evaluate the recycling center production design are recycled material content in downstream production, overall production cost, and the amount of recycled products incorporated as liquid into downstream production. The recycling center production plan is characterized by calculating the optimal recycled product volumes, compositional specifications, allocation of recycled products across finished alloys, and recipes or the relative recycled material content in the recycled products. The performance of the recycling center depends on its ability to operate cooperatively with the downstream aluminum remelters. As a result, the recycling center production design must be robust to perturbations in the variables characterizing downstream production including downstream production uncertainty, downstream production variation, and the level of coordination between the operations of the recycling center and the downstream remelting facilities.

Traditional metallurgical recycling models focus on the optimal blending of a set of raw materials without explicit incorporation of a secondary recycling facility. New types of secondary materials may necessitate a secondary recycling facility to limit contamination risks which may introduce operational challenges that have been overlooked by previous work. The introduction of a secondary intermediate facility is similar to a branch of optimization models called pooling models that have not yet been applied to metallurgical operations. The subsequent section discusses the relevant previous work and the proposed gap this work is intended to address. This thesis will build upon previous metallurgical batch planning work by presenting a set of decision making tools and evaluation of production design analyses to assist in the development of an aluminum recycling center that delivers liquid metal products to a set of downstream remelting production facilities.

This thesis is structured in the following way. Chapter 2 examines previous research on experimental and computational modeling investigations on aluminum dross, metallurgical batch planning tools, and research on pooling problems in other industries. Chapter 3 explains the methodology used to develop the decision making tools and perform the analyses. Chapter 4 establishes a benchmark performance for the aluminum recycling center based on historical data and long term production constraints describing the recycling center and the downstream remelting facilities. Chapter 5 explores the robustness of the benchmark performance production plan to projected downstream remelter production uncertainty. Chapter 6 evaluates the value of coordination and flexibility to the recycling center production design by performing daily operational simulations of three levels of coordination; high coordination, middle coordination, and low coordination case and four degrees of recycling center operational flexibility embedded in the daily optimization model. Chapter 6 also evaluates the ability of the proposed simulation optimization technique to improve performance in the presence of downstream remelter demand uncertainty. A summary of the key results and conclusions of this thesis is presented in chapter 7. Finally, the limitations of the presented work and a proposal for further study are presented in chapter 8.

Effective recycling center production designs are calculated using a long term production model with a fixed level of coordination between the recycling center and downstream remelting facilities and their performance is evaluated with daily operational models that allowed varying degrees of daily operational level flexibility at the recycling center. The quantification of the value of providing flexibility to the recycling center to deviate from the calculated optimal long term production plans and varying the level of coordination with the downstream remelters is a key contribution of this thesis. The range of performance of the proposed recycling center production design with variations in the proposed design motivates the implementation of a set of decision making tools at the recycling center. This thesis determined that the value of coordinating the operation of a set of recycled material reprocessing and remelting facilities depends on the time frame examined. The impact on recycling center performance of several operational parameters is quantified. This thesis also quantifies the impact of external downstream remelter production variables on the performance of the recycling center production designs. This thesis also proposes an alternative simulation optimization technique to calculate the recycling center production design and evaluates its ability to improve performance.

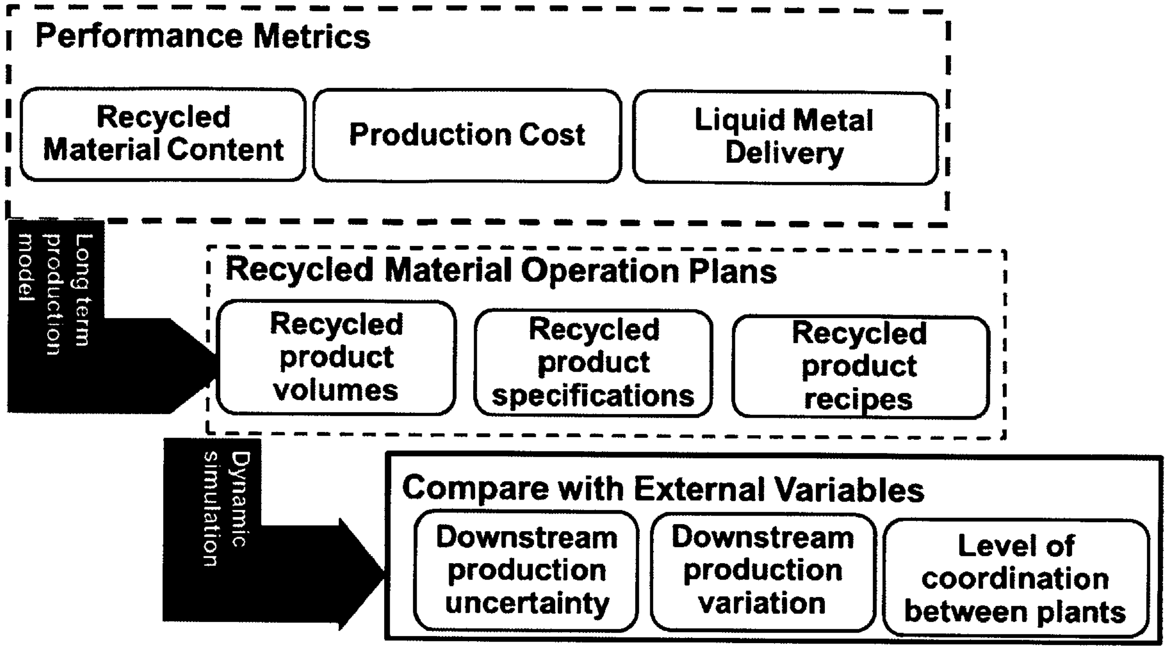

Figure 7. Outline of the analyses presented in the thesis to quantify the value of coordinating the production of the recycling center and the downstream aluminum remelting facilities.

Chapter 2. Literature review and gap analysis

Determining the value of coordinating the production of the recycling center and the downstream aluminum remelting facilities will require 1) development of a long term metallurgical optimization model, 2) a method to evaluate the performance impact of downstream production uncertainty, 3) development of daily operational level models with varying degrees of flexibility, 4) simulation of daily recycling center production to determine the impact of production parameters including downstream demand variation, furnace capacity mismatch, recycled material perishability, and recycled material management on overall system performance. The motivation and importance of pursuing each of these topics was introduced in the proceeding chapter. This chapter presents a literature review of related previous work and discusses current gaps in the existing related research that may be addressed by this research.

2.1 Previous work researching and modeling aluminum dross generation and reprocessing methods

Accurate modeling of the operations of the aluminum recycling center requires an in-depth understanding of the relationship between the properties of the recovered material and the production parameters involved in aluminum dross generation and reprocessing. The uncertain and variable quality of aluminum dross byproduct necessitates a separate reprocessing step to refine the material to an extent that it can be used as a raw material feedstock for high quality aluminum alloys. For example, the large oxide content in the aluminum dross prohibits direct delivery to the downstream remelting facilities and the additional re-processing operation separates a large fraction of the entrapped metal from the non-metallic material. After reprocessing, the recycled material can be included in the downstream remelting facilities with the more expensive and compositionally certain primary materials, prompt scrap, and alloying elements without damaging the remelting furnace or the quality of the finished aluminum alloy products. The potential to recover valuable entrapped metal in the aluminum dross byproduct and sell the reprocessed material as an alternative secondary material has motivated thorough research on aluminum dross byproduct generation and reprocessing.

2.1.1 Previous work researching the influence of aluminum remelting production parameters on dross generation

Significant research has been performed on characterizing the physical and chemical properties of aluminum dross to better evaluate the viability of reprocessed aluminum dross as an alternative secondary material feedstock for aluminum remelters. Figure 8 is a schematic showing a cross section of an aluminum remelting furnace with the relative locations of aluminum dross, salt, and the bulk aluminum melt. Salt fluxes are commonly added during aluminum remelting as a protective cover to reduce atmospheric exposure of the liquid aluminum metal and thereby limit oxidation reactions that promote aluminum dross generation (Hermsmeyer, Diekmann et al. 2002). Salt fluxes are also added during aluminum production to help remove inclusions from the liquid aluminum (Majidi, Shabestari et al. 2007). The thickness of the salt layer on the melt surface is on the order of 1 mm (Utigard 1998). Aluminum dross tends to accumulate at the surface of the melt near the salt layer because it is has a lower density than liquid aluminum metal at its melting point; 0.828-1.118 t/m^3 (Manfredi, Wuth et al. 1997) versus 2.375 g/cm^3. Other impurities with densities that are also less than the density of liquid aluminum metal at its melting point also accumulate at the liquid metal surface causing aluminum dross to contain in addition to aluminum oxide; salt flux, chlorides, carbides, nitrides, other oxides of the alloying elements, and entrapped aluminum metal particulates (Manfredi, Wuth et al. 1997; Xiao, Reuter et al. 2005). Further research quantifying the chemical composition can inform assessments of the aluminum dross value.

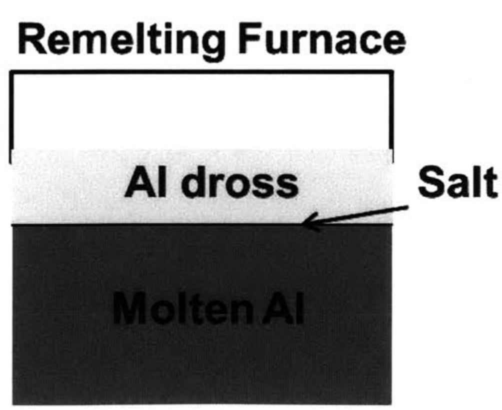

Figure 8. Schematic showing the relative locations of the aluminum dross, salt, and molten aluminum within a remelting furnace.

Previous research quantifying the chemical composition of aluminum dross can provide estimates for the attainable chemical compositions by purchasing aluminum dross by-product from aluminum remelters. After aluminum dross is removed from a remelting furnace by skimming or tapping, it commonly contains aluminum metal particulates as a result of imperfect removal at the interface (Manfredi, Wuth et al. 1997). (Manfredi, Wuth et al. 1997) performed extensive experimental work characterizing the material properties of compact and granular aluminum dross samples obtained from industrial aluminum foundries and smelters. Table IV is a summary of the key aluminum dross properties found in the study including metal content, particle size distribution, relative salt content, and density of granular and compact dross determined by the authors (Manfredi, Wuth et al. 1997). (Manfredi, Wuth et al. 1997) found significant entrapped metal content in the industrial aluminum dross samples ranging from 46.9%-93% depending on the dross type and generation source facility. The economic viability of aluminum dross as an alternate secondary material is determined by the entrapped metal content and the significant metal content reported in (Manfredi, Wuth et al. 1997) supports that aluminum dross may be an economically viable alternate secondary material. Table IV also shows the compositional similarity of aluminum dross and post consumed secondary materials including significant alloying element content and associated compositional uncertainty. The total alloying element content ranges from 1.03-6.80% depending on the aluminum dross type and generation source facility (Manfredi, Wuth et al. 1997). The similarity in alloying element content and compositional uncertainty supports that incorporating aluminum dross as an alternative secondary material feedstock will present many of the same compositional challenges that have been identified in commonly used aluminum secondary materials. (Manfredi, Wuth et al. 1997) determined that the alloying element and overall metal content in the aluminum dross samples was determined by the chemical composition of the alloy the aluminum production facility was producing to generate the dross and the parameters of the reprocessing operation performed to recover entrapped metal. Further understanding the dependence of the recovered metal content on the conditions of aluminum dross generation and the parameters involved in dross reprocessing can inform optimal aluminum dross reprocessing operations at the recycling center to maintain economic viability.

Table IV. Key Properties of Aluminum Dross Determined Experimentally by (Manfredi, Wuth et al. 1997).

Table I. The Range of Physical and Chemical Properties Measured

Properties	Granular Dross	Compact Dross
Alloy Content (%)		
Melt	2.44–11.77	1.34–10.03
Recovered Metal	1.03–5.51	0.33–6.80
Distribution(q) (mm^{-1})	0.08 (coarse)–0.452 (fine)	—
Density (t/m^3)	0.828–1.118 (bulk)	2.396–2.528 (apparent)
Metal Content (%)	46.9–69.1	71–93
Lixiviate (pH)	9.52–10.14	9.03–9.48
Salt Content (%)	0.18–6.21	0.01–0.03
Gas Evolution (l/kg dross)	0.25–1.17	No evolution

Several researchers have studied the impact of the raw material characteristics used in production and the remelting conditions on the material properties of aluminum dross produced as a byproduct during aluminum production. For example, the entrapped metal content in aluminum dross that has been removed and cooled depends on operational factors (Manfredi, Wuth et al. 1997), added salt flux compositions (Xiao, Reuter et al. 2005), cooling schedule (Manfredi, Wuth et al. 1997), accuracy of skimming practice (Manfredi, Wuth et al. 1997), and characteristics of the raw materials in the melt (Xiao, Reuter et al. 2005). The diverse set of available secondary materials and the tendency of secondary materials to promote dross generation have motivated experiments exploring the effects of secondary material characteristics on aluminum dross generation. (Xiao, Reuter et al. 2005) studied the recyclability of several secondary materials by measuring material yield and amount of aluminum dross generated during remelting. (Xiao, Reuter et al. 2005) determined that the volume of generated aluminum dross during remelting depends on the following characteristics of the secondary materials: the presence of impurities, shape, lifecycle, and relative surface area. Table V is a reproduction of the summary of the key findings of the recyclability study, including the relative rankings as evaluated by the authors, the rate of metal recovery, and the relative degree of scrap coalescence (Xiao, Reuter et al. 2005). The relative degree of scrap coalescence is an important metric for evaluating secondary material recyclability because metal droplet coalescence aides the liquid metal to sink into the aluminum melt and without coalescence the smaller particles tend to remain at the melt surface near the aluminum dross (Xiao, Reuter et al. 2005). The authors found that secondary materials with larger shapes had larger metal recovery rates because coalescence occurs more readily for larger metal particles (Xiao, Reuter et al. 2005). The authors determined that the entrapped metal content in aluminum dross decreases during remelting according to the following remelting production parameters: higher remelting temperatures, faster rates of stirring, longer remelting durations, and maintaining the optimal concentrations of cryolite in the salt flux for the particular charge (Xiao, Reuter et al. 2005). (Amini Mashhadi, Moloodi et al. 2009) performed a separate set of recycling experiments and determined that scrap recyclability was not improved by cold pressing scrap prior to recycling. Adding salt fluxes is another method to improve scrap recyclability. Adding salt fluxes during aluminum remelting can significantly reduce metal losses during tapping (Utigard 1998). Manipulating salt flux chemistry is an important area of research for improving the efficiency of aluminum recycling and aluminum dross reprocessing operations.

Table V. Reproduction of the Findings of (Xiao, Reuter et al. 2005) on the Relative Recyclability, Recoverable Metal Fraction, and Relative Coalescence Ability of 10 Secondary Materials.

Scraps	Recyclability ranking	Recoverable metal, wt-%	Coalescence factor
Cast Ingots	1	99.5	10
Profiles	2	99.6	9
Rolling mill cuttings	3	98.3	8
Printing plates	4	97.0	8
Fridge shreds	5	95.5	7
Bottle caps	6	88.6	6
Car plates	7	89.3	5
Granules	8	85.2	5
Turnings	9	84.3	4
Margarine foils	10	86.2	2

Researchers have explored the capabilities of salt fluxes additions during aluminum remelting and recycling operations to minimize aluminum oxidation and liquid metal entrapment in the dross that cause metal losses. (Utigard 1998) explored the value of using salt fluxes during aluminum remelting operations for removing gases, removing magnesium, limiting melt exposure to the oxygen atmosphere, and inhibiting aluminum entrapment in the dross. Because a eutectic occurs at a relatively low temperature for this composition (Utigard 1998), a 70 wt.% sodium chloride and 30 wt.% mixture potassium chloride is the most frequently used salt flux to cover the melt surface during industrial aluminum remelting (Hermsmeyer, Dieckmann et al. 2002). Fluoride salt additions such as cryolite provide additional advantages by further lowering the eutectic point and decreasing the salt viscosity causing the aluminum dross and salt flux mixture to have the viscosity of a slurry (Xiao, Reuter et al. 2005). Fluoride containing salt flux additions further reduce metal losses during remelting because in addition to limiting oxidation reactions by serving as a protective cover, fluoride salt fluxes also increase the interfacial tension between the oxide based dross and metallic aluminum (Utigard 1998). Increasing the interfacial tension between metallic aluminum and aluminum oxide reduces the tendency for metallic entrapment in the oxide (Xiao, Reuter et al. 2005) and assists coalescence of liquid aluminum particulates (Utigard 1998). The ability of the salt flux to promote liquid metal droplet coalescence is crucial because agglomeration resulting from coalescence generates a significant density gradient between the higher density liquid metal droplet and the lower density oxide based dross. As a result of the density gradient, the liquid aluminum droplets have a stronger drive to sink back into the melt instead of remaining near the interface between the melt and the aluminum dross layer where they can become entrapped (Utigard 1998). (Utigard 1998) studied the ability of several types of salt fluxes to assist aluminum droplet coalescence at 740°C. Another advantage of using salt fluxes composed of mixtures of sodium chloride, potassium chloride, and fluoride beyond providing a protective cover on the melt surface and assisting liquid aluminum droplet coalescence is the ability of these fluxes to slightly dissolve the aluminum oxide coating the entrapped liquid metal droplet (Utigard 1998). Despite the benefits of using a salt flux containing fluoride, there are environmental and safety concerns associated with the use and disposal of fluoride salts (Utigard 1998).

Adding salt fluxes during aluminum remelting is a valuable method to limit metal losses but losses resulting from entrapment in the aluminum dross layer and oxidation cannot currently be eliminated entirely. Methods to reprocess aluminum dross and separate entrapped metal from the resulting oxide based salt cake remain valuable as a means to transform aluminum dross into a secondary material feedstock that can be broadly incorporated into industrial aluminum recycling operations.

2.1.2 Previous work researching aluminum dross reprocessing methods

Researchers have investigated and developed a wide variety of aluminum dross reprocessing methods aimed at transforming aluminum dross into a saleable product that can be marketed to aluminum remelters as an economical raw material feedstock. The presemt aluminum dross reprocessing methods have varying degrees of process complexity and performance. Perhaps the simplest dross reprocessing method is pressing the aluminum dross immediately after removing it from the remelting furnace to release a portion of the liquid metal (Kevorkijan 2002). Common steps performed in aluminum dross reprocessing methods include crushing, leaching, and sieving large particles of relatively high aluminum content out of aluminum dross (Shinzato and Hypolito 2005). A more industrial equipment intensive method involves using hammer mills to crush aluminum dross and separate the metallic content from the non-metallic content (Hermsmeyer, Diekmann et al. 2002). Researchers have also explored chemical methods to recover entrapped aluminum from aluminum dross byproduct. For example, (Yan 2008) explored using electrochemical methods to cause reduction reactions to recover metallic aluminum not only from the entrapped metallic content in the aluminum dross but to recover additional aluminum by reducing aluminum oxide and aluminum nitride. This dross reprocessing method offers many of the advantages of chemical methods without requiring environmentally hazardous cryolite, but disadvantages of this method include high temperatures, an argon atmosphere, calcium chloride based molten salts, and electrolytic cells (Yan 2008). The authors demonstrated success in reducing aluminum from aluminum oxide but were unable to recover metallic aluminum from aluminum nitride (Yan 2008). (Amer 2010) performed leaching and extraction in an autoclave to recover aluminum from industrially produced dross tailings. (Amer 2010) also quantified the impact of reaction duration, acid content, and temperature on the ability to recover aluminum in the presented leaching and extraction method. Another chemical method to recover metallic aluminum from aluminum dross was developed by (Ueda, Tsukamoto et al. 2005) who performed a flotation process to separate the oxide and metallic content and an electrolysis process in a molten salt to transform a proportion of the aluminum oxide to elemental aluminum. However, unlike the method develop by (Yan 2008) this method requires salt fluxes containing fluoride (Ueda, Tsukamoto et al. 2005). The molten salt bath was composed of 51 mol% sodium fluoride and 33 mol% aluminum fluoride and consequentially industrial implementation of this method would present environmental concerns and risk (Ueda, Tsukamoto et al. 2005). Reprocessing aluminum dross in a rotary furnace is another promising dross reprocessing method to economically recover entrapped metal. Employing a rotary furnace to reprocess aluminum dross has been demonstrated to increase aluminum metal recovery and is a promising area of current research to further improve the efficiency of aluminum dross reprocessing operations.

Dross reprocessing in a rotary furnace is a relatively inexpensive method to recover entrapped metal in dross and many researchers have investigated the impact of rotary furnace production parameters to improve metal recovery. A rotary furnace provides an important intermediary step during aluminum dross recycling because it can separate a large fraction of the non-metallic content from the entrapped metal and thereby protect the more expensive furnaces used in industrial aluminum remelting from excessive exposure to oxide material which can form deposits on the sides of the furnace that are difficult to remove. A common application of rotary furnaces used to reprocess aluminum dross and post consumed scrap involves adding a salt flux to promote metal droplet agglomeration and using the rotation of the furnace to separate the liquid metal content from the oxide and other low density materials (Zhou, Yang et al. 2006). Frequently, recyclers pretreat the dross with mechanical crushing to remove some of the oxide content prior to charging in the rotary furnace (Yan 2008). The total salt flux content in the rotary furnace including the salt originally in the aluminum dross and the salt flux added to the rotary furnace can be significant, on the order of 50% of the total weight (Ünlü and Drouet 2002). Aluminum recyclers run rotary furnace charges at temperatures near 800°C; a temperature sufficient to melt aluminum and provide sufficient fluidity to facilitate separation between the liquid metal and non-metallic content during furnace rotation (Zhou, Yang et al. 2006). Crushing bodies can also be added to rotary furnace charges to provide mechanical force to weaken the oxide coating surrounding the entrapped liquid metal droplets (Tzonev and Lucheva 2007). Research has also been performed on post rotary furnace aluminum dross reprocessing steps to improve metal recovery. For example, (Prillhofer, Prillhofer et al. 2009) incorporated a multiple step leaching-crystallization process to treat salt slag after reprocessing aluminum dross and other secondary materials in a rotary furnace. Although the authors demonstrated improvement in material recovery, because of the extensive labor required for the additional leaching and crystallization step, scaling up this process for industrial operations might be difficult (Prillhofer, Prillhofer et al. 2009). Many rotary furnace based dross reprocessing operations involve the use of a fluoride containing salt flux to improve metal recovery by assisting liquid droplet agglomeration. However, adding a fluoride containing salt flux increases the environmental hazard of the resulting salt cake and challenges disposal (Prillhofer, Prillhofer et al. 2009). As a result, alternative aluminum dross reprocessing methods that provide significant metal recovery without requiring fluoride containing salt fluxes would pose reduced environmental risk and have garnered industrial interest.

Despite improved metal recovery, the addition of salt fluxes containing fluoride during dross reprocessing in a rotary furnace presents environmental concerns and many researchers have explored alternative rotary furnace based dross reprocessing techniques that demonstrate significant metal recovery and do not require reactive salt fluxes (Ünlü and Drouet 2002). (Ünlü and Drouet 2002) have performed an in-depth review of several dross reprocessing techniques performed in rotary furnaces that do not require salts including the Alcan plasma torch method (Lavoie and Dubé 1991), Hydro-Quebec graphite electrode process DROSCAR (Drouet, Handfield et al. 1994), (Drouet, Meunier et al. 1995), AGA and its partners Hoogovens Aluminum and MAN GHH developed the ALUREC process which allows atmospheric control and uses oxygen as a fuel source (Gripenberg, Grab et al. 1995), (Gripenberg, Mullerthann et al. 1997), PyroGenesis' DROSRITE technique reprocesses hot dross in an argon atmosphere soon after tapping (Drouet, Leroy et al. 2000), and FOCON developed the ECOCENT process which does not use a rotary furnace and instead recovers entrapped metal by centrifuging dross immediately after it has been removed from the remelting furnace (Kos 1997), (Kos 2000). Further improvement in the metal recovery rates achieved during industrial aluminum dross reprocessing operations can be accomplished by investigating the effects of rotary furnace production parameters on the characteristics of the recovered material.

Extensive experimental research has been performed on quantifying the relationship between rotary furnace production parameters and the recovered material properties during aluminum dross reprocessing. (Tzonev and Lucheva 2007) performed an experimental study to determine the impact of several production factors including: the effect of adding refractory bodies, holding time prior to tapping, rate of argon gas consumption, temperature at tapping, and rotary furnace rotation rate on metal recovery during aluminum dross reprocessing in a rotary furnace. The aluminum dross reprocessed in this experiment was pretreated with mechanical crushing and sieving to remove fine oxide particles and reprocessed without salt flux additions (Tzonev and Lucheva 2007). Figure 9 shows the direct current electric arc rotary furnace with a 150 kg capacity used in the experiments (Tzonev and Lucheva 2007). A diagram of a rotary furnace cross section reprocessing aluminum dross in the presence of an argon atmosphere is included in Figure 10 (Tzonev and Lucheva 2007). As indicated in the diagram, higher density liquid aluminum accumulates at the rotary furnace wall and lower density materials such as aluminum oxide accumulate at the melt surface (Tzonev and Lucheva 2007). The significant oxidation potential of liquid aluminum causes the entrapped liquid metal droplets to become encapsulated in hard aluminum oxide shells (Tzonev and Lucheva 2007). The motivation for including the crushing bodies is to weaken the hard oxide shells and release the entrapped liquid metal so it can sink into the melt at the furnace wall (Tzonev and Lucheva 2007). The authors found that the furnace rotation rate has a nonlinear impact on metal recovery (Tzonev and Lucheva 2007). The nonlinear relationship results from the two competing mechanisms involved in furnace rotation during aluminum dross reprocessing; mechanical crushing of the hard oxide coatings is favored at higher speeds while metal agglomeration is favored at lower speeds (Tzonev and Lucheva 2007). The nonlinear relationship between furnace rotation speed and metal recovery can be seen by the peak in Figure 11 (Tzonev and Lucheva 2007).

The authors also found a moderate increase in aluminum metal recovery by increasing the rate of argon gas consumption, the holding time prior to tapping, temperature at tapping, and adding refractory materials to the rotary furnace to promote crushing the hard oxide shells surrounding the liquid metal droplets (Tzonev and Lucheva 2007). Although (Tzonev and Lucheva 2007) quantified many valuable relationships between metal recovery and rotary furnace production parameters and conditions, several aspects of the experiment may not be scalable to a large scale industrial operation. For example, the labor intensive pre-treating operations and the cost to maintain an argon gas atmosphere in the rotary furnace may not be economically viable. Additionally, scaling up the reprocessing operation to a 24 ton industrial furnace might lead to different metallurgical events than those seen in a 150 kg rotary furnace. Experimental studies on aluminum dross reprocessing can provide key practical insights on methods to improve metal recovery rates. However, developing computational tools that model aluminum dross processing operations are another method that can provide non-intuitive insights that are challenging to determine experimentally to improve aluminum metal recovery rates.

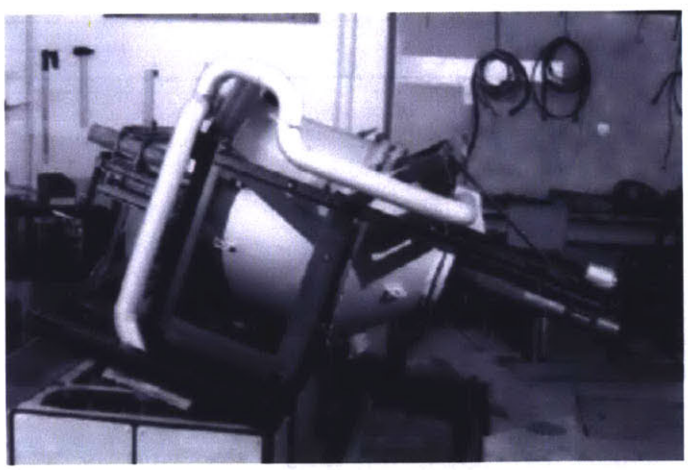

Figure 9. Photograph of the direct current electric arc rotary furnace used by (Tzonev and Lucheva 2007).

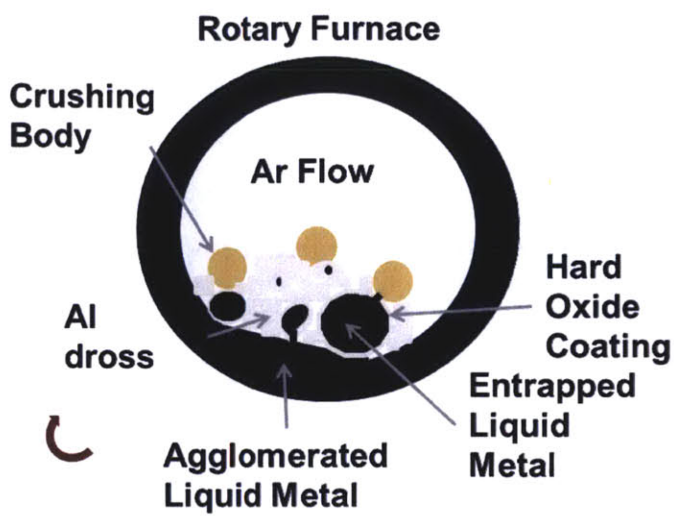

Figure 10. Diagram of a rotary furnace cross section while reprocessing aluminum dross byproduct *adapted from (Tzonev and Lucheva 2007).*

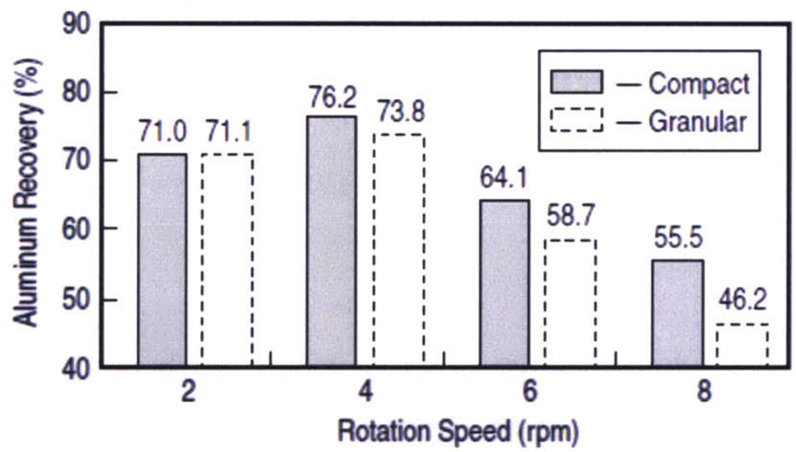

Figure 11. Aluminum recovery rate achieved at various rotary furnace rotation speeds (Tzonev and Lucheva 2007).

Research has been performed developing computational models that use secondary material characteristics and reprocessing production parameters to predict aluminum metal recovery rates. (Zhou, Yang et al. 2006) studied the complex metallurgical reactions involved in aluminum dross and scrap reprocessing in a rotary furnace by developing a computational model centered on fluid dynamics. In particular, (Zhou, Yang et al. 2006) were attempting to quantify the relationship between scrap characteristics and the thermodynamic and kinetic state of the rotary furnace. The complex thermodynamic reactions that occur at the high temperatures used in rotary furnaces for aluminum dross reprocessing, large variety of secondary material geometries, and impurity concentrations in the secondary materials challenges predictions of the thermodynamic and kinetics state of the furnace (Zhou, Yang et al. 2006). A computational tool able to quantify the relationship between secondary material characteristics and heat transfer in a rotary furnace can provide significant insight for optimizing rotary furnace parameters to maximize metal recovery, but further work is necessary because of the tremendous number of production parameters involved with reprocessing aluminum dross and post consumed scrap in a rotary furnace.

Much research has been performed studying aluminum dross generation and aluminum dross reprocessing in an attempt to produce an alternative secondary material feedstock for industrial aluminum production. The previous work explored in this section explores the effects production parameters and secondary material characteristics have on dross generation and reprocessing from experimental work in smaller controlled environments. For example, (Xiao, Reuter et al. 2005) performed melting experiments using 20-40 g scrap samples which is significantly smaller than industrial recycling operations which require using rotary furnaces with capacities on the order of 20 tons. The rotary furnace capacity used in the experiments performed by (Tzonev and Lucheva 2007) was 150 kg which is also smaller than industrial scale rotary furnaces. Larger scale dross reprocessing operations may require explicit modeling of a different set of material characteristics such as the optimal mixtures of secondary and aluminum dross materials to produce intermediate products that have the most economic value to industrial remelters as material feedstocks. A research gap persists in quantifying the operational and production factors that can limit metal recovery and recycling in a large scale industrial aluminum recycling operation.

Another industrial limitation that is not explored in the discussed experimental research is the need to operate the rotary furnace at maximum capacity to ensure energy efficiency. The effect of this constraint on material yield must be explicitly modeled to accurately optimize aluminum recycling operations. A computational model that can simulate dross reprocessing operations at a large volume scale can aide in quantifying the economic viability of using aluminum dross as a secondary material feedstock in industrial aluminum remelting operations. The metallurgical complexities associated with dross reprocessing necessitate a computational model to optimize metal recovery and calculate the optimal recycled product characteristics that are best able to be incorporated into aluminum alloy products.

2.2 Metallurgical batch planning tools

The economic and environmental implications of aluminum dross recycling can be quantified using computational tools that characterize the metallurgical and operational constraints limiting performance. Researchers have developed many computational tools to describe metallurgical batch planning for academic and industrial use, but opportunities for improvement persist. Particularly prevalent in industry are linear blending optimization models that calculate the minimum cost mix of materials to produce a finished good with an associated set of quality constraints such as compositional specifications. These blending models provide much value to industrial aluminum remelting operations but the scope of these models does not presently include the complexity associated with incorporating new and lower quality secondary materials such as aluminum dross. There is presently an industrial need for a computational tool that models the impact of flexibility and coordination in an aluminum dross reprocessing operation for a large aluminum production company.

The uncertain character of post consumed secondary materials is one of the key factors inhibiting global aluminum recycling operations despite the well-established economic and environmental benefits of recycling. As a result, many of the most recent and advanced metallurgical batch planning tools explicitly incorporate compositional uncertainty in the mathematical formulation to calculate charges that are robust to compositional uncertainty and variation in secondary materials. For example, a chance constrained aluminum recycling optimization model was developed by (Gaustad, Li et al. 2007) to explicitly incorporate the uncertain character of secondary aluminum materials into a batch planning model. The model developed by (Gaustad, Li et al. 2007) built upon the work of (Charnes and Cooper 1959) who created chance constrained optimization as a method to include probabilistic constraints into mathematical models. The uncertainty aware aluminum recycling model developed by (Gaustad, Li et al. 2007) uses stochastically dependent joint probabilistic constraints that were originally developed by (Prekopa 1972). The uncertainty aware aluminum recycling batch planning model characterizes secondary material elemental compositions according to normal distributions with associated means and variances determined empirically (Gaustad, Li et al. 2007). The uncertainty aware aluminum recycling model provides flexibility to aluminum recyclers to control the risk a calculated optimal combination of raw materials would violate the compositional specifications of the finished product (Gaustad, Li et al. 2007). This risk is quantified and referred to as the "batch error frequency" and can be altered with a user defined confidence level (Gaustad, Li et al. 2007). The "batch error frequency" is the associated probability the charge will not meet specifications after remelting and is calculated using a Monte Carlo simulation after the blending model is solved (Gaustad, Li et al. 2007). Providing remelters with the ability to decide and adjust the risk associated with the optimal combination of raw materials to produce a finished product gives remelters additional operational flexibility to manage their plants.

Incorporating explicit knowledge of thermodynamic effects that occur during aluminum remelting into metallurgical batch planning models are expected to become increasingly important to ensuring solution accuracy when aluminum dross is incorporated as a raw material feedstock in aluminum production. Thermodynamic effects have been incorporated into computational tools to describe the production of other metals including brass (Baykoc and Sakalli 2009) and steel (Wilson, Kan et al. 2001), (Rong and Lahdelma 2008). (Baykoc and Sakalli 2009) developed a mathematical model to determine the minimum cost mixture of raw materials to meet compositional specifications during brass production over an extended time period on the order of months. Material yield effects and the uncertainty characteristics of composition, cost, bounds on raw material purchasing amounts, and finished product demand were explicitly included in the brass production model formulation (Baykoc and Sakalli 2009). (Wilson, Kan et al. 2001) developed a computational tool for steel production that optimizes the characteristics of the electric arc furnace and the mixture of raw materials while considering the effects of raw material compositional uncertainty and accounting for the production of slag. An alternative optimization model formulation to incorporate compositional uncertainty in steel production was developed by (Rong and Lahdelma 2008). The authors used chance constraints linearized by fuzzy sets to incorporate steel scrap compositional uncertainty into the optimization model (Rong and Lahdelma 2008).

The authors also included the effect of thermodynamic factors on bulk material and elemental yield with deterministic coefficients (Rong and Lahdelma 2008). In a previous report on the same topic, (Rong and Lahdelma 2006) originally demonstrated that applying probabilistic compositional specification constraints to steel production creates a compromise between minimizing the cost to produce the steel alloy and the risk of violating the compositional specifications. Although the explicit incorporation of material yield effects into metallurgical computational tools with deterministic coefficients is an important contribution to promoting recycling, further production complexities resulting from material yield effects must be taken into account to accurately optimize recycling processes that involve lower quality secondary materials.

Although explicitly incorporating compositional uncertainty of the secondary materials when calculating the optimal combinations of raw materials to produce a set of products subject to compositional specifications is important to reduce the frequency of batches that do not meet specifications, in the recycling operation presented in this work, the presence of a separate aluminum recycling center mitigates the risk compositional uncertainty poses to meeting alloy product specifications. Precise compositional measurements of the recycled products are easily taken at the recycling center prior to delivery to the downstream remelting facilities because the recycled products are liquid. Although compositional uncertainty still presents an obstacle because the recycled product compositions are not precisely known prior to reprocessing, the risk of compositional uncertainty causing the finished aluminum alloy to violate compositional specifications is minimized. Unlike in the previously discussed single facility metallurgical production operations, the recycling center is presented with a challenge of establishing a long term production plan that characterizes the recycled products for an extended period on the order of six months. The long term production plan is expected to be strongly influenced by the downstream remelter production schedule. However, the downstream remelters cannot precisely determine their production schedule months in advance. Thus, by incorporating a separate aluminum recycling center, downstream remelter demand uncertainty poses a bigger risk to increasing secondary material content than compositional uncertainty. A research gap presently exists in developing strategies to mitigate performance risk resulting from inherent uncertainty and variation in downstream remelter demand in aluminum recycling.

Recycling aluminum dross and post consumed secondary materials requires the addition of a separate recycling center that was unnecessary to include in previous metallurgical batch planning tools. The incorporation of a separate recycling center to reprocess aluminum dross increases the importance of including material yield effects into the batch planning tool because the material yields of aluminum dross are significantly lower than scrap materials. The recycling center uses a separate rotary furnace with distinct capacity limits from the remelting furnaces used at the downstream facilities. The material yield of the aluminum dross and post consumed secondary materials more strongly influences the optimal combination of recycled materials to include in the furnace because the furnace must be run at maximum capacity and must maximize liquid metal delivery to the downstream remelting facilities. A research gap persists in the area of metallurgical batch planning tools because a computational tool does not yet exist that can calculate the optimal characteristics of recycled materials to produce at a separate recycling center to deliver to downstream remelting facilities based on secondary material yield effects, daily operational, and long term production constraints. In particular, the computational tool to describe the optimal recycling center production parameters must explicitly address the impact of the mismatch between the recycling center and downstream remelter furnace capacity, the uncertain long term alloy demand of the downstream remelting facilities, and the inherent variation in the daily production schedule of the downstream remelting facilities.

2.3 Pooling problems

The scope of the metallurgical batch planning tools discussed previously is limited to a single raw material mixing operation or blending step per batch of finished alloys produced. The proposed recycling operation requires two separate blending processes; the first to blend the secondary materials into recycled products and the second to blend the liquid recycled products into finished aluminum alloys. A type of optimization model called the pooling problem is commonly used to describe a two part blending process; the formulation and industrial applications of the pooling problem is explored in this section.

Blending models are commonly applied to industries besides aluminum remelting to minimize production cost subject to a set of constraints, typically including required product attributes, raw material supplies, and desired production volumes. Examples of blending models applied to other industries include: gasoline (Baker and Lasdon 1985; DeWitt, Lasdon et al. 1989; Rigby, Lasdon et al. 1995), asphalt (Martin, Lubin et al. 1985), hazardous waste (Flowers and Linderman 2003), coal production including energy and environmental constraints (Candler 1991), starch and wheat based products (Karmarkar and Rajaram 2001), and chemical fertilizers (Ashayeri, van Eijs et al. 1994), (Glen 1988). Because of the tremendous opportunities to improve profitability, there are several examples of blending models applied to petrochemical and gasoline operations. In the original publication describing the Texaco OMEGA gasoline blending model by (DeWitt, Lasdon et al. 1989) the model scope was limited to a single time interval. (DeWitt, Lasdon et al. 1989) prevented the model from depleting the highest quality materials early on in production by including upper limits on material use and modifying the objective function to reward conservative usage of the highest quality materials. The OMEGA gasoline blending model used at Texaco was expanded to include multiple blending periods to improve raw material allocation without using heuristics (Rigby, Lasdon et al. 1995). Including multiple blending periods in the model more accurately reflects the conduct of the operators in practice who tend to run a few days' worth of blend optimizations at a time (Rigby, Lasdon et al. 1995). Petrochemical processing and blending models are frequently formulated nonlinearly to capture additional operational complexity. Example sources of nonlinearities in petrochemical process models include: preserving qualities when raw materials are pooled together, nonlinear effects on qualities that occur during blending, nonlinear material yields effects, and cost (Baker and Lasdon 1985). Pooling crude oil feedstocks is an important area of applying optimization methods to petrochemical production that is similar to the proposed recycling center operation because the proposed operation involves pooling recycled materials together for reprocessing. In order to inform the development of a computational tool that can address the challenges of an intermediate secondary material reprocessing facility, existing research on pooling problems is explored.

Including a separate and additional blending step that combines raw material feedstocks prior to a final blending operation is commonly referred to as the pooling problem in optimization circles. As a result of the intermediate blending step, the pooling problem is theoretically two blending models in sequence (Amos, Rönnqvist et al. 1997). The structural difference between blending and pooling problems can be seen by comparing the schematics in Figure 12. Schematic of a standard blending problem.Figure 12 and Figure 13. Figure 13 shows the generalized pooling problem, which in addition to allowing material to flow from the pools to the finished products allows material to be transferred between pools as proposed in (Audet, Brimberg et al. 2004). Allowing material transfer between pools causes the generalized pooling problem to be more complex than the original pooling problem (Audet, Brimberg et al. 2004). The original pooling problem which does not allow material flow between pools, most similarly resembles the proposed recycling center operation because recycled products are not transferred from rotary furnaces to other rotary furnaces. Solving pooling problems can be more computationally intensive than solving blending problems because of the intermediate pooling step. For example, the presence of the pooling step causes the model to be nonlinear because of quality conservation from the raw materials to the pools (Haverly 1978). The pooling problem also tends to have more complexity than single stage blending models because more decision variables are required to formulate the model. Additional decision variables required in the pooling problem include, the combination of raw materials to include in the pools, the quality values to characterize the pools, and the relative allocation of the pools across the finished products. The complexity of the pooling problem has motivated research on model solution strategies and methods to reduce model complexity.

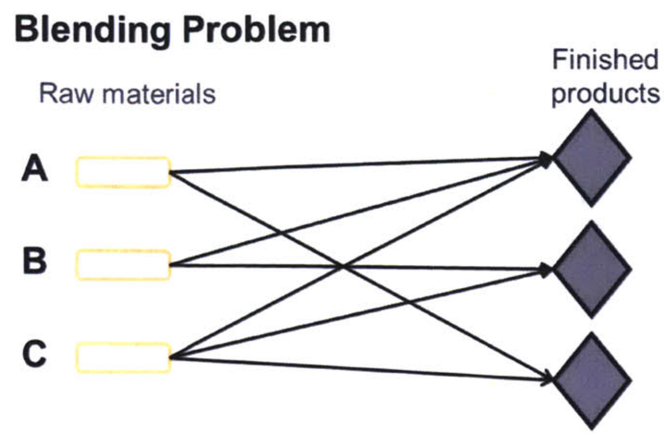

Figure 12. Schematic of a standard blending problem.

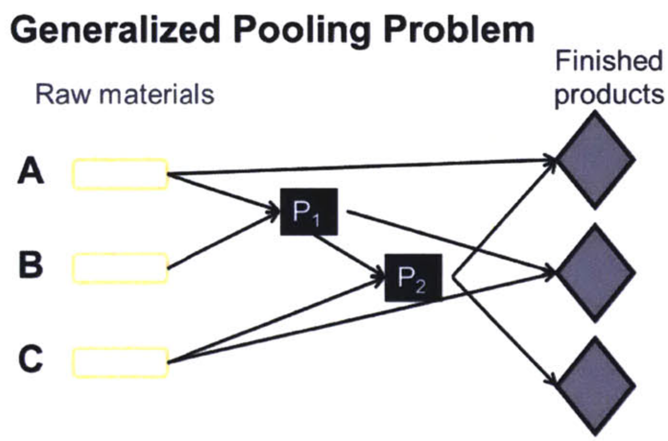

Figure 13. Schematic of the generalized pooling problem as adapted from (Audet, Brimberg et al. 2004).

(Misener and Floudas 2009) performed a comprehensive review of pooling problem applications and solution methods. Maintaining proportional pool qualities such as composition create nonlinear terms in the model (Misener and Floudas 2009). (Audet, Brimberg et al. 2004) presented three formulations of the pooling problem; in terms of the material flows, in terms of the relative material flows, and in terms of both the bulk and relative material flows. (Audet, Brimberg et al. 2004) also studied the accuracy of several computational techniques including a heuristic in solving these formulations applied to previously published problems. The pooling problem is not convex because of the nonlinear terms and therefore requires global optimization techniques to identify globally optimal solutions (Adhya, Tawarmalani et al. 1999). (Meyer and Floudas 2006) demonstrated successful application of the global optimization technique, reformulation-linearization to a mixed integer pooling problem. Understanding the importance of the pooling problem to the proposed recycling operation can be revealed by examining previous applications of the pooling problem to other industries.

(Amos, Rönnqvist et al. 1997) applied the pooling problem to optimize production parameters at the New Zealand Refining Company, a petrochemical refining company. The pooling problem can be applied to petrochemical refining because crude oils are commonly pooled together in distillation units to reduce refining costs (Amos, Rönnqvist et al. 1997). (Amos, Rönnqvist et al. 1997) formulated the pooling problem to conserve sulfur and density in the two pools corresponding to the distillation units to ensure the solution would meet final product specifications. Special consideration was required to calculate the resulting yield of the pool because material yield in petrochemical refining is a nonlinear function of temperature and depends on the origin of the crude (Amos, Rönnqvist et al. 1997). As a result of the nonlinear relationship between yield and temperature, the model must also calculate the optimal thermal schedule in the distillation unit (Amos, Rönnqvist et al. 1997). The importance of quality conservation in the petrochemical industry is very similar to aluminum recycling because of the unique elemental compositional specifications that must be satisfied for each finished alloy. One key difference between the model formulation proposed by (Amos, Rönnqvist et al. 1997) and the proposed aluminum recycling operation is the assumed deterministic demand volumes for the finished products. Previous research on stochastic pooling problems that has explored the impact of stochastic demand is of particular importance to the proposed aluminum recycling operation.

In another example of an industrial application of the pooling problem, (Li, Armagan et al. 2011) applied the pooling problem to natural gas operations and formulated the model with stochastic recourse to explicitly model uncertain parameters. The first stage decisions in the stochastic pooling model determined the design of the natural gas operation such as the number of pools to include in the system (Li, Armagan et al. 2011). The second stage decisions determined the operation variables such as the amount of gas to transport along each pipeline in the network (Li, Armagan et al. 2011). The authors also proposed an alternative decomposition method to solve the stochastic pooling model because of the significant associated computational burden (Li, Armagan et al. 2011). Two case studies were examined to evaluate the ability of the proposed decomposition technique to solve the stochastic pooling problem in comparison to the commercially available software package BARON (Li, Armagan et al. 2011). Descriptions of the case studies including the number and types of stochastic parameters, number of decision variables, and number of scenarios examined is included in Table VI below (Li, Armagan et al. 2011). The number of scenarios examined for each case is determined by the number of stochastic parameters and the number of values each parameter can have (Li, Armagan et al. 2011). The maximum number of scenarios corresponds to the case where each stochastic parameter can be realized as five distinct values (Li, Armagan et al. 2011). The authors were able to calculate a solution for the proposed case studies with each number of scenarios in a reasonable calculation period (under 800 seconds) using the proposed decomposition method (Li, Armagan et al. 2011). Applications of the pooling problem to petrochemical refining and natural gas can serve as a foundation for applying the pooling problem to an aluminum dross and post-consumed scrap recycling operation involving an intermediate reprocessing step.

Table VI. Summary of Case Studies Examined in (Li, Armagan et al. 2011).

Case study	Stochastic parameters	Number of decision variables	Number of scenarios
A	Quality of 1 source Demand of 2 products	4 sources, 1 pool, 2 products, 1 quality	1,8,27,64,125 *(1),(2),(3),(4),(5)*
B	Quality of 2 sources Demand of 2 products	15 sources, 13 pools, 3 products, 1 quality	1,16,81,256,625 *(1),(2),(3),(4),(5)*

The two stage stochastic pooling model to describe natural gas operations and the decomposition method developed by (Li, Armagan et al. 2011) is a tool to study the impact of stochastic raw material qualities and finished product demand volumes in pooling problems. However, the problem size of the proposed natural gas operations is somewhat smaller than an industrial aluminum recycling operation which may require significantly more raw material sources, pools, finished alloy products, and compositional specifications. For example, the proposed aluminum recycling operation requires 47 post-consumed scrap and aluminum dross raw materials, 10 finished aluminum alloys, and compositional specifications for seven elements. The large tonnages required in aluminum recycling operations and the perishable nature of the recycled products are expected to cause stochastic demand to have a larger influence on the recycling center performance than stochastic raw material composition. Providing five scenarios for each of the ten finished alloys as was performed for the stochastic demand parameters in the work of (Li, Armagan et al. 2011) would require a total of 9.77 x 10^6 scenarios to represent. A research gap persists in the development of an uncertainty aware optimization method that can incorporate demand uncertainty into design to improve performance in larger systems.

There presently exists a gap in pooling problem research for the application of the pooling problem to aluminum recycling. There are many unique constraints characterizing aluminum recycling operations that must be addressed. For example, the significant energy requirement to remelt aluminum and perishability of reprocessed liquid aluminum requires explicit consideration of the ability of the recycling center to deliver recycled material in the form of liquid products. Another unique constraint in the proposed aluminum recycling operation is the degree of independence between the recycling center and the downstream remelting facilities' management. The downstream remelting facilities have unique production constraints that offer minimal flexibility to adjust production to facilitate the operations of the recycling center. A research gap exists in this space of quantifying the performance limitations resulting from the independent operations. Another unique constraint in a two stage aluminum recycling operation is the inability of the recycling center to produce the exact volume of liquid recycled product required by the downstream remelting facilities due to energy efficiency concerns. The requirement that the rotary furnace must be run at maximum capacity introduces integer variables into the daily operational level pooling model because charge runs are only defined for whole number values. Satisfying quality constraints is more complex in aluminum recycling than in previous applications of the pooling problem because more qualities must be satisfied. As a result, the calculated pool qualities are expected to more significantly influence and limit performance in aluminum recycling than in previous applications of the pooling problem to other industries. This research seeks to contribute knowledge to pooling problems by applying the pooling problem to long term aluminum recycling production and daily operational production.

2.4 Gap- Value of coordination in a multi-step aluminum recycling operation

There is presently a research gap for the development of computational tools that can support production planning decisions for aluminum dross and post-consumed secondary material recycling. The compositional characteristics and low material yield characterizing aluminum dross motivate the development of computational tools which can calculate the optimal characteristics of recycled products from a complex set of raw material feedstocks. The development of computational tools to describe aluminum dross and post-consumed secondary material recycling allow economic feasibility analyses that can model the production of recycled products from the large tonnages of recycled materials required for reprocessing. A metallurgical batch planning tool does not presently exist for aluminum dross and scrap recycling operation that involves a separate recycling center that must reprocess material to be incorporated into external remelting plants. The need to reprocess the secondary materials in a separate facility generates a material flow structure similar to the field of optimization problems called pooling problems. Pooling problems have been successfully applied in the petrochemical and natural gas industries, but have not yet been studied for a metallurgical operation.

The unique constraints in aluminum recycling introduce the need for several important analyses regarding a two-step blending operation that have not yet been explored. In the case of the proposed two step aluminum recycling operation, it is possible to vary the degree of coordination between the recycling center and the downstream remelting facilities by reducing the number of recycled products produced at the recycling center. Quantifying the value of reducing the degree of coordination between the recycling center and the downstream remelting facilities requires simulating the recycling center operation on a daily time scale. There presently exists a research gap for an analysis quantifying the benefits of reducing the degree of coordination between the processes in the two step aluminum recycling operation. Another opportunity to contribute new research is quantifying the optimal amount of recycling center production parameters calculated using the long term model to enforce during daily operations at the recycling center. From a practical perspective, reducing the number of recycling center production parameters to enforce by daily operators at the recycling center is desirable because this reduces the logistical complexity for the operators. However, it is anticipated that recycled material management can be improved by enforcing recycling center parameters calculated using the long term production model. It is hypothesized that an optimal daily operational plan exists because of the performance tradeoff between enforcing long term parameters and providing flexibility to the recycling center. Quantifying the value of coordination and flexibility in a two stage aluminum recycling operation should provide insights to other industrial applications involving perishable intermediate products.

Chapter 3. Mathematical methods used to model the proposed recycling operation

Quantifying the value of coordinating the operations of the recycling center with the downstream remelters and the value of recycling center flexibility requires the development of a methodology that describes the recycling center operations 1) in terms of long term production and 2) in terms of daily production constraints. Figure 14 maps the analyses that are performed in this work to assess the recycling center design with the optimal level of coordination and flexibility. There are three proposed levels of coordination for the recycling center production, a high coordination case, a middle coordination case, and a low coordination case. The specific recycled product parameters corresponding to these coordination cases are calculated using the long term production model. A dynamic simulation using historical production data is used to calculate the performance of four daily operational optimization model formulations of varying levels of flexibility. The objective of the analyses is to determine the optimal level of coordination and flexibility for the recycling center production design by calculating the maximum amount of liquid recycled product incorporated into downstream production, the weight of cast sow, and the deviation from the recycled product consumption calculating with the long term production model. The methodology required to model the production cases outlined in Figure 14 are described in this chapter.

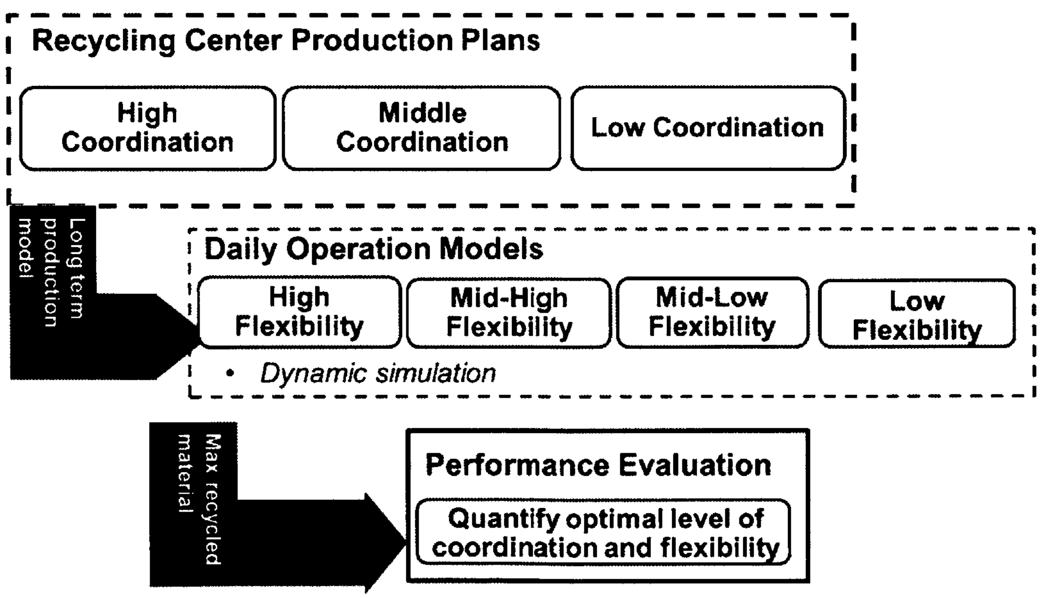

Figure 14. Schematic detailing the analyses progression and the relationship between the long term production and daily operational model formulations.

This thesis describes several computational tools and analyses to support recycling operations of aluminum dross, post-consumed scrap, and prompt scrap. The material flow of the recycling operation is mapped schematically in Figure 15. An intermediate recycling center is used to reprocess aluminum dross and post-consumed secondary materials to deliver to two aluminum remelting plants. The purpose of the intermediate reprocessing facility is to limit contamination from the compositionally uncertain aluminum dross and post-consumed secondary materials at the downstream remelters. The intermediate reprocessing facilitiy is also able to reprocess secondary materials of poorer quality than remelting furnace and achieve higher material yields. Incorporating a separate recycling facility adds operational complexity beyond conventional single stage recycling operations. Modeling the recycling operations requires formulating a model that incorporates both production stages, production at the recycling center and the downstream remelting facilities. In the first step at the recycling center, aluminum dross and post-consumed scrap are processed with rotary furnaces into low quality liquid metal recycled products. Then in the second stage at the downstream remelters, the liquid recycled products are blended with primary, alloying, and prompt scrap to satisfy the final compositional specifications of the finished aluminum alloy products. Any liquid recycled product that cannot be incorporated into downstream production must be cast as sow and sold at discounted value. The downstream remelters produce two independent sets of finished aluminum alloys with distinct compositional specifications. Because the downstream remelters have been in operation for a long period of time, the production schedule has been optimized to meet plant specific operational constraints and the plant managers have less flexibility to modify the production schedule to better fit the needs of the proposed recycling center. The objective of this section is to describe the underlying methods and techniques of a series of computational tools that model recycling operations at different time scales and different levels of operational detail.

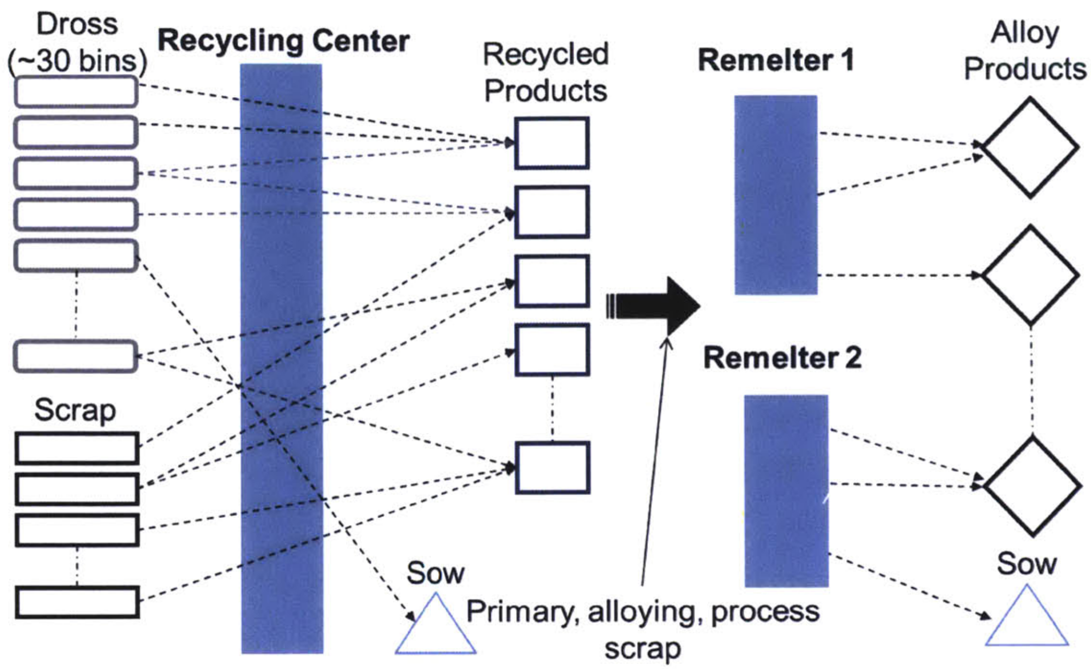

Figure 15. Material flow from aluminum dross and post-consumed scrap raw materials to final alloy products.

3.1 Two stage recycling process

One of the key distinctions of the proposed recycling operation from traditional recycling operations is the production of liquid recycled products from highly compositionally uncertain aluminum dross and post-consumed secondary materials in a separate facility. Due to compositional uncertainty and a large non-metallic content, aluminum dross materials require reprocessing operations prior to inclusion in a remelting furnace unlike conventional prompt scrap recycling. Additionally, the large aluminum dross volumes required for a recycling operation necessitates a second facility to store the large volumes of material. Concerns with the aluminum dross reacting with water and the release of hazardous gases, necessitates indoor storage. The rotary furnaces used to reprocess aluminum dross must be filled to capacity to maximize energy efficiency of the dross reprocessing operation. After reprocessing, the resulting liquid metallic aluminum will be sent to the downstream remelting facilities, these liquid metal shipments are referred to as recycled products. The requirement to incorporate the recycled products as liquid is expected to introduce operational difficulties because of associated scheduling challenges.

One of the goals of this thesis is to quantify the coordination challenges of delivering the reprocessed aluminum dross and post-consumed scrap as liquid. Delivering the recycled product as liquid improves overall energy efficiency of the production process because of the significant energy that would be required for the downstream facility to remelt the recycled products if they had been cast as sows by the recycling center. However, delivering cast or solid metallic aluminum would provide significant advantages to the recycling center because it would provide more flexibility in its scheduling and operations. Delivering liquid recycled products requires the recycling center to coordinate its production with the downstream facilities because of the energy expense to heat and the quality degradation of the recycled products over time. In the case of liquid recycled product delivery, it is essential for the recycling center to produce only recycled products that can be used that day and preferably immediately. Delivering recycled products in the form of sows would allow the recycling center to operate with more flexibility and focus on its specific constraints such as, raw material supplies and constant production volumes since the quality of the cast recycled products is time independent. Two sets of models are presented to study the recycling center operation at different time scales: models that describe longer term production and models that describe daily operations of the recycling center at varying levels of production flexibility. Pooling optimization models with and without recourse are presented to study production over a six month time horizon with explicit incorporation of demand variation. Four daily optimization model formulations with varying degrees of fixed inputs from the longer term models describe the production at the recycling center in response to day to day downstream remelter production variation.

3.2 Performance metrics

The dual environmental and economic advantages of aluminum recycling lead to two performance metrics to evaluate the recycling center recycled material utilization and cost. The general tendency is for the performance metrics to be complementary; increasing recycled material utilization translates to decreasing raw material cost. One challenge in formulating the objective function is accounting for energy costs at the recycling center. For example, incorporating energy costs into the objective function is challenging because heating the reprocessed liquid recycled products is expensive for the recycling center but saves money and time for the downstream remelting facilities. Another challenge results from the lack of established prices because the aluminum dross market is presently poorly defined. To simplify cost discrepancies, the objective functions for the optimization model formulations included below maximize aluminum dross and post-consumed secondary material utilization and penalizing additions of more expensive primary and alloying materials in proportion to their prices. It is necessary to penalize primary and alloying additions to incorporate the relative prices since alloying additions tend to be more expensive than primary material.

3.2.1 Key recycling center process parameters

The incorporation of a recycling center to reprocess aluminum dross and post-consumed secondary materials introduces several new process parameters in addition to the process parameters in existing aluminum recycling computational models. Figure 16 maps the relationship between the computational tools and the relevant parameters and variables to the recycling center. The key performance metrics used to evaluate a recycling center production design are, recycled material content, production cost, and liquid metal delivery. The production of recycled products introduces new decision variables that must be calculated using the long term production model. In addition to calculating the optimal combinations of raw materials, the model must also calculate the optimal recycled product characteristics including recycled product volumes, recycled product specifications, and the allocation of recycled materials across the recycled products. Material yield after reprocessing must be explicitly considered because of the significant oxide content in the aluminum dross. Optimization model formulation can be assisted by using existing optimization models for operations in other industries that are similar to the proposed aluminum recycling center. In order to evaluate the performance of the recycling center under varying conditions including downstream production uncertainty, downstream production variation, and level of coordination between the recycling center and downstream remelting facilities a simulation tool is developed.

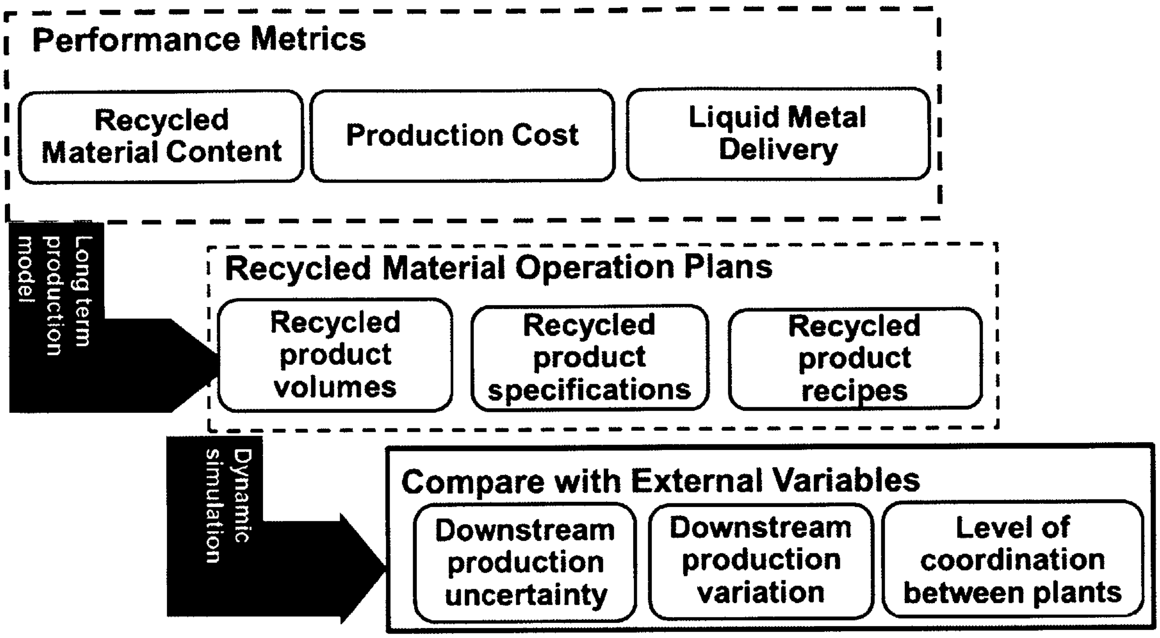

Figure 16. Key performance metrics, decision variables describing recycling center production, and external factors expected to influence recycling center performance.

3.3 Longer term models

3.3.1 Deterministic formulation

Building upon previous work on pooling problems informs the formulation of an aluminum recycling optimization model that incorporates an intermediary recycling center that can deliver liquid recycled products to downstream remelting facilities. Pooling problems are conventionally formulated to allow perfect coordination between intermediate storage facilities such as the recycling center and final blending plants. Although for the reasons explained earlier, perfect coordination is a substantial assumption for aluminum recycling applications, we can represent long term production with the pooling problem to provide a reasonable estimate for the magnitudes of the material flows. Table VII lists the recycling center and downstream remelting facilities production parameters, decision variables, and constants included in the long term production model. The proposed model follows the 'P'-formulation originally developed by (Haverly 1978) and reviewed by (Misener and Floudas 2009) and incorporates the effects of material yield.

Table VII. Decision Variable and Parameter Definitions for the Nonlinear Aluminum Remelting and Dross Reprocessing Pooling Problem Formulation.

Indices	$i \in \{1,2,...,I\}$	Dross and post-consumed scrap materials at recycling center
	$h \in \{1,2,...,H\}$	Prompt scrap, primary, and alloying materials
	$l \in \{1,2,...,L\}$	Recycled products
	$j \in \{1,2,...J\}$	Finished alloys at the downstream remelters
	$k \in \{1,2,...,K\}$	Elements
Variables	$x_{i,l}$	Weight of dross and scrap material i in recycled product l
	$y_{l,j}$	Weight of recycled product l in finished alloy j
	$z_{h,j}$	Weight of prompt scrap, primary, and alloying material h in finished alloy j
	$r_{l,j}$	Relative amount of recycled product in finished alloy
	$E_{l,k}$	Total weight of element in k recycled product l
Parameters	p_h	Penalty weighted in proportion to the relative costs of prompt scrap, primary, and alloying material h
	A_i^U	Availability of dross and post-consumed scrap material i
	A_h^U	Availability bounds of prompt scrap, primary, and alloying materials h
	S_l	Capacity of recycled product l
	D_j	Demand for finished alloy j
	$\varepsilon_{i,k}$	Weight fraction of element k in dross and post-consumed scrap material i
	$\varepsilon_{h,k}$	Weight fraction of element k in prompt scrap, primary, and alloying material h
	$E_{j,k}^L - E_{j,k}^U$	Upper and lower limits of weight of element k in finished alloy j
	Y_i	Material yield for dross and post-consumed scrap material i
	X_h	Material yield for prompt scrap, primary, and alloying materials h
	Z_k	Compositional yield for element k

The objective function is Eq. 2 and maximizes aluminum dross and post-consumed secondary material incorporation in downstream production and penalizes the use of primary and alloying materials. Eq. 3 constrains aluminum dross and post-consumed secondary material use at the recycling center to be within availability limits.

Eq. 4 constrains prompt, primary, and alloying material used in downstream production to be within the material availability limits. Eq. 5 prevents the recycling product volumes from exceeding production capacity. Eq. 6 ensures that the amount of recycled product used in the final alloys does not exceed the amount produced from aluminum dross and post-consumed scrap materials. Eq. 7 forces the relative consumption of each recycled product in the finished alloys to sum to one. Eq. 8 ensures that the weight of the finished alloy products satisfies the demand requirement. The conservation of elemental material entering the recycled products from the aluminum dross and post-consumed secondary materials is ensured by Eq. 9. Eq. 10 ensures the blends of recycled products, prompt scrap, primary, and alloying materials meet the compositional targets of the finished products. Finally, Eqs. 11-13 bound the decision variables to be positive.

Objective Function

$$\max \sum_i \sum_l x_{i,l} - \sum_h \sum_j p_h z_{h,j} \qquad \textbf{Equation 2}$$

Constraints

$$\sum_l x_{i,l} \le A_i^U \quad \forall i \qquad \textbf{Equation 3}$$

$$\sum_j z_{h,j} \le A_h^U \quad \forall h \qquad \textbf{Equation 4}$$

$$\sum_i x_{i,l} \le S_l \quad \forall l \qquad \textbf{Equation 5}$$

$$\sum_i Y_i x_{i,l} - \sum_j y_{l,j} = 0 \quad \forall l \qquad \textbf{Equation 6}$$

$$\sum_j r_{l,j} = 1 \quad \forall l \qquad \textbf{Equation 7}$$

$$\sum_l \sum_i x_{i,l} Y_i r_{l,j} + \sum_h X_h z_{h,j} \ge D_j \quad \forall j \qquad \textbf{Equation 8}$$

$$\sum_i x_{i,l} \varepsilon_{i,k} = E_{l,k} \quad \forall l,k \qquad \textbf{Equation 9}$$

$$E^{L}_{j,k} \leq \sum_{l} E_{l,k} r_{l,j} + \sum_{h} Z_{k} \varepsilon_{i,k} z_{h,j} \leq E^{U}_{j,k} \quad \forall j,k$$ **Equation 10**

$$0 \leq x_{i,l} \quad \forall i,l$$ **Equation 11**

$$0 \leq y_{lj} \quad \forall l,j$$ **Equation 12**

$$0 \leq z_{h,j} \quad \forall h,j$$ **Equation 13**

The deterministic long term recycling center production model formulation is nonlinear as a result of the compositional constraints Eqs. 9-10. The nonlinearity of the pooling problem resulting from quality balance constraints was originally demonstrated by (Haverly 1978). A simplified recycling operation is included in Figure 17 that is used to demonstrate the nonlinearity arises from conserving the alloying elemental weight throughout the operation. One significant simplification performed in this example is removing the primary, alloying, and process scrap materials from the system. This example was adapted from the example in (Amos, Rönnqvist et al. 1997) modeling sulfur concentration throughout the petroleum refining operation and applied to a simplified case of the long term production model presented above.

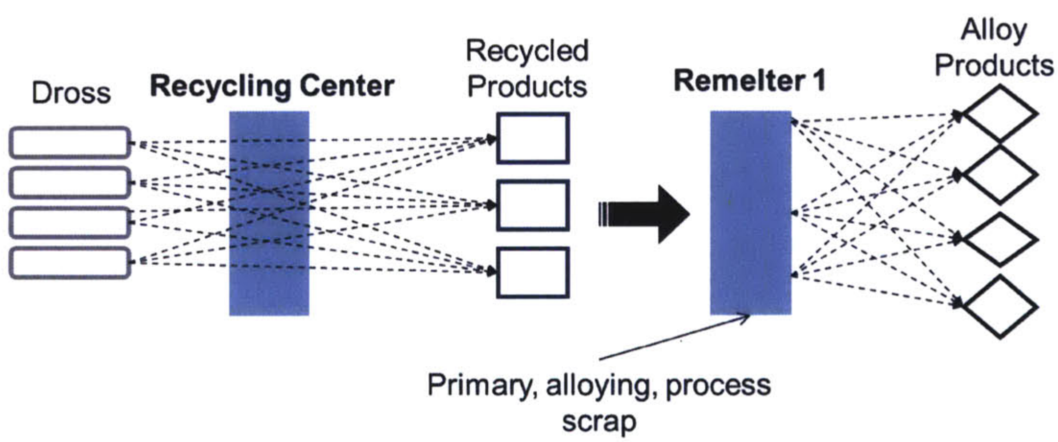

Figure 17. Schematic of a simplified recycling operation to demonstrate an example of nonlinear quality relationships.

For the purpose of simplifying the subsequent mathematical relationship, define the following variable to represent the recycled product composition.

Variables	$e_{l,k}$	Weight fraction of element k in recycled product l

Material flow through the system must be conserved, so the yielded weight of dross materials incorporated into the recycled products must equal the weight of the recycled products incorporated into the finished alloys as formulated in Eq. 14. The silicon composition or element one in recycled product one is determined by the weight of silicon in the dross materials used and the total weight of recycled product one calculated for production. This relationship can be expressed in terms of the weights of recycled products into finished alloys using the material flow conservation equation as included in Eq. 15 below. Analogous relationships for the silicon composition in recycled products two and three are included in Eqs. 16 and 17 respectively. The product of the silicon compositions in the recycled products and the weight of recycled product incorporated into each finished alloy determines the weight of silicon in the finished product as included in Eq. 18 below. Additional nonlinear relationships for the remaining six alloying element compositions in finished alloy one as well as seven nonlinear relationships for the elemental compositions in each of the nine remaining finished alloys.

$$Y_1x_{1,1} + Y_2x_{2,1} + Y_3x_{3,1} + Y_4x_{4,1} = y_{1,1} + y_{1,2} + y_{1,3} + y_{1,4} \qquad \textbf{Equation 14}$$

$$e_{1,1} = \frac{\varepsilon_{1,1}x_{1,1} + \varepsilon_{2,1}x_{2,1} + \varepsilon_{3,1}x_{3,1} + \varepsilon_{4,1}x_{4,1}}{Y_1x_{1,1} + Y_2x_{2,1} + Y_3x_{3,1} + Y_4x_{4,1}} = \frac{\varepsilon_{1,1}x_{1,1} + \varepsilon_{2,1}x_{2,1} + \varepsilon_{3,1}x_{3,1} + \varepsilon_{4,1}x_{4,1}}{y_{1,1} + y_{1,2} + y_{1,3} + y_{1,4}} \qquad \textbf{Equation 15}$$

$$e_{2,1} = \frac{\varepsilon_{1,1}x_{1,2} + \varepsilon_{2,1}x_{2,2} + \varepsilon_{3,1}x_{3,2} + \varepsilon_{4,1}x_{4,2}}{y_{2,1} + y_{2,2} + y_{2,3} + y_{2,4}} \qquad \textbf{Equation 16}$$

$$e_{3,1} = \frac{\varepsilon_{1,1}x_{1,3} + \varepsilon_{2,1}x_{2,3} + \varepsilon_{3,1}x_{3,3} + \varepsilon_{4,1}x_{4,3}}{y_{3,1} + y_{3,2} + y_{3,3} + y_{3,4}} \qquad \textbf{Equation 17}$$

$$e_{1,1}y_{1,1} + e_{2,1}y_{2,1} + e_{3,1}y_{3,1} = \frac{\varepsilon_{1,1}x_{1,1} + \varepsilon_{2,1}x_{2,1} + \varepsilon_{3,1}x_{3,1} + \varepsilon_{4,1}x_{4,1}}{y_{1,1} + y_{1,2} + y_{1,3} + y_{1,4}}y_{1,1} + \frac{\varepsilon_{1,1}x_{1,2} + \varepsilon_{2,1}x_{2,2} + \varepsilon_{3,1}x_{3,2} + \varepsilon_{4,1}x_{4,2}}{y_{2,1} + y_{2,2} + y_{2,3} + y_{2,4}}y_{2,1}$$

$$+\frac{\varepsilon_{1,1}x_{1,3}+\varepsilon_{2,1}x_{2,3}+\varepsilon_{3,1}x_{3,3}+\varepsilon_{4,1}x_{4,3}}{y_{3,1}+y_{3,2}+y_{3,3}+y_{3,4}}y_{3,1}$$

Equation 18

3.3.2 Recourse Formulation

The long term production model can be used to optimize recycling center production parameters for deterministic production volumes at the downstream remelters but modifications are required to incorporate downstream production uncertainty. The optimal compositional and volume characteristics of the recycled products produced at the recycling center depend on the expected long term production volumes at the downstream remelters. Deviations from the expected volumes, especially reduced production volumes could significantly decrease the performance of the calculated recycling center production plan. A recourse pooling optimization model was formulated to explicitly incorporate downstream production uncertainty into calculations of optimal recycling center production. The recourse model is formulated to solve for the optimal amount of dross and scrap material to purchase explicitly considering downstream demand uncertainty. Table VIII provides details on the decision variables and process parameters for the recourse pooling optimization model. Explicitly incorporating production uncertainty allows the model to calculate recycled product compositional specifications and volumes that perform optimally on average rather than for specific production scenarios.

Table VIII. Decision Variable and Parameter Definitions for the Pooling Problem Formulation with Recourse.

Indices	$i\in\{1,2,...,I\}$	Dross and post-consumed scrap materials at recycling center
	$h\in\{1,2,...,H\}$	Prompt scrap, primary, and alloying materials
	$l\in\{1,2,...,L\}$	Recycled products
	$j\in\{1,2,...J\}$	Finished alloys at the downstream remelters
	$k\in\{1,2,...,K\}$	Elements
	$m\in\{1,2,...,M\}$	Downstream facility production scenarios
Variables	$x_{i,l,m}$	Weight of dross and scrap material i to recycled product l during scenario m
	$y_{l,j,m}$	Weight fraction of recycled product l in finished alloy j during scenario m
	$z_{h,j,m}$	Weight of prompt scrap, primary, and alloying material

		h in finished alloy j during scenario m
	U_i	Total weight of dross and post-consumed scrap material i purchased for production
	$R_{i,m}$	Weight of dross and post-consumed scrap material i purchased but not used in recycled products in scenario m
	$E_{l,k}$	Total weight of element k in recycled product l
	$\varepsilon_{l,k}$	Weight fraction of element k in recycled product l
Parameters	c_i	Unit cost of dross and post-consumed scrap material i
	c_h	Unit cost of prompt scrap, primary, and alloying material h
	A_i^U	Upper availability limit of dross and post-consumed scrap material i
	A_h^U	Upper availability limit of prompt scrap, primary, and alloying material h
	S_l	Capacity of recycled product l
	$D_{j,m}$	Demand for finished alloy j in scenario m
	$\varepsilon_{i,k}$	Weight fraction of element k in dross and post-consumed scrap material i
	$\varepsilon_{h,k}$	Weight fraction of element k in prompt scrap, primary, and alloying material h
	$E_{j,k,m}^L - E_{j,k,m}^U$	Upper and lower limits of composition weight of element k in finished alloy j
	Y_i	Material yield of dross and post-consumed scrap material i
	X_h	Material yield prompt scrap, primary, and alloying material h
	Z_k	Material yield of element k
	α_m	Probability of scenario m
	v_i	Value of recovered dross and post-consumed scrap material i

The proposed demand uncertainty aware pooling formulation builds upon the previous nonlinear pooling formulation and adds probabilistic production scenarios to incorporate demand uncertainty. The objective function, Eq. 19 minimizes production costs while including revenue from the recovered material value. Eq. 20 confines the total weight of aluminum dross and post-consumed scrap material purchased for production to be within the availability limits. Eq. 21 limits the prompt scrap, primary, and alloying materials used in production to be within the availability limits. Eq. 22

conserves the weight of aluminum dross and post-consumed scrap materials used to produce the recycled products into the amount of material purchased for production and calculates the weight of the residual aluminum dross and post-consumed scrap. Eq. 23 prevents the weight of each recycled product from exceeding production capacity. Eq. 24 ensures that the total fraction of recycled product used for a finished alloy in a given demand scenario cannot exceed one. Eq. 25 prevents the weight of recycled product used in the final alloys from exceeding the yielded weight of the produced recycled products. Eq. 26 ensures that the calculated production of each finished alloy in each demand scenario is satisfied. Eq. 27 conserves elemental compositional from the aluminum dross and post consumed secondary materials into the recycled products. Eq. 28 ensures that the finished alloy from the recycled products, prompt scrap, primary, and alloying materials satisfies compositional specifications. The non-negativity of the decision variables is provided by Eqs. 29-32.

Objective Function

$$\min \sum_i c_i U_i + \sum_m \sum_j \sum_h c_h \alpha_m z_{h,j,m} - \sum_m \sum_i v_i \alpha_m R_{i,m} \qquad \text{Equation 19}$$

Constraints

$$U_i \le A_i^U \quad \forall i \qquad \text{Equation 20}$$

$$\sum_j z_{h,j,m} \le A_h^U \quad \forall h,m \qquad \text{Equation 21}$$

$$\sum_l x_{i,l,m} + R_{i,m} = U_i \quad \forall m,i \qquad \text{Equation 22}$$

$$\sum_i x_{i,l,m} \le S_l \quad \forall l,m \qquad \text{Equation 23}$$

$$\sum_j y_{l,j,m} \le 1 \quad \forall l,m \qquad \text{Equation 24}$$

$$\sum_i Y_i x_{i,l,m} - \sum_j \sum_i Y_i x_{i,l,m} y_{l,j,m} = 0 \quad \forall l,m \qquad \text{Equation 25}$$

$$D_{j,m} \le \sum_l \sum_i x_{i,l,m} Y_i y_{l,j,m} + \sum_h X_h z_{h,j,m} \quad \forall j,m \qquad \text{Equation 26}$$

$$\sum_i x_{i,l,m}\varepsilon_{i,k} = E_{l,k} \quad \forall k,l,m$$ Equation 27

$$E^L_{j,k,m} \le \sum_l Z_k y_{l,j,m} E_{l,k} + \sum_h Z_k z_{h,j,m}\varepsilon_{h,k} \le E^U_{j,k,m} \quad \forall j,k,m$$ Equation 28

$$0 \le x_{i,l} \quad \forall i,l$$ Equation 29

$$0 \le y_{lj} \quad \forall l,j$$ Equation 30

$$0 \le z_{h,j} \quad \forall h,j$$ Equation 31

$$0 \le R_{i,m} \quad \forall i,m$$ Equation 32

3.4 Batch fitting analysis

Historical production data from the downstream remelters revealed that production volumes vary over time because of the dynamic nature of customer orders. Establishing a long term recycling center production plan requires knowledge of the long term trends in downstream remleter demand and production. Significant variation from expected volumes in long term downstream remelter production can render the long term recycling center production plan sub-optimal. In the effort to develop a recycling center production plan that is robust to uncertainty, the uncertainty of the downstream remelter production for each alloy group was characterized. Batch fitting was used to fit probability distributions to the production of the downstream remelters. The batch fitting analysis was performed using the Excel Add-In Crystal Ball. The batch fitting tool was used to fit probability distributions to 84 days of historical production at the second downstream remelter and 256 days of historical production at the first remelter including the number of charges of each alloy group produced on each day. Since the number of charges or the number of times a remelting or rotary furnace can be operated is limited to integer values, the daily production volumes were characterized by Poisson and Binomial distributions. The probability distribution that best characterized the production data was determined with the Chi-Square value.

3.5 Monte Carlo simulation

Monte Carlo simulations were performed to generate daily downstream remelter production scenarios. The Monte Carlo simulations generated pseudo-random numbers according to the distributions calculated with the batch-fitting analysis from the historical daily production data. In total, 54,300 daily production plans were generated for the downstream remelters. The generated daily production volumes were aggregated into six month volumes to be input into the longer term recycling production model and simulation. Generating the six month production schedule from daily production schedules is expected to preserve accuracy to the underlying trends in production variation.

3.6 Cluster analysis

K-Means clustering analysis was performed to analyze the calculated recycled product characteristics from the long term production simulation. The Excel Add-In, XLMiner was used to perform the k-Means clustering analysis. The data was normalized and 50 iterations through the data were performed for each k-Means clustering analysis. The data was normalized to allow each element in the recycled material composition to have an equal impact on the cluster assignment despite the actual differences in the relative amounts.

3.7 Simulation optimization

Simulation optimization was performed to calculate recycling center production plans with compositional specifications that account for downstream remelter production volume uncertainty. The assembly of the methods used to perform simulation optimization including the Monte Carlo simulation, long term production model, and k-means clustering analysis is included in Figure 18 below. The recycled product compositional specifications determined using k-means clustering analysis were input into the long term production model to calculate the associated recycling center production plan including the recycled product recipes, production plan, and the allocation of recycled products across downstream alloys. The simulation optimization can be performed for different compositional specifications depending on the desired percentile in the clustering results.

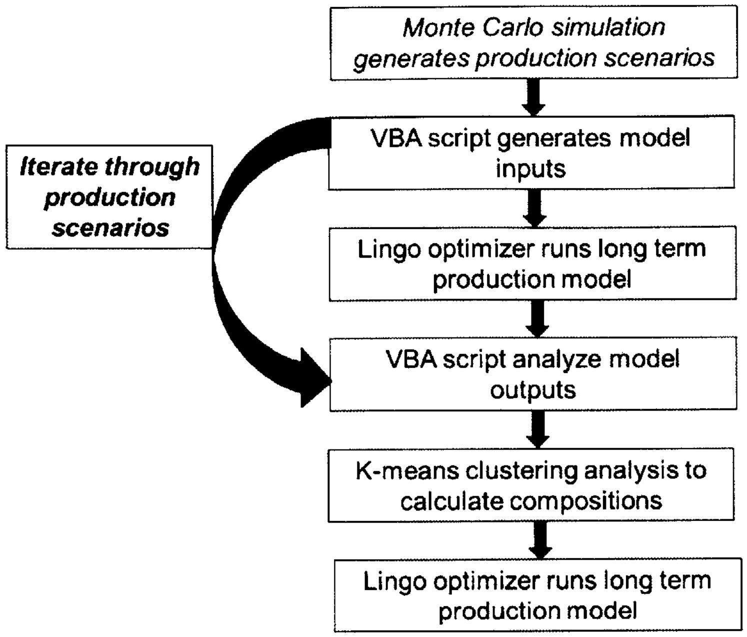

Figure 18. Schematic of the process sequence involved in the simulation optimization.

3.8 Daily scale operation models

Although the longer term production models described offer advantages, including simplified structure and easier result interpretation, these models do not include daily operational factors at the recycling center which may significantly influence performance. In particular, delivering the recycled products as liquid presents logistical challenges because of the energy cost for storage and the quality degradation of the recycled products over time. Presently, it is assumed that the recycled products can be heated for a 24 hour period without significant losses in quality, but beyond 24 hours the liquid recycled products must be cast as sows.

Another coordination challenge results from the mismatch between rotary furnace capacity at the recycling center and the recycling product volume the downstream remelters can include in a charge. Figure 19 illustrates an example of material losses that can result from the volume mismatch between the rotary furnace at the recycling center and the amount of recycled product the downstream facility is able to incorporate. This volume mismatch challenges the intuitive solution of producing one recycled product of customized volume per finished alloy. More secondary material usage may result if the recycled products can be incorporated into multiple finished alloys. However, the longer term model formulation is unable to recognize the benefits of flexible recycled product compositions. Additionally, the day to day variations in downstream remelter production can contribute coordination challenges. The recycling center must have an adaptive and flexible production plan to meet the variations in the daily production schedules of the downstream remelters. These day to day variations are not well captured in the longer term models presented above because these models do not incorporate daily production parameters. A series of optimization models are formulated to quantify the effect of physical limitations at the recycling center, such as liquid metal storage constraints, technical complications of aluminum dross reprocessing, daily production schedules, and rotary furnace size. These production factors are expected to reduce the performance of a coordinated plant from the theoretical performance calculated with the long term production model. The optimization models are used to simulate daily recycling center production based on historical downstream remelter daily production volumes.

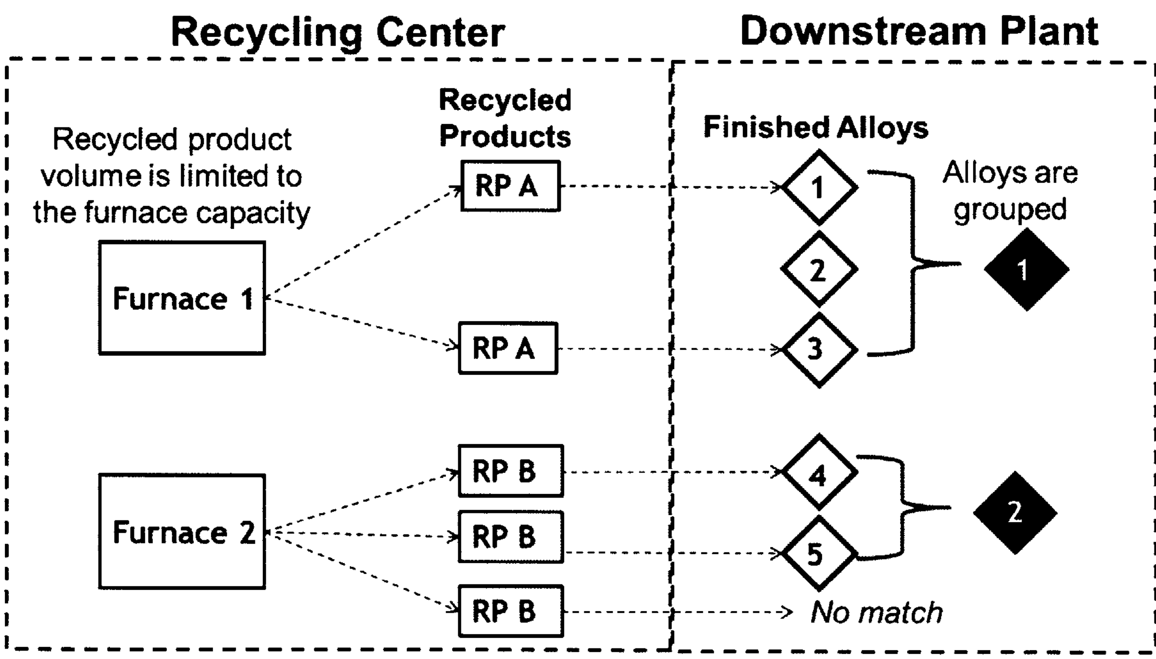

Figure 19. Diagram of the performance losses resulting from the mismatch in the furnace volume at the recycling center from the furnace volume at the downstream facility.

To inform the operation and logistics of the recycling center, it is necessary to address both longer and shorter term production factors. A series of daily optimization models describing the operations outlined in Figure 15**Error! Reference source not found.** and Figure 19 is constructed with varying degrees of information from the longer term model. The longer term model optimizes the recycling center production plan, including the volumes of each recycled product, the relative amounts of aluminum dross and post-consumed scrap materials in each recycled product, and the recycled product composition based on the aggregated downstream production schedule. Four daily models are formulated to determine the value of embedding different degrees of information about the optimal long term production calculations versus providing flexibility to recycling center to deviate from the long term production calculations. Table IX lists the parameters included in each of the daily production models. Certain combinations of parameters were not included because of dependencies between the parameters. For example, a fixed recipe requires fixed specifications because the combination of the same materials generates a fixed composition. Additionally, a fixed production plan calculated by the longer term model is based on fixed specifications of the recycled products. Fixing the optimal production plan calculated by the long term model requires the development of an algorithm because the larger long term parameters must be translated into daily parameters. The long term model calculates the optimal production without considering the recycling center furnace capacity limits or the production plan of the downstream remelters on that particular day. The optimal production plan is converted into a daily production plan according to the schematic in Figure 20.

Table IX. Parameters Included in the Four Daily Optimization Models.

	Fixed recipe with fixed production	**Fixed recipe with flexible production**	**Flexible recipe with fixed production**	**Flexible recipe with flexible production**
Flexible production plan		X		X
Flexible recipe			X	X
Flexible specification				

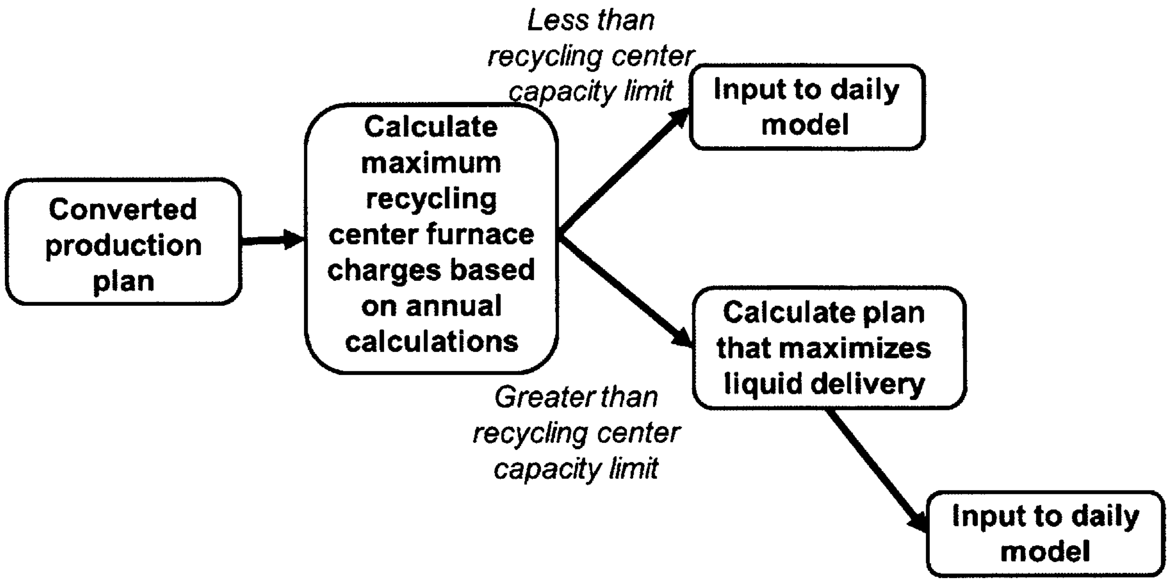

Figure 20. Diagram of the algorithm transforming the optimal longer term production plan to a daily production plan.

3.8.1 Model Assembly

Accurate quantification of the value of coordinating the operations of the recycling center and the downstream remelters requires assembling the long term and daily models to estimate production performance. Imbedding long term production information within the daily model requires inputs from the long term model. The diagrams in Figure 21, Figure 22, Figure 23, and Figure 24 show the key inputs for the four daily recycling center operation model formulations; the fixed recipe with fixed production, the fixed recipe with flexible production, the flexible recipe with fixed production, and the flexible recipe with flexible production. The key distinction between the first two model formulations and the second two model formulations is that the first two model formulations have pre-pooled recycled materials. The second two daily recycling center operational models have dynamically pooled recycled materials; the model is able to select individual recycled materials to blend to produce recycled products. Each figure includes the long term downstream facility production requirements and aluminum dross and post-consumed scrap characteristics as inputs to the long term model. The key performance metrics that are output after the model assemblies are solved are the weight of recycled material delivered as liquid and the amount cast as sows which are used to distinguish the performance of the proposed assemblies. Figure 21 shows the assembly for fixed recipe with fixed production model formulation including the use of an algorithm to convert the long term production plan to a daily production plan. Figure 21 provides the least amount of operational flexibility to the recycling center because includes the most inputs from the long term model including the recycled product volumes, recycled product recipes, recycled product compositions, and the daily production plan. Figure 22 shows the assembly of the fixed recipe with flexible production daily model formulation which provides slightly more flexibility than the fixed recipe with fixed production model formulation by using fewer inputs from the long term model. The fixed recipe with flexible production model formulation incorporates the recycled product volumes, recycled product recipes, and recycled product compositions from the longer term model. Figure 23 depicts the assembly of the flexible recipe with fixed production model formulation which includes recycled product compositions and the daily production plan calculated by the long term model. Finally, Figure 23 depicts the assembly of the flexible recipe with flexible production model formulation which incorporates only the recycled product compositions calculated from the long term model. The flexible recipe with flexible production daily model formulation provides the most flexibility to the recycling center for modifying the daily production plan to account for variations in the daily production schedules of the downstream remelters. The parameters and decision variables used in the fixed recipe optimization models are given in Table X and the parameters and decision variables used in the flexible recipe optimization models are given in Table XI. Following the tables of parameters and decision variables, the subsequent equations describe the daily operational constraints included in the daily production model formulations.

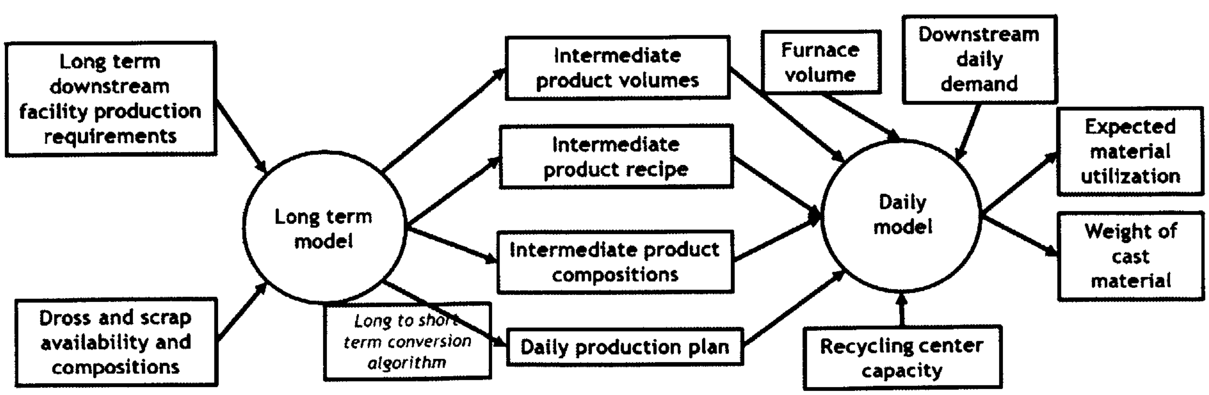

Figure 21. Assembly of the long term production model and the fixed recipe with fixed production model formulation.

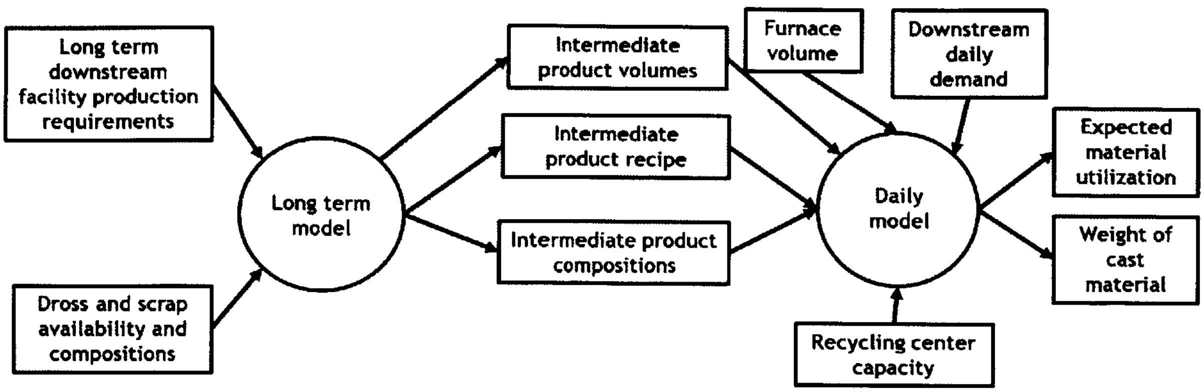

Figure 22. Assembly of the long term production model and the fixed recipe with flexible production model formulation.

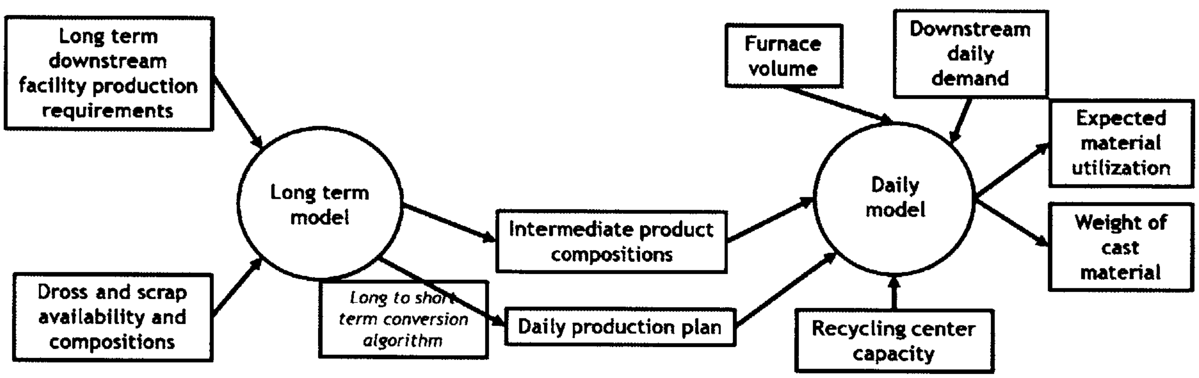

Figure 23. Assembly of long term production model and the flexible recipe with fixed production model formulation.

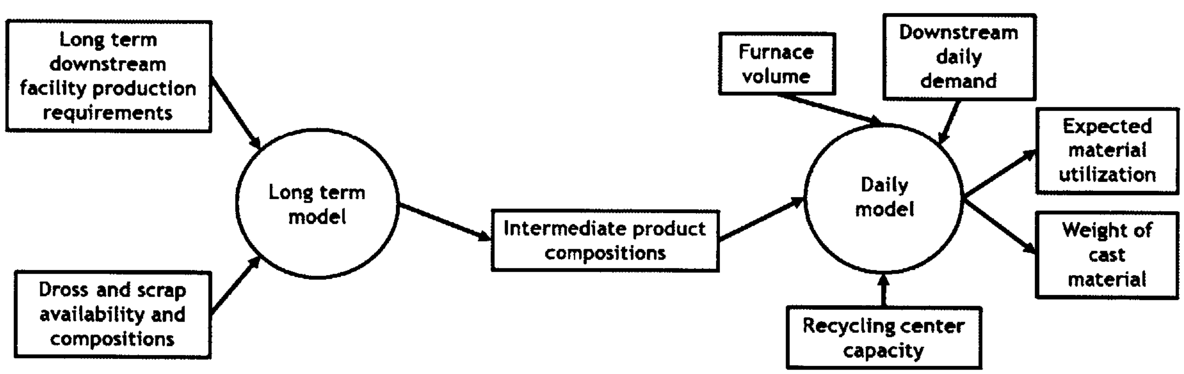

Figure 24. Assembly of long term production model and the flexible recipe with flexible production model formulation.

Table X. Decision Variable and Parameter Definitions for the Fixed Recipe Daily Operational Model Formulations.

Indices	$h \in \{1,2,...,H\}$	Prompt scrap, primary, and alloying materials
	$l \in \{1,2,...,L\}$	Recycled products
	$j \in \{1,2,...J\}$	Finished alloys at the downstream remelters
	$k \in \{1,2,...,K\}$	Elements
Variables	x_l	Integer number of furnace charges of recycled product l
	$y_{l,j}$	Weight of recycled product l used to produce finished alloy j delivered directly as liquid
	$y_{h,j}$	Weight of prompt scrap, primary, and alloying material h is used to produce finished alloy j
	z_l	Weight of recycled product l cast
Parameters	A_l	Availability limit of recycled product l
	P_h	Penalty for using prompt scrap, primary, and alloying material h
	P_l	Penalty for casting recycled product l as a sow.
	V	Volume of furnace
	Y_l	Material yield of recycled product l
	D_j	Required demand for alloy product j
	n_l	Minimum required furnace charges of recycled product l
	$\varepsilon_{l,k}$	Weight fraction of element k in recycled product l
	$\varepsilon_{h,k}$	Weight fraction of element k in clean raw material h
	$E^L_{j,k} - E^U_{j,k}$	Upper and lower limits of composition weight of element k in finished alloy j
	L	Limit on the number of total furnace charges in a day

The following mathematical framework describes the daily production model formulations with fixed recycled product recipes. The fixed recipe with fixed production model formulation incorporates a fixed production plan, recipe, and compositional specifications for the recycled products calculated from the longer term model. The fixed recipe with flexible production model formulation is a variation of the fixed recipe with fixed production model formulation and allows the optimal daily production plan to be calculated by the daily production optimization model based on the downstream remelting production of that day. The objective function, Eq. 33 maximizes the volume of liquid metal delivered to the downstream remelters, penalizes sow creation, and penalizes the use of more expensive prompt scrap, primary, and alloying elements to produce the finished alloys. Eq. 34 limits the number of rotary furnace charges performed at the recycling center to the capacity. Eq. 35 allocates the total volume of recycled products produced at the recycling center as cast sows or delivered as liquid and incorporated into final alloys produced at the downstream remelters. The optimal recycling center production plan calculated by the longer term model is enforced by Eq. 36. Removing Eq. 36 transforms the fixed recipe with fixed production model formulation to the fixed recipe with flexible production model formulation. Eq. 37 ensures that the downstream remelters meet customer demand requirements. Eq. 38 prevents the total volume ordered for production of each recycled product from exceeding the amount of available material. The composition specifications of the finished alloys are satisfied by Eq. 39. Eq. 40 requires the number of calculated rotary furnace charges at the recycling center to be an integer. Non-negativity of the decision variables are ensured by Eqs. 41-43.

Objective Function

$$\max \sum_j \sum_l y_{l,j} - \sum_l P_l z_l - \sum_j \sum_h P_h y_{h,j} \qquad \textbf{Equation 33}$$

Constraints

$$\sum_l x_l \le L \qquad \textbf{Equation 34}$$

$$x_l V Y_l - \sum_j y_{l,j} = z_l \quad \forall l \qquad \textbf{Equation 35}$$

$$x_l \ge n_l \quad \forall l \qquad \textbf{Equation 36}$$

$$\sum_l y_{l,j} + \sum_h y_{h,j} = D_j \quad \forall j \qquad \textbf{Equation 37}$$

$$x_l V \le A_l \quad \forall l \qquad \textbf{Equation 38}$$

$$E_{j,k}^L \le \sum_l y_{l,j}\varepsilon_{l,k} + \sum_h y_{h,j}\varepsilon_{h,k} \le E_{j,k}^U \quad \forall j,k \qquad \textbf{Equation 39}$$

x_l is an integer **Equation 40**

$$0 \leq x_{i,l} \quad \forall i,l$$ **Equation 41**

$$0 \leq y_{lj} \quad \forall l,j$$ **Equation 42**

$$0 \leq z_{h,j} \quad \forall h,j$$ **Equation 43**

A penalty term was incorporated into the objective function to penalize casting sows. A sensitivity analysis was performed to determine the influence of the magnitude of the penalty coefficient on the total weight of sow cast. The effect of the penalty coefficient on the liquid weight incorporated is included in **Figure 25** and the effect of the penalty coefficient on the cast weight is included in **Figure 26.** Varying the penalty coefficient for casting sows has a minimal impact on the liquid weight incorporated over the 84 day dynamic simulation for the fixed recipe model formulations. However, varying the penalty coefficient for casting sows can significantly impact the total cast weight over the 84 day dynamic simulation. To minimize sow creation, a penalty coefficient of one was selected for the daily operational optimization model formulations.

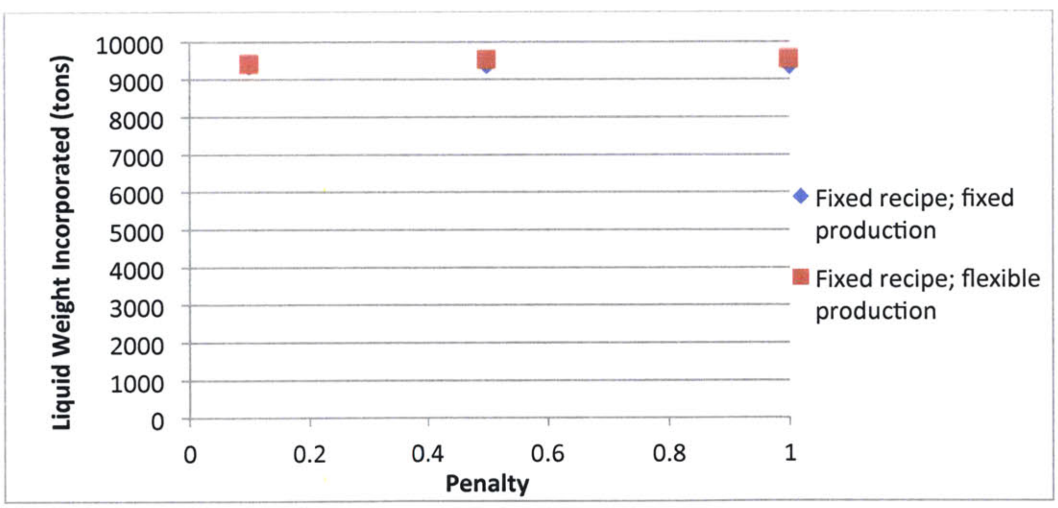

Figure 25. Liquid weight incorporated into downstream remelter production for different penalty coefficients for casting sows.

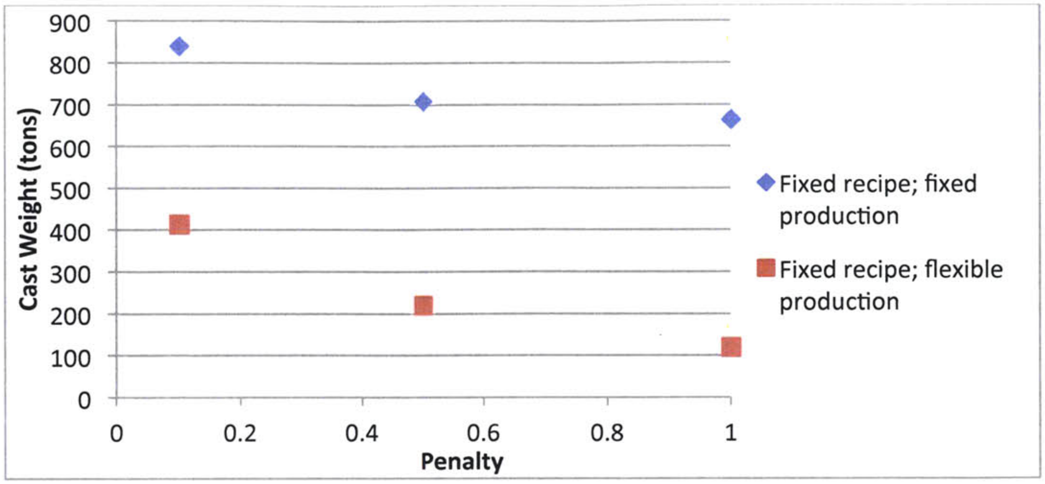

Figure 26. Cast sow weight for different penalty coefficients.

Table XI. Parameter and Decision Variable Definitions for the Flexible Recipe Daily Operational Model Formulations.

Indices	$i \in \{1,2,\ldots,I\}$	Dross and post-consumed scrap materials at the recycling center
	$h \in \{1,2,\ldots,H\}$	Prompt scrap, primary, and alloying materials
	$k \in \{1,2,\ldots,K\}$	Elements
	$l \in \{1,2,\ldots,L\}$	Recycled products
	$j \in \{1,2,\ldots J\}$	Finished alloys at the downstream remelters
Variables	x_l	Integer number of furnace charges of recycled product l
	$y_{l,j}$	Weight of recycled product l delivered directly as liquid to finished alloy j
	$y_{h,j}$	Weight of prompt scrap, primary, and alloying material h used to produce finished alloy j
	$w_{i,l}$	Weight of dross and post-consumed scrap material i used in recycled product l
	z_l	Weight of recycled product l cast
Parameters	A_i	Availability of dross and post-consumed scrap material i
	A_h	Availability of prompt scrap, primary, and alloying material h
	c_i	Unit cost of dross and post-consumed material i
	c_h	Unit cost of clean material h
	P_l	Penalty for casting recycled product l
	P_h	Penalty for using prompt scrap, primary, and alloying material h
	V	Volume of furnace

Z_k	Material yield of element k
Y_i	Yield of dross and post-consumed scrap material i
X_h	Yield of prompt scrap, primary, and alloying material h
D_j	Required demand for each finished alloy j
n_l	Minimum required furnace charges of recycled product l
q_l	Window size for recycled product l compositional specifications
$E_{l,k}$	Total weight of element in k recycled product l
$E^L_{j,k} - E^U_{j,k}$	Upper and lower limits of composition weight of element k in finished alloy j
$\varepsilon_{i,k}$	Weight fraction of element k in dross and post-consumed scrap material i
$\varepsilon_{h,k}$	Weight fraction of element k in prompt scrap, primary, and alloying material h
L	Limit on the total number of furnace charges in a day

The following mathematical formulation describes the daily production models with flexible recipes. The flexible production with fixed production incorporates the optimal production plan and recycled product specification calculated by the long term production model. The flexible production with flexible production is a more flexible variation of the flexible production with fixed production model formulation because it removes the fixed production plan and allows the model to calculate the optimal daily charge plan. As a result, the flexible production with flexible production can be considered a representation of a more flexible response to production variation at the downstream remelters. The objective function, Eq. 44 maximizes the aluminum dross and post-consumed scrap material used to produce the recycled products and penalizes casting sows and the use of more expensive prompt scrap, primary, and alloying elements. The model prevents the number of furnace charges from exceeding the daily capacity of the recycling center with Eq. 45. Eq. 46 ensures that the recycled products ordered for production are allocated as liquid shipments or cast sows. Eq. 47 relates the weight of the aluminum dross and post-consumed scrap material used to produce each recycled product with the number of charges and the furnace volume. The total weight of aluminum dross and post-consumed scrap material ordered for production is prevented from exceeding the material availability with Eq. 48. The total weight of prompt scrap, primary, and alloying elements incorporated into the finished alloys is required to be within material availability limits with Eq. 49. Eq. 50 ensures that the customer demand requirement of the downstream remelters is met. The recycled product compositional specifications calculated by the longer term model are incorporated with Eqs. 51-52 which transforms the calculated mean composition into a specification using a window factor. Eq. 53 calculates the resulting composition of the recycled products based on the calculated combination of dross and post-consumed scrap material. Eqs. 54-55 ensure the calculated production plan for the downstream remelters meet the finished alloy compositional specifications. Eq. 56 enforces the production plan for the fixed production model formulation. Eq. 56 is removed for the flexible production model formulation. Eq. 57 limits the number of charges of recycled product produced at the recycling center to integer values. Eqs. 58-60 maintain non-negativity of the decision variables

Objective Function

$$\max \sum_j \sum_l y_{l,j} - \sum_l P_l z_l - \sum_j \sum_h P_h y_{h,j} \qquad \textbf{Equation 44}$$

Constraints

$$\sum_l x_l \le L \qquad \textbf{Equation 45}$$

$$z_l + \sum_j y_{l,j} = \sum_i w_{i,l} Y_i \quad \forall l \qquad \textbf{Equation 46}$$

$$\sum_i w_{i,l} = x_l V \quad \forall l \qquad \textbf{Equation 47}$$

$$\sum_l w_{i,l} \le A_i \quad \forall i \qquad \textbf{Equation 48}$$

$$\sum_l y_{h,l} \le A_h \quad \forall h \qquad \textbf{Equation 49}$$

$$\sum_l y_{l,j} + \sum_k Z_k y_{h,j} \ge D_j \quad \forall j \qquad \textbf{Equation 50}$$

$$\sum_i w_{i,l} \varepsilon_{i,k} \le (1+q_l)\varepsilon_{l,k}\left(\sum_j y_{l,j} + z_l\right) \quad \forall l,k \qquad \textbf{Equation 51}$$

$$\sum_i w_{i,l}\varepsilon_{i,k} \ge (1-q_l)\varepsilon_{l,k}\left(\sum_j y_{l,j} + z_l\right) \quad \forall l,k$$ Equation 52

$$\sum_i w_{i,l}\varepsilon_{i,k} = \varepsilon_{l,k}\sum_i w_{i,l}Y_i \quad \forall l,k$$ Equation 53

$$\sum_l \sum_i y_{l,j}\varepsilon_{l,k}Y_k + \sum_h Y_k\varepsilon_{h,k}y_{h,j} \le E^U_{j,k} \quad \forall j,k$$ Equation 54

$$\sum_l \sum_i y_{l,j}\varepsilon_{i,k}Y_k + \sum_h Y_k\varepsilon_{h,k}y_{h,j} \ge E^L_{j,k} \quad \forall j,k$$ Equation 55

$$x_l \ge n_l \quad \forall l$$ Equation 56

x_l is an integer Equation 57

$$0 \le x_{i,l} \quad \forall i,l$$ Equation 58

$$0 \le y_{lj} \quad \forall l,j$$ Equation 59

$$0 \le z_{h,j} \quad \forall h,j$$ Equation 60

3.9 Dynamic simulation

Dynamic simulation is used to study the impact of downstream demand variation, furnace capacity mismatch, recycled material perishability, and recycled material management on the performance of the modeled production plans over an extended period of time. A schematic of the methodology describing the dynamic simulation is included in Figure 27 below. Dynamic simulation is used to solve the daily operation models sequentially eighty-four times with historical production data to model six shipment periods. The historical production data includes the total weight of each alloy group produced at the downstream remelters on each day from 1/1/2011-3/25/2011. The compositional specifications of the alloys are approximated by the specifications of the group. This approximation is an overly conservative representation of the compositional specifications of the alloys and in practice the individual alloy compositional specifications would be used. The individual alloy compositional specifications could not be used in this simulation because of insufficient available data. Optimizing the daily operation model calculates a recycling center production plan that includes the number of times to run the rotary furnace to produce each recycled product and outputs the expected weights of recycled product delivered as liquid and cast as sow. The simulation also calculates the amount of primary materials, prompt scrap, and alloy materials required for each charge over the eighty-four day period. The dynamic simulation also explicitly incorporates the stocks of the recycled materials at the recycling center. A two week equal weight shipment frequency is assumed over the six shipment simulation period. The simulation is dynamic because the daily production plan calculated for the recycling center depends on the production plan calculated for the previous day because the recycled material stocks change over time. The supplies of recycled materials are updated prior running the daily operation model to adjust the raw material availabilities in the recycling center for the subsequent day which can cause the optimal recycling center production plan to deviate from the theoretical value if infinite recycled material supplies were available. The key performance metric determining the value of the recycling center production design is determined by the total weight of liquid recycled product incorporated into the downstream remelters production during the entire dynamic simulation.

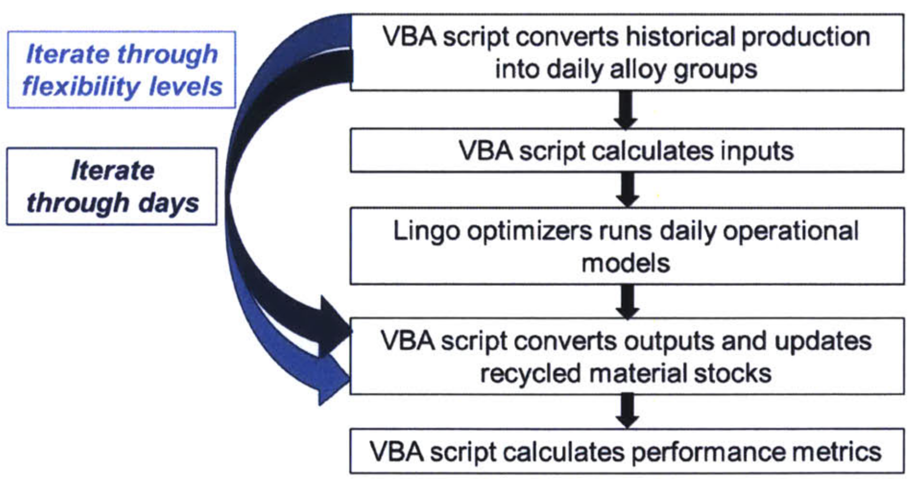

Figure 27. Schematic of the process sequence involved in the dynamic simulation.

3.10 Methodology Synthesis

The methods presented in this chapter can be applied to quantify the value of coordination and operational flexibility with the downstream aluminum remelters in recycling center production. The long term recycling center production model provides calculations that reflect upper performance limits because daily operational level constraints are not resolved by the model. Clustering analysis, Monte Carlo simulations, and the proposed simulation optimization method can be employed to inform a recycling center production plan that is more robust to the effect of long term downstream remelter production uncertainty and variation. The recycling center production plans calculated by the long term production model and the production uncertainty simulation provides inputs to the suite of daily models. The effect of coordination on the performance of the recycling center can be quantified by calculating recycling center production plans for three cases of recycled product production: two recycled products, five recycled products, and nine recycled products. Increasing the number of recycled products increases the amount of coordination between the recycling center and the downstream remelting facilities because the recycling center must more closely match the downstream production schedule to ensure the liquid metal products are able to be used by the downstream remelting facilities as liquid. Lowering the number of recycled products decreases the amount of coordination between the recycling center and the downstream remelting facilities because the recycling center can heat the liquid products for periods less than 24 hours until the downstream facilities are ready to incorporate the liquid recycled products into finished alloys. The daily model formulations provide optimized charge plans preserving varying degrees of information from the calculated recycling center production plan using the long term production model. Dynamic simulation is applied to the different recycling center production plans with historical daily production plans to compare the performance of different degrees of flexibility and coordination.

Chapter 4. Evaluating the feasibility of the aluminum recycling center with historical data

4.1 Transforming production parameters into model inputs

4.1.1 Recycling center

This research explores the implementation of a recycling center at a large aluminum producer. The aluminum dross and post-consumed scrap materials available to the recycling center are from internal sources, aluminum production plants owned by the same company but located in a different geographic region and external sources, aluminum production plants owned by a different company and located in a different geographic region. The recycling center is obligated to purchase the aluminum dross from internal sources but is not obligated to sell the reprocessed materials to the downstream remelters. Alternatively, the recycling center can reprocess and sell these materials back to the internal customer at a discount to the value of selling the reprocessed materials as liquid to the downstream remelters. The recycling center's purchasing strategy for materials from external sources is more flexible because the center can choose not to purchase poor quality and expensive materials. The portfolio of available recycled materials includes 22 aluminum dross and 15 post-consumed scrap materials. The aluminum dross and post-consumed scrap compositions and material yields incorporated into the model are empirically determined means based on prior reprocessing work. The compositions are reported after reprocessing and the material compositions at delivery to the recycling center are not included in the model formulation. Accurate material yields based on physical experience are crucial to the accuracy of the results because aluminum dross material yields are smaller than post-consumed scrap material yields ranging from 47-72% recovery compared to 98-88% recovery. The longer term production model is solved for a six month production horizon because some of the material supply limits are negotiated for six month periods. It is expected that after the expiration of six month supply contract the production manager would be able re-evaluate his/her production strategy. As a result, the aluminum dross and post-consumed scrap material availabilities are one half of the estimated annual supply.

4.1.2 Downstream remelters

The downstream remelters also have a set of production factors that must be incorporated. To ensure the final product compositional specifications are met, additional more expensive and compositionally pure materials are available at the downstream remelters that are not available at the recycling center. The adjacent electrolytic plant supplies electrolysis, liquid metal of very high purity to the downstream remelters. Primary aluminum ingot, process scrap, and alloying materials are also available to the downstream remelters that can be used to modify the compositional specifications of the alloy products to be within the compositional targets. These alloying materials are more expensive than primary materials and as a result, the potential to decrease the need to use these materials by incorporating recycled materials is a motivating factor for the recycling center. The production volume of the first downstream remelter is larger than the production volume of the second. As a result, the first downstream remelter is expected to incorporate more recycled products than the second. The first downstream remelter frequently experiences a production bottleneck due to insufficient remelting furnace capacity. Improving the overall efficiency of the first remelter is another motivating factor for the construction of the recycling center because liquid metal deliveries from the recycling center would reduce the remelting bottleneck. A greater proportion of the recycled products should be sent to the first downstream remelter than the second because of the large production volume and need for liquid metal. Comparing the compositional specifications of the entire aluminum alloy production portfolio of the downstream remelters with the high concentration of alloying elements in the recycled products led to the conclusion that the recycled products should be incorporated into a subset of the alloys. The alloys produced at the downstream remelters selected to incorporate recycled products are the 3xxx, 6xxx, and 8xxx series. The 1xxx series, colloquially referred to as primary alloys, were excluded from the analysis because of their strict compositional specifications that prohibit incorporating post-consumed secondary materials and aluminum dross. The plant has requested to exclude recycled product incorporation into these alloys to avoid producing alloys that do not meet compositional specifications.

Several simplifications were made to modify the downstream remelters production portfolio to reduce model complexity and confidentiality concerns. Approximately 54 finished alloys are produced by the first downstream remelter each year. The annual production tends to be dominated by a smaller subset; the ten most frequently produced aluminum alloys constitute 72% of the annual production. Additionally, because several of the alloys belong to the same series the compositional specifications are similar and overlapping. Combining the alloys produced at the first downstream remelter into five groups captured 88.3% of the entire production from 1/1/2011-5/31/2011 and 91.9% of the production from the alloy series able to incorporate recycled products. The minimum compositional specifications of the groups are determined by the maximum minimum specification of the alloys in the group and the maximum compositional specification of the group is determined by the minimum maximum specification of the alloys in the group. Determining the compositional specifications of the alloy groups according to this method provides the most conservative representation. In practice, the compositional specifications of the individual alloys within the groups are more relaxed or equal to the compositional specifications of the group. The total number of alloys produced at the second downstream remelter is seven, four of which are eligible to be incorporated into recycled products. Since four is a relatively small number of alloys these alloys were not grouped and their compositional specifications did not need to be adjusted.

4.2 Estimated six month material flows

The long term pooling production model can be used to provide an estimate of the six month material flows of the process and insight regarding the potential challenges of implementing the recycling center. The calculated material flows are estimates because the longer term production model does not include some of the key daily operational challenges which will be explored in future chapters. The material flows are based on historical downstream remelter production volume data.

The complexity of the proposed recycling center production design requires careful consideration of the choice of objective function. Minimizing cost is the preferred objective function in many operations and production studies but may be less valuable to this particular case. The aluminum dross market is small and immature with prices that are strongly influenced by local factors. The aluminum dross market is small because most recycled dross is generated internally and not purchased on an open market. A tolling system is another common method of dross reprocessing; the dross is sent to an external reprocessor and re-sold to the same plant for recycling. The cost of reprocessing the aluminum dross is a percentage determined by the characteristics of the metal recovery. Neither of these transactions involves a seller and a distinct buyer which would promote the effects of supply and demand to determine price. As a result of the immature dross market, the proposed recycling center developed another method to calculate costs based on the material properties and internal costs. An additional degree of complexity for obtaining objective aluminum dross prices results from purchasing the dross materials within the same company. For example, political pressure may motivate the recycling center to purchase a material that may be suboptimal for reprocessing into recycled products to sell to the downstream remelters but economically advantageous to the overall organization because recycling this material may be cheaper than treating for landfill disposal. From the perspective of the company as a whole, recycling material is economically advantageous to landfilling material because it improves overall operational efficiency by minimizing waste. However, simply maximizing the recycled content would allow the model to ignore the cost differences between the primary materials; electrolysis, ingot, and alloying elements. The objective function used to estimate the material flows is a hybrid of maximizing recycled content and minimizing costs. The optimization model maximizes the total weight of recycled material minus the total weight of the primary materials times a penalty function that is proportional to their relative costs; thereby penalizing the more expensive alloying elements over the primary aluminum in proportion to their economic burden.

The objective of this section is to estimate the material flows from the recycling center to the downstream remelters which depends on the number of recycled products. Since the number of recycled products is an input to the model, the first set of results fixes the number of recycling center products to be equal to the number of downstream product groups. The case of an equal number of recycled products to downstream product groups represents an upper estimate of recycled material consumption and is worth establishing prior to further refining the model. Setting the number of recycled products equal to the number of finished products represents the upper estimate of recycled material consumption because it assumes perfect coordination between the recycling center and the downstream remelting facilities. This case assumes that the recycling center is able to meet the entire production of the downstream remelters without consideration of shorter term production constraints.

The material flows calculated by the longer term pooling model provide a high level estimate of the viability of the proposed recycling center to deliver liquid recycled products to the downstream remelters. The calculated material flows from the longer term model for the case of an equal number of recycled products and aluminum alloys are included in Table XII. The weight of alloying material incorporated is limited by the significant cost of alloying materials. The high concentration of alloying elements in the aluminum dross and post-consumed scrap reduces the amount of alloying material that must be added to meet the compositional specifications of the finished products. All of the available process scrap is incorporated into the production plan because of the relative inexpensiveness and the closeness of the composition to the downstream production alloys specifications. The highest purity and most expensive raw material, the electrolysis metal accounts for approximately half the total weight of downstream remelters finished alloys. 79% of the total aluminum dross available was incorporated into the downstream production accounting for 21% of the total weight of the downstream remelter production. 85% of the total weight of the available post-consumed scrap material was incorporated into downstream production accounting for 16% of the total weight of the downstream remelter production. The estimated total weight of recycled materials incorporated into the downstream remelter production is 30,777 tons comprising 37% of the downstream production weight that is able to incorporate recycled materials. 30,777 tons is a significant volume of recycled material indicating that the upper estimate of recycling center performance is economically viable.

Table XII. Estimated Material Flows for the Case of 10 Recycled Products and 10 Finished Products.

Material Categories	Weight Incorporated (tons)	Relative Use in Downstream Production	Proportion of the Amount Used to the Total Available
Alloying	330	0.0	-
Process Scrap	10,000	0.12	1.0
Electrolysis	42,812	0.51	-
Ingot	0	0	-
Dross	17,615	0.21	0.79
Scrap	13,162	0.16	0.85
Total Recycled Content	30,777		

An equal number of recycled products and finished aluminum alloys represents the case of strong coordination between the operations of the recycling center and the operations of the downstream remelters. Figure 28 depicts the calculated allocation of the volume of the recycled products generated to the finished products at the downstream remelters. The model tends to customize a recycled product for each alloy product group. One exception is the use of two distinct recycled products for a single finished product group at the first downstream remelter. A second exception is the use of a single recycled product for two alloy products at the second downstream remelter. These two alloy products have very similar compositional specifications and as a result the optimizer may be able to use the same recycled product without compromising recycled material utilization. Without an incentive to create distinct recycled products for two of the alloys at the second downstream remelter and since the optimization model does not penalize the creation of additional recycled products, two recycled products were created for a single finished alloy at the first downstream remelter despite the physical equality of combining the two recycled products into one. As a result, the case of having an equal number of recycled products and alloy products is equivalent to having nine recycled products since two of the recycled products can be combined without impacting recycled material consumption.

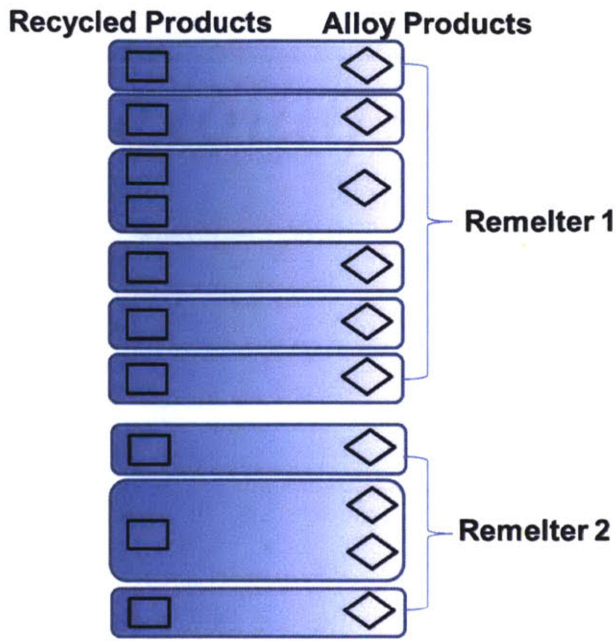

Figure 28. Schematic of the calculated material flow from the recycled products to the finished alloy products.

The overall material flow estimates can reveal the relative value of customizing recycled materials for each finished alloy group in the downstream remelter production portfolio. Table XIII lists the relative recycled product consumption and the required alloying additions in each of the product groups. Certain alloy groups, such as Group R4, Group R2, and Group C2 are able to incorporate more recycled products than the other product groups. For example, the compositional specifications of Group R4 can be met using exclusively recycled material. Table XIII further demonstrates the value of incorporating recycled material to reduce the production costs by decreasing the weight of alloying elements required to meet compositional specifications of the finished products. The downstream remelters would no longer need to purchase silicon, chromium, and zinc alloying material. However, Group C1, Group C5, Group R1, Group R2, and Group R3 have a substantial required amount of manganese that necessitates alloying material additions. Purchasing aluminum drosses or post-consumed scrap materials with a higher concentration of manganese could mitigate the cost of the additions. The required alloying additions after the incorporation of the recycling center can reveal a few of the characteristics of the aluminum dross and post-consumed scrap materials. Since additional silicon, chromium, and zinc additions are not required it can be deduced that the aluminum dross and post-consumed scrap materials at the recycling center have relatively high concentrations of these elements. Further information about the compositions of the recycled products can be inferred from Table XIV which lists the calculated optimal recycled product compositions and weights. The assertion that there is a high concentration of silicon in the aluminum dross and post-consumed scrap materials is further supported by the high silicon compositional specifications in recycled products four, six, seven, and nine. Although the manganese content in the recycled product specifications is not insignificant, it is still not sufficient to fulfill the demand from the downstream facilities.

Table XIII. The Relative Recycled Product Used and Relative Alloying Elemental Additions for the Ten Product Groups

Products	Relative Recycled Product Used	Fe -pure	Mg - pure	Si - pure	Mn - pure	Cu - pure	Cr - pure	Zn - pure
C1	0.37	39.70%	0%	0%	64.65%	0%	0%	0%
C2	0.46	0%	52.55%	0%	0%	0%	0%	0%
C3	0.25	0%	85.22%	0%	0%	0%	0%	0%
C4	0.23	0%	95.61%	0%	0%	0%	0%	0%
C5	0.32	0%	19.34%	0%	73.89%	0%	0%	0%
C6	0.25	0%	5.68%	0%	1.41%	77.14%	0%	0%
R1	0.37	21.32%	0%	0%	69.41%	3.60%	0%	0%
R2	0.86	0%	31.20%	0%	37.86%	0%	0%	0%
R3	0.18	50.65%	89.45%	0%	86.70%	0%	0%	0%
R4	1.00	0%	0%	0%	0%	0%	0%	0%

Table XIV. The Calculated Optimal Recycled Product Weight and Compositional Specifications

Recycled Product	Weight (tons)	Fe	Mg	Si	Mn	Cu	Cr	Zn
1	910	0.79%	0.05%	0.95%	0.05%	0.03%	0.03%	0.05%
2	3632	0.67%	0.06%	0.34%	0.95%	0.04%	0.03%	0.04%
3	1318	0.34%	0.38%	1.11%	0.06%	0.02%	0.02%	0.03%
4	1668	0.49%	1.54%	2.91%	0.37%	0.06%	0.00%	0.02%
5	1569	0.66%	0.1%	0.33%	0.83%	0.13%	0.03%	0.06%
6	1768	0.59%	0.18%	2.20%	0.14%	0.05%	0.10%	0.07%
7	923	0.54%	1.59%	2.39%	0.47%	0.07%	0.01%	0.02%
8	4493	0.51%	0.18%	0.47%	0.12%	0.04%	0.06%	0.06%
9	4788	0.40%	0.35%	2.42%	0.12%	0.03%	0.02%	0.04%
10	2338	0.56%	0.16%	0.34%	0.72%	0.15%	0.04%	0.08%

The silicon concentration in the aluminum dross and post-consumed scrap materials especially influences their incorporation into the downstream remelter production. Figure 29 demonstrates the trend of decreasing relative recycled material utilization as the concentration of silicon in the recycled material increases. The exception for this trend is the modest incorporation of post-consumed scrap materials S12, S5, and S10 into the downstream production despite a moderate silicon concentration. This discrepancy can be resolved by examining the iron and zinc concentration of these post-consumed scrap materials as given in Figure 30 and Figure 31. Scrap materials S12 and S10 have the second and third highest iron concentration of all the recycled materials. Scrap material S5 has the second highest concentration of zinc. The high concentration of these elements in scrap materials S12, S5, and S10 contributes to their limited incorporation into the downstream remelter production. The relationship between silicon, iron, and zinc concentration and the incorporation of the recycled material into the downstream remelter production further supports that the recycled materials have disproportionate amounts of certain elements than the compositional specifications of the finished products require. The mismatch between the recycled material compositions and the compositional requirements of the downstream remelters introduces significant complexity to the proposed recycling center operation. Such complexity motivates the use of computational tools to analyze the impact of the recycling center production design on performance.

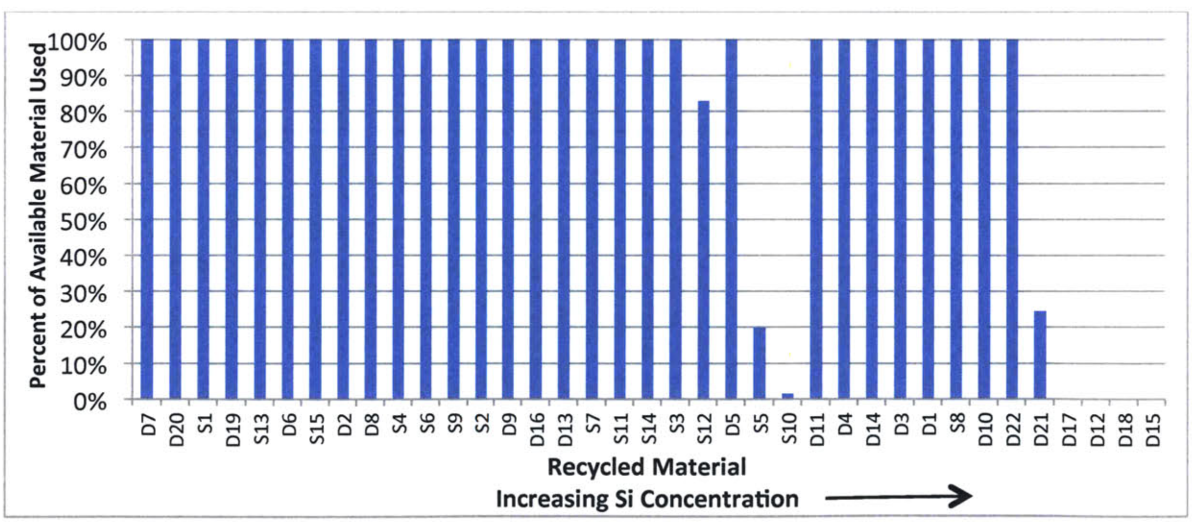

Figure 29.The rate of recycled material use with increasing silicon concentration.

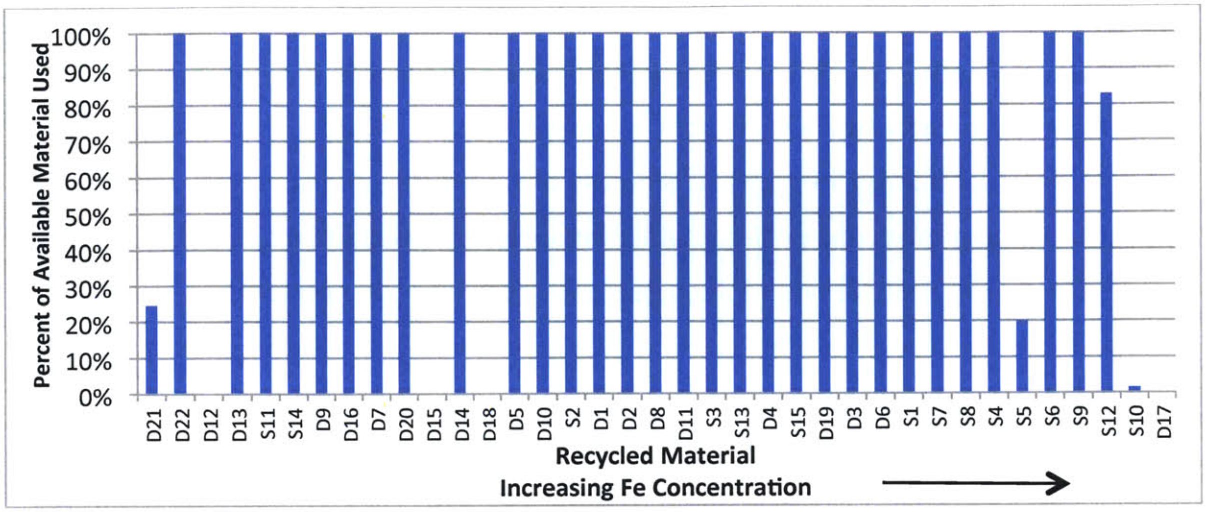

Figure 30. The rate of recycled material use with increasing iron concentration.

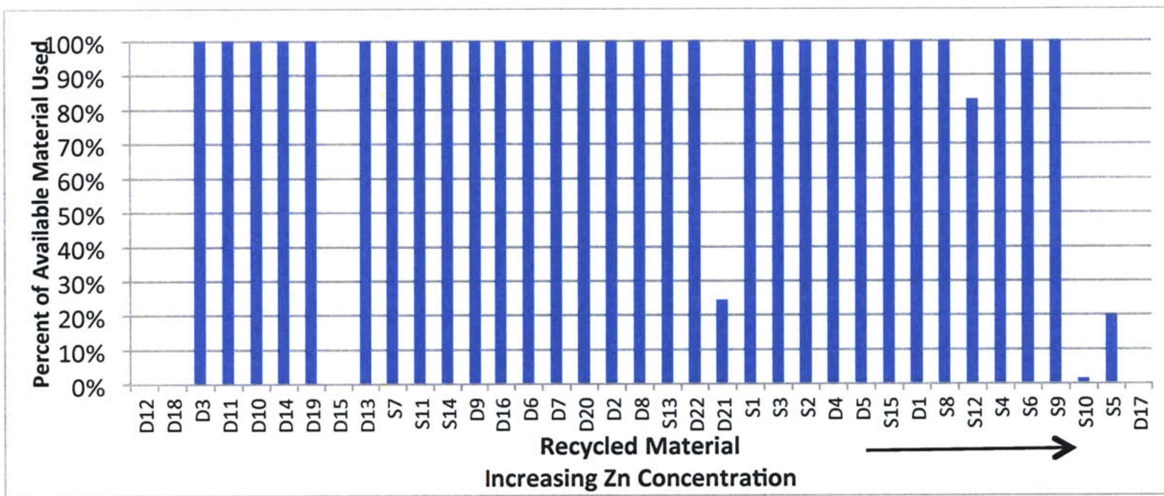

Figure 31. The rate of recycled material use with increasing zinc concentration.

The proposed recycling production plan must be evaluated in the context of production complexity to assess its operational value. Figure 32 compares the recycled material allocation across the recycled products. Using an aluminum dross or post-consumed scrap material for multiple recycled products is an example of logistical complexity because operators must access the material multiple times as the recycled products are selected for production. Operational simplicity could result if the entire volume of aluminum dross or post-consumed scrap was used for a single recycled product because the recycled materials could be consolidated by binning and mixing the aluminum dross and post-consumed scrap materials that are used for the same recycled product together. Binning aluminum dross and post-consumed scrap materials together is advantageous from a logistics perspective because it reduces the number of times a material must be accessed and reduces the storage costs. Figure 32 indicates that in the case of an equal number of recycled products as finished aluminum alloys, only thirteen of the aluminum dross and post-consumed scrap materials could be binned. Minimizing operational complexity is one of the objectives of the recycling center production design because it is advantageous for the initial implementation because operational simplicity reduces the likelihood of mistakes. Reducing the number of recycled products produced at the recycling center is expected to promote the ability to bin the aluminum dross and post-consumed scrap materials. Further operational simplicity would result from reducing the number of recycled products because it would require less compositional specifications for the operators at the recycling center to manage. The effect of reducing the number of recycled materials on the estimated recycling center performance is explored in the subsequent section.

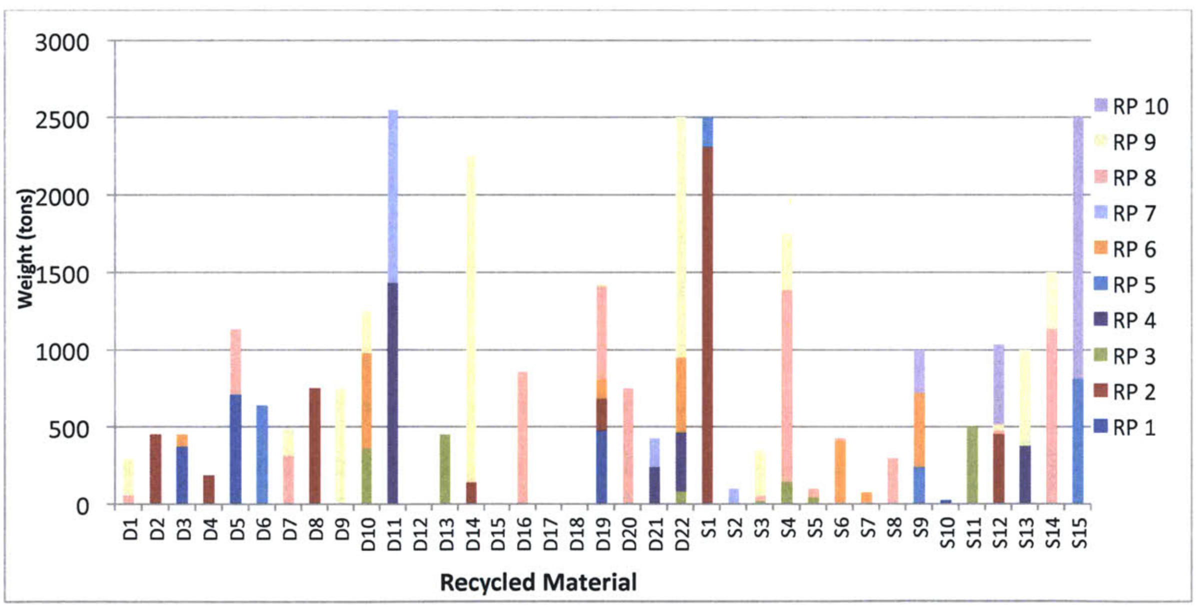

Figure 32. The recycled product allocation of each recycled material.

4.3 Implications of Recycling Center Coordination

This research attempts to determine a recycling center production design that minimizes operational complexity without significantly decreasing performance. Reducing the number of recycled products produced at the recycling center offers advantages by reducing operational complexity, including the option to bin the aluminum dross and post-consumed scrap materials, less risk for large scale deviations in downstream production volumes, and less scheduling requirements between the recycling center and the downstream remelting plants. The proposed production plan at the recycling center is calculated based on the historical mean six month production volumes of the downstream remelters. A deviation such as a significant increase in the production of one alloy from the historical mean could lead to the recycling center having allocated an insufficient volume of recycled product to meet the realized demand. In response to the variation in downstream demand, the recycling center could deliver an alternative recycled material that is sub-optimal for that particular finished alloy, resulting in lower aluminum dross and post-consumed scrap use than the estimates calculated with the long term production model. Alternatively, a recycling center production design with fewer recycled products has embedded recycled product substitutions and the effects of downstream remelting production volume deviations from the mean are expected to be less dramatic. Recycled product substitutions would also provide the recycling center with more flexibility to determine their production schedule more independently from the downstream remelter production schedule. The previously proposed recycling center production design with an equal number of recycled products and finished alloys requires the recycling center to coordinate production closely with the scheduling constraints of the downstream remelting facilities. Such an extreme degree of coordination and the furnace capacity mismatch between the recycling center and the downstream remelting plants could present challenges to the recycling center. For example, on a particular day both the downstream remelters could produce a large volume of alloys that can incorporate significant recycled material content. However, because the downstream remelters are producing the large volume of alloys in a single day, the rotary furnaces at the recycling center might have insufficient production capacity to meet downstream remelting demand for recycled products. This situation could also force the recycling center to make a sub-optimal recycled product substitution preventing the recycling center from realizing the long term production model performance estimates. One proposed strategy to minimize performance losses due to these challenges is to solve the long term production model for fewer recycled products to endogenously account for recycled product substitution opportunities.

Achieving production simplicity and relaxing scheduling requirements must be balanced with optimizing recycling center performance. The large volume of recycled material incorporated into downstream remelting production achieved by customizing the recycled products to finished alloys is expected to decrease when the number of recycled products decreases. The mechanism for the decrease in performance is the model's inability to push against as many aluminum alloy product composition specifications when the ability to customize recycled products for finished alloy products decreases. The effect of decreasing the number of recycled products on the recycling center performance is quantified by solving the long term production model for various numbers of recycled products. The total weight of recycled material as the number of recycled products varies from one to ten is shown in Figure 33 below. The material consumption does not change by decreasing the number of recycled products from ten to nine because there is close similarity between the compositional specifications of two of the alloy product groups at the second downstream remelter. As previously hypothesized, the two recycled products delivering to a single alloy in Figure 28 can be consolidated without reducing the overall recycled material use. The rate of reduction in recycled material consumption increases as the number of recycled products decreases. The percent difference between recycled material consumption for ten recycled products and five recycled products is 1.3%. Decreasing the number of recycled products to one results in 32.7% less recycled material consumption than in the ten recycled products case. A similar trend is depicted in Figure 34 showing the decrease in the required alloying weight as the number of recycled products increases. The rate of decrease is more dramatic for the weight of alloying additions than total recycled material consumption. The sensitivity of recycled material consumption and required alloying additions with the number of recycled products demonstrates that simplifying the production plan must be approached cautiously to avoid diminishing recycling center performance.

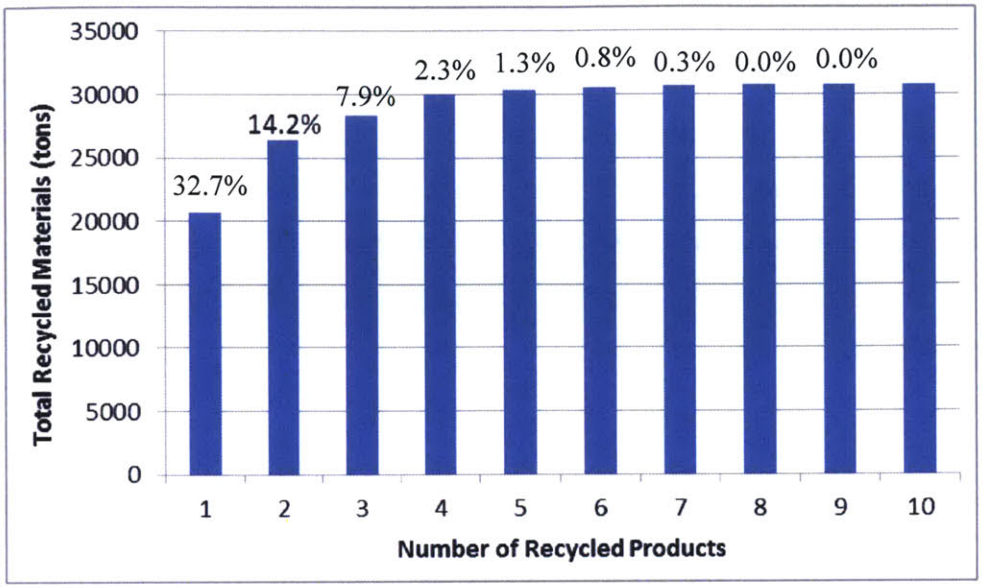

Figure 33. The total weight of aluminum dross and post-consumed scrap material incorporated for varying numbers of recycled products.

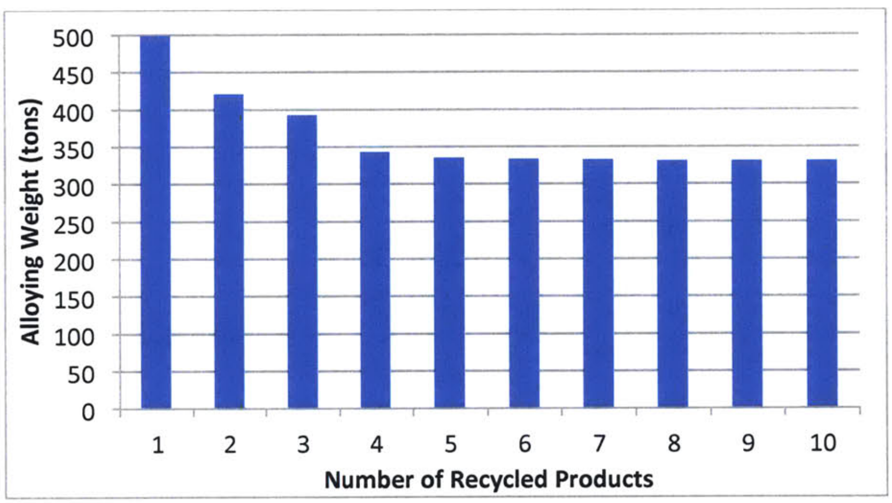

Figure 34. The total weight of alloying material added for varying numbers of recycled products.

Decreasing the number of recycled products promotes multiple finished alloy group destinations for the recycled products. Figure 35 shows a schematic representing the allocation of the five recycled products across the ten alloy products. Only a single recycled product is customized for a finished alloy in this case. The other four recycled products are distributed across multiple finished alloys. Two of the recycled products are used to produce three finished alloys, one is used to produce four finished alloys, and one is used to produce five finished alloys. Having multiple destinations for each recycled product provides more flexibility to the recycling center by reducing the required degree of coordinating recycling center production with the downstream remelter production schedule. Short term incidences of high production volumes at both remelting facilities are less likely to result in reduced recycled material consumption because a recycled product could be produced that can be used in both plants. The complexity illustrated in Figure 35 further supports the necessity for computational tools to model the recycling center production.

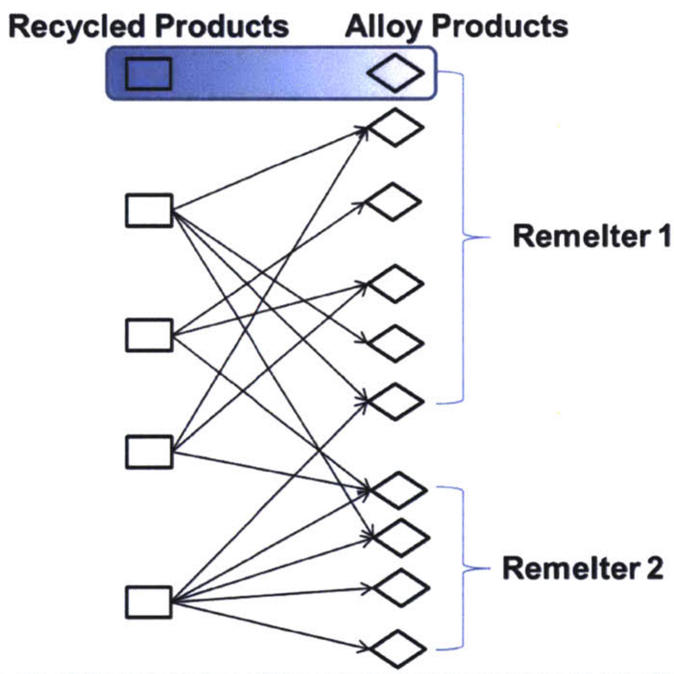

Figure 35.Schematic of the distribution of five recycled products across the ten finished alloy groups.

One disadvantage of reducing the number of recycled products is the increase in the required alloying addition weight to meet finished alloy specifications. Reducing the number of recycled products decreases the frequency of opportunities to reach the minimum product specifications using recycled materials. The opportunities to avoid having to dilute certain aluminum dross and post-consumed scrap materials are also less frequent. The calculated material flows for the five recycled products scenario are included in Table XV. The relative recycled product use and the relative alloying additions are listed in Table XVI. One difference from the previously reported recycled product consumption across the aluminum alloys is that the relative recycled product use of group R4 has decreased from 100% to 41%. This sharp decrease suggests that the composition of group R4 is significantly different from the other alloy groups and the production volume is not sufficient to warrant a customized recycled product such as the customized recycled product for group C1. The relative recycled product consumption of group C2 has decreased from 46% to 20%. The relative recycled product consumption of group C4 increased from 23% to 29%. The changes in recycled product consumption across the finished products indicate that reducing the number of recycled products tends to favor product groups with similar compositional specifications.

Table XV. Estimated Material Flows for the Case of 5 Recycled Products and 10 Finished Products.

Material Categories	Weight Incorporated (tons)	Relative Use in Downstream Production	Proportion of the Amount Used to the Total Available
Alloying	335	0.00	-
Process Scrap	10,000	0.12	1.0
Electrolysis	43,182	0.51	-
Ingot	0	0	-
Dross	17,638	0.21	0.79
Scrap	12,750	0.15	0.82
Total Recycled Content	30,387		

Table XVI. Relative Recycled Product Used for Each Product Grouping and Relative Alloying Additions for the Five Recycled Products Case

Products	Relative Recycled Product Used	Fe -pure	Mg - pure	Si - pure	Mn - pure	Cu - pure	Cr - pure	Zn - pure
Group C1	0.41	33.16%	0.00%	0.00%	63.53%	0.00%	0.00%	0.00%
Group C2	0.20	0.00%	91.42%	0.00%	0.00%	0.00%	0.00%	0.00%
Group C3	0.26	0.00%	79.61%	0.00%	0.00%	0.00%	0.00%	0.00%
Group C4	0.29	0.00%	87.50%	0.00%	0.00%	0.00%	0.00%	0.00%
Group C5	0.29	0.00%	28.01%	0.00%	72.44%	0.00%	0.00%	0.00%
Group C6	0.25	0.00%	33.88%	0.00%	0.00%	71.72%	0.00%	0.00%
Group R1	0.34	28.71%	0.00%	0.00%	74.75%	0.00%	0.00%	0.00%
Group R2	0.79	0.00%	41.95%	0.00%	42.94%	0.00%	0.00%	0.00%
Group R3	0.18	49.09%	91.75%	0.00%	86.82%	0.00%	0.00%	0.00%
Group R4	0.41	56.97%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Reducing the number of recycled products causes the calculated optimal compositions of the recycled products to change. The optimal recycled product specifications for the five recycled products case are listed in Table XVII below. The maximum silicon specification has increased from 2.91% to 3.17%. The maximum manganese specification has decreased from 0.95% to 0.89%. The compositional specifications have a tendency to concentrate certain elements into single recycled products. For example, recycled product one has the highest concentration of magnesium and silicon. Another example is recycled product three which has the highest concentration of iron and manganese.

Table XVII. Calculated Recycled Product Specifications for the Five Recycled Products Case

Recycled Product	Weight (tons)	Fe	Mg	Si	Mn	Cu	Cr	Zn
1	2263.0	0.52%	1.51%	3.17%	0.42%	0.06%	0.01%	0.02%
2	11276.5	0.44%	0.33%	1.42%	0.11%	0.03%	0.04%	0.05%
3	4028.0	0.70%	0.05%	0.31%	0.89%	0.03%	0.03%	0.04%
4	1583.5	0.58%	0.10%	2.36%	0.11%	0.05%	0.05%	0.06%
5	3880.3	0.61%	0.14%	0.35%	0.73%	0.14%	0.04%	0.08%

Previously it was asserted that reducing the number of recycled products may reduce the operational complexity of the recycling center by providing opportunities to bin the aluminum dross and post-consumed scrap materials together. Figure 36 shows allocation of the aluminum dross and post-consumed scrap materials across the five recycled products. Many of the aluminum dross and post-consumed scrap materials are used for a single recycled product which allows them to mixed and binned without affecting recycled material incorporation into downstream production. Twenty-three of the aluminum dross and post-consumed scrap materials are used for a single recycled product which is nearly double the thirteen single destination recycled materials in the ten recycled product case. Thirty-two of the total thirty seven available aluminum dross and post-consumed scrap materials were incorporated into downstream production compared to thirty-three in the ten recycled products case. The value of maintaining the operational complexity of the ten recycled products case versus the logistically simpler five recycled products case must be examined further. The advantage of having multiple destinations for the recycled products is expected to be more pronounced as additional production parameters are incorporated into the model and analyses.

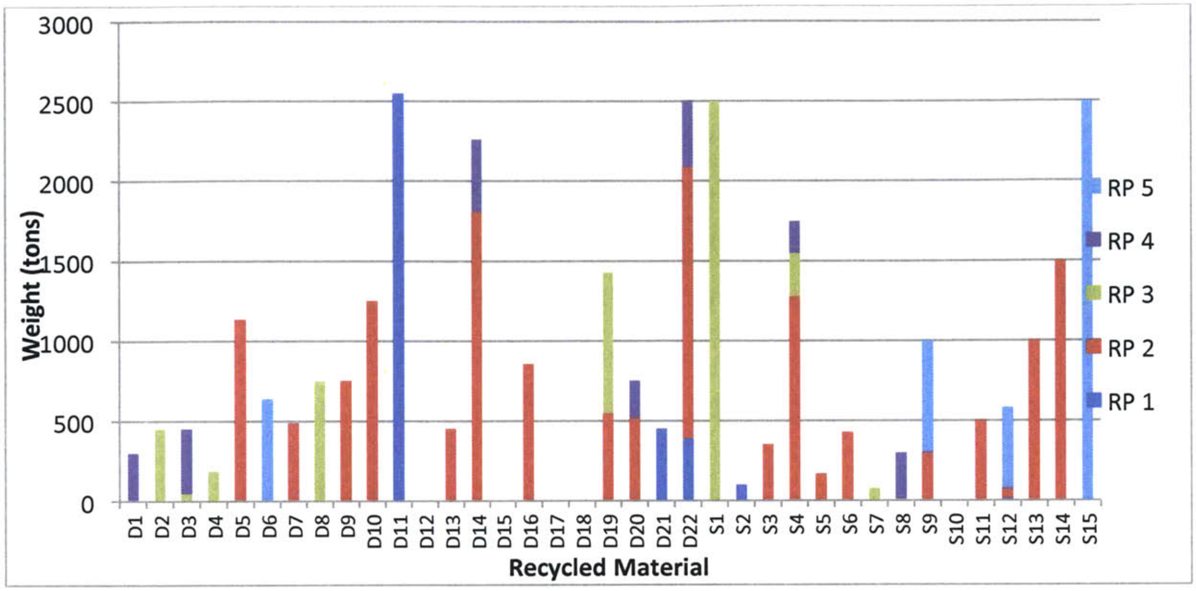

Figure 36. The allocation of aluminum dross and post-consumed scrap materials across the recycled products.

4.4 Challenge of incorporating recycled materials for fewer than four recycled products

Plotting the recycled material incorporation as a function of decreasing coordination or decreasing number of recycled products in Figure 33 revealed an increasing rate of decreasing recycled material incorporation below four recycled products. To explain the mechanism for this decrease in recycled material utilization, schematics showing the distribution of the recycled products across the ten finished alloy groups are included below for the one recycled product case in Figure 37, two recycled products case in Figure 38, three recycled products case in Figure 39, and four recycled product case in Figure 40. The total recycled product incorporated in each product group for the one recycled product case is included in Figure 37 and the change in recycled product incorporation from the previous case is included in Figure 38, Figure 39, and Figure 40. The four and three recycled products cases show a single recycled product that is customized for a downstream remelter product group that is characterized by low magnesium concentration. The two recycled products case does not include a customized recycled product resulting in less recycled material incorporation than in the three and four recycled product cases. The recycled products in the four recycled products case are incorporated into fewer alloys than the three recycled products case. For example, two of the recycled products in the four recycled products case are incorporated into five alloys while one of the alloys in the three recycled products case is incorporated into seven. In order to facilitate the ability to incorporate the recycled products into more alloy product groups, the recycled products are characterized by having high concentrations of single elements, silicon and manganese. As a result, these recycled products become sources of these elements and are less customized to the alloy product groups such as in the four recycled products case. The three recycled product case incorporates less recycled material than the four recycled product case because of the reduced ability to tailor the recycled product compositions to the needs of the alloy product groups.

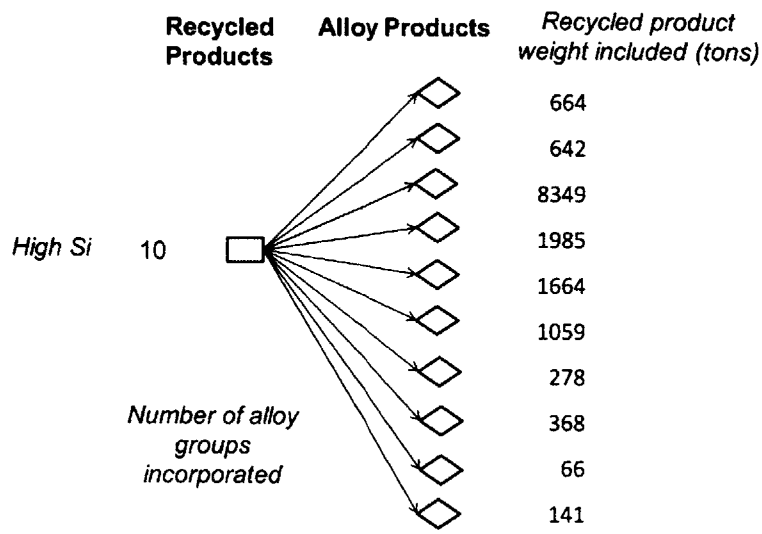

Figure 37. Schematic of the distribution of one recycled product across the ten finished alloy groups.

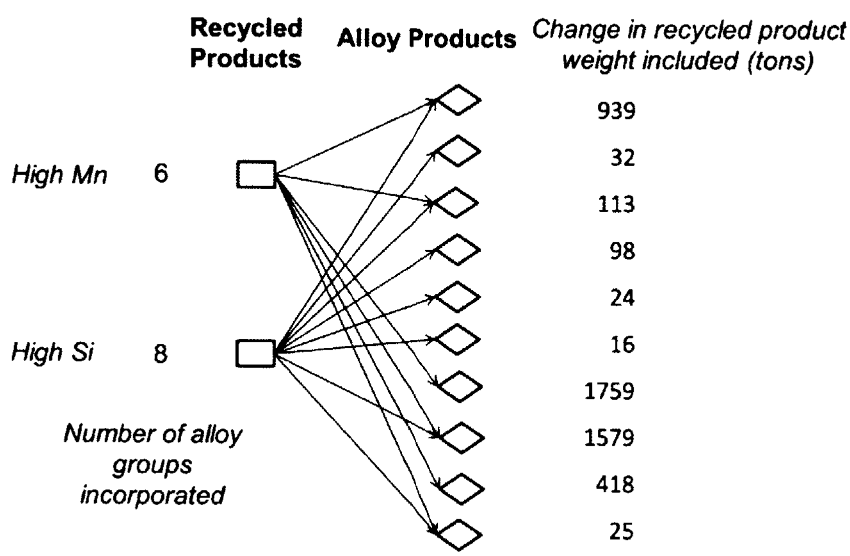

Figure 38. Schematic of the distribution of two recycled products across the ten finished alloy groups.

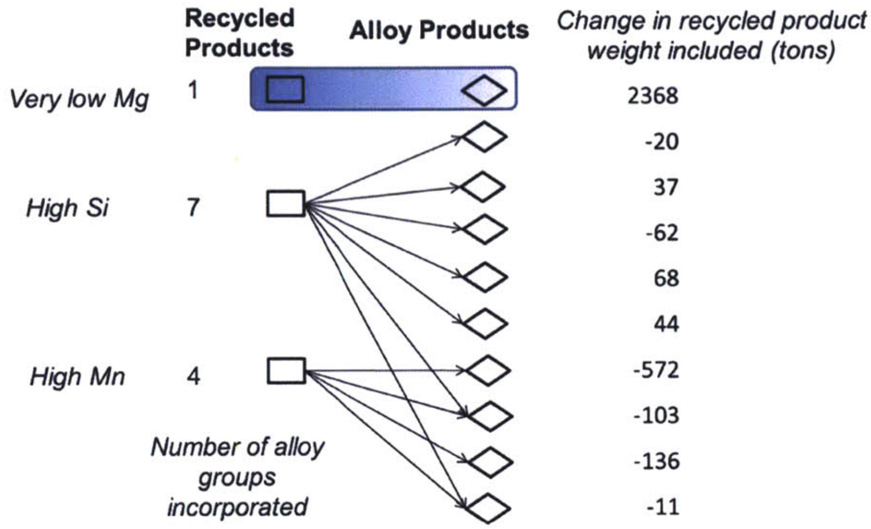

Figure 39. Schematic of the distribution of three recycled products across the ten finished alloy groups.

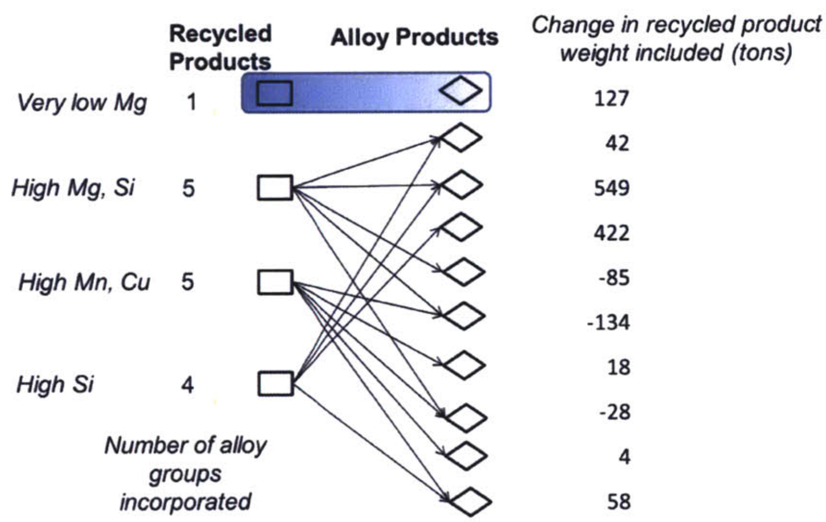

Figure 40. Schematic of the distribution of four recycled products across the ten finished alloy groups.

Chapter 5. Challenge of Long Term Downstream Production Uncertainty

The analyses presented have demonstrated the relationship between the downstream remelter's production schedule and the optimal characteristics of the recycling products. The requirement for the recycling center to develop a production plan for a six month horizon in advance of realized downstream production necessitates using projected finished alloy demand weights in the long term model calculation since actual demand weights are unknown. Although a long term production plan is calculated in this section, the level of information from this calculation that will be implemented at the recycling center for daily operations will be determined in the subsequent chapter. As a result, realized demand variations from the projected weights could cause the calculated optimal recycled product characteristics to be sub-optimal and reduced recycled material utilization could result. For example, the model allocates specific volumes of aluminum dross and post-consumed scrap materials for certain finished alloys using the six month demand projected weights. A reduction in realized demand for these finished alloys would force the operator to question the calculated allocation of the aluminum dross and post-consumed scrap materials. Maintaining the recycled material allocation calculated by the long term production model requires the recycling center to keep the materials aside for future expected demand but it may be more advantageous to the recycling center to deviate from the calculated material allocation and incorporate the aluminum dross and post-consumed scrap materials into alternate recycled products. Reducing the number of recycled products, somewhat reduces the risk of recycled material misallocation because the recycled products can be incorporated into multiple finished alloys. In addition to the aluminum dross and post-consumed secondary material allocation, the calculated optimal recycled product compositional specifications are also expected to vary with deviations in the downstream production volumes. This section explores a few methods of explicitly incorporating downstream demand uncertainty in the recycling center production plan.

5.1 Modeling stochastic downstream production

5.1.1 Statistical analysis of historical demand

The principal challenge with incorporating aluminum dross and post-consumed scrap materials into downstream remelting production is allocating the large quantities of alloying elements in the aluminum dross and post-consumed scrap materials to finished alloys without violating the compositional specifications. The proposed system was characterized in the previous section as having more alloying element weight in the aluminum dross and post-consumed scrap materials than can be fit into the downstream remelter production schedule. For example, every finished alloy product group was at the maximum compositional specification for at least one element when recycled materials were incorporated. More production volume, regardless of the specific alloy group, provides a sink for the large quantities of alloying element weight at the recycling center. Thus it is expected that reduced downstream production volume, regardless of the specific alloy group, challenges the recycling center's ability to incorporate aluminum dross and post-consumed scrap materials, especially the materials with high alloying element concentrations. Historical data supports that demand variation and uncertainty characterizes the production schedules at the downstream remelters as indicated in Figure 41. This variation in daily relative finished alloy production can manifest uncertainty when the production is aggregated to the six month level. The overall production volume is governed by customer orders which fluctuate based on macroeconomic factors including commodity prices. For example, the recent economic crisis in the European Union has already caused the total tonnage in 2011 to decrease below the 2010 total. Quantifying the lower bound on recycling center performance is more important than quantifying the upper bound because the upper limit is fixed by the plant capacity while the lower bound could theoretically extend to zero. Quantifying the potential risk of reduced production at the downstream remelters to the recycling center is particularly important because of the advantages large downstream production levels provide to the recycling center.

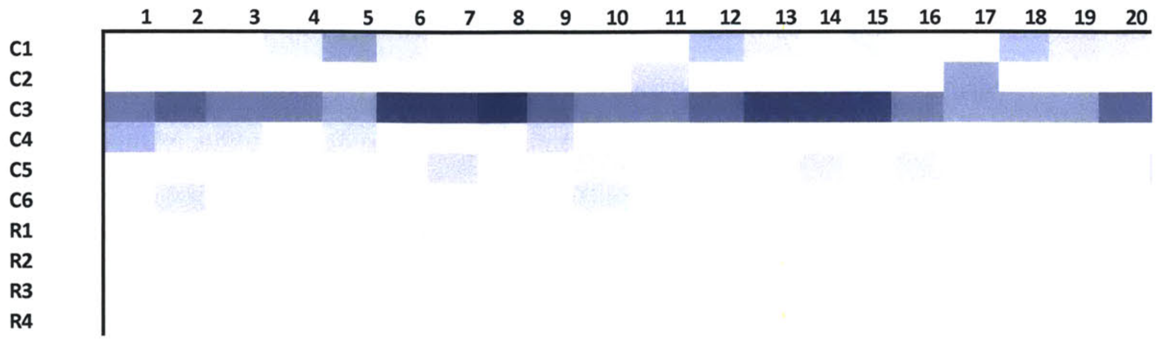

Figure 41. Graphical representation of demand variation at the downstream remelters.

Historical production data for the first downstream remelter has been reported from 1/1/2011 until 9/18/2011 and for the second downstream remelter from 1/1/2011 until 3/31/2011. The characteristics of the production schedule vary significantly depending on the finished alloy group. Figure 42 and Figure 43 show the daily production volumes for two examples of the finished alloy groups. The daily production weights are discrete because the remelting furnace must be filled due to energy concerns and the production is expressed in terms of number of charges. The distribution of the number of charges for alloy group C3 appears somewhat symmetric while the distribution of group C1 is asymmetric. Alloy group C3 is the most frequently produced alloy group constituting 49.2% of the total production weight. Alloy group C1 constitutes 12.8% of the total production weight and is most frequently not produced for any given day.

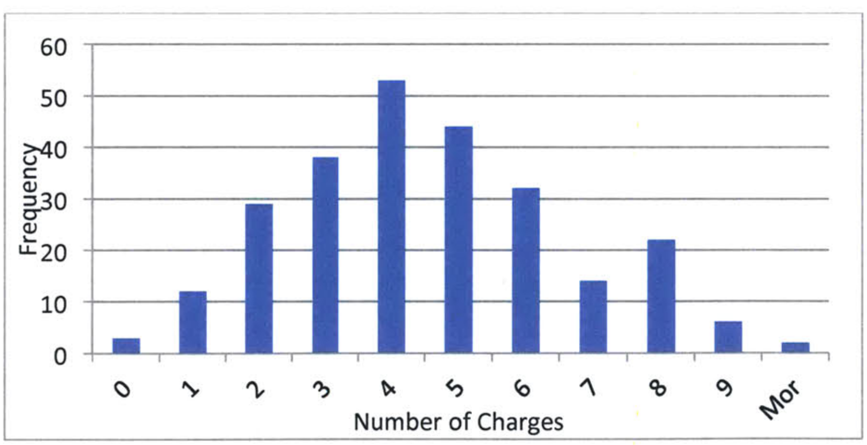

Figure 42. Histogram of the number of charges per day for finished alloy group C3.

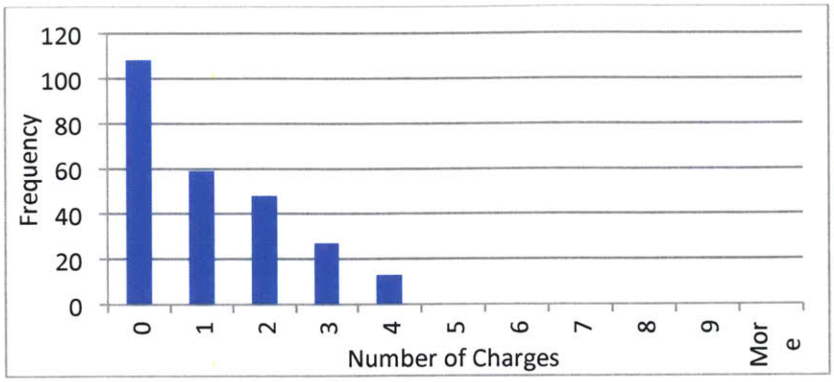

Figure 43. Histogram of the number of charges per day for finished alloy group C1.

The historical daily production weight probability distributions can be used to project the six month production volumes. Crystal Ball's batch fitting tool was used to generate daily probability distributions for each of the ten finished alloy groups. The distribution generated for alloy groups C3 and C1 are given in Figure 44 below. All correlations between the alloy group productions were included to more accurately limits the total production weight to be within the plant capacity. Both of the distributions were found to most closely follow a Poisson distribution with Chi-square values of 12.3 and 27.4 respectively. One key difference between the calculated C1 distribution and the actual C1 distribution is the frequency of zero charges produced in a day; the actual frequency is 42% vs. the calculated frequency 32%. The other eight distributions were calculated in this manner with nine of the distributions most closely fitting a Poisson while alloy group R4 most closely resembled a binomial distribution. The table of Chi-square values is included in Table XVIII below.

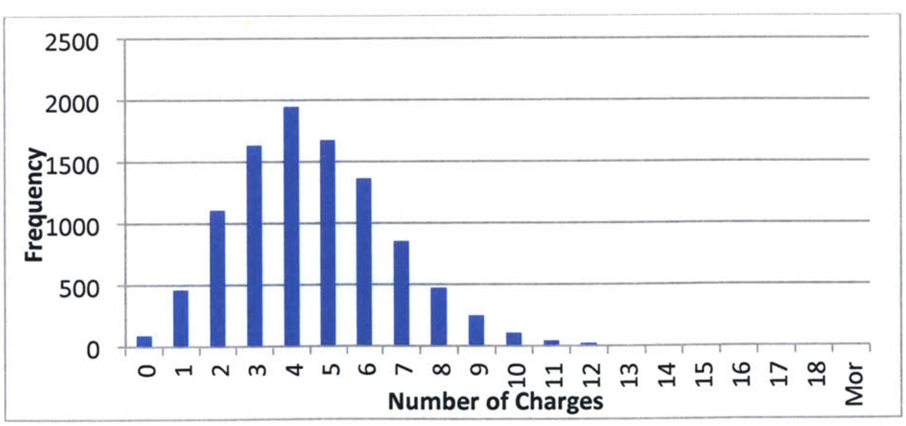

Figure 44. Histogram of the distribution calculated with Crystal Ball's batch fitting tool for finished alloy group C3.

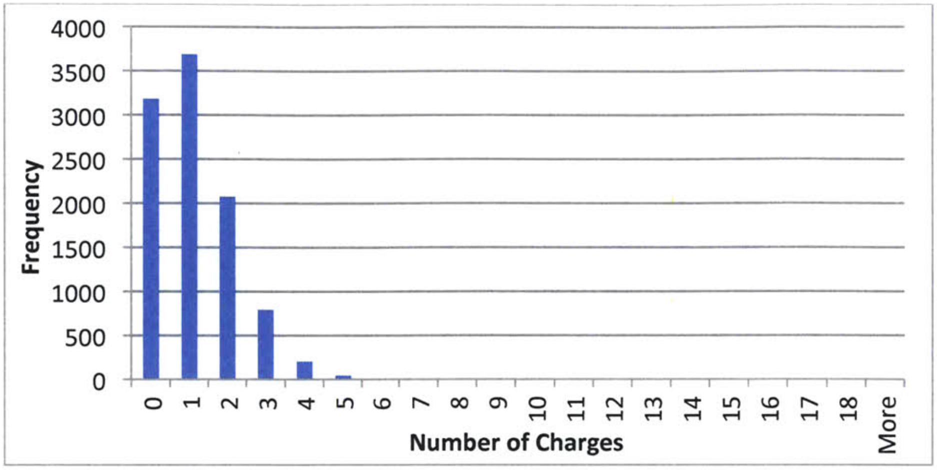

Figure 45. Histogram of the distribution calculated with Crystal Ball's batch fitting tool for finished alloy group C1.

Table XVIII. Best Probability Distributions for Each Alloy Group with Corresponding Chi-Square Values

Alloy Group	Distribution	Chi-Square
C1	Poisson	27.45
C2	Poisson	45.52
C3	Poisson	12.26
C4	Poisson	16.12
C5	Poisson	6.37
C6	Poisson	10.65
R1	Poisson	2.28
R2	Poisson	0.36
R3	Poisson	0.53
R4	Binomial	0.00

The generated daily probability distributions can be used to estimate the longer term six month production distribution. The estimated six month production distributions of the downstream remelters are included in Figure 46 and Figure 47 respectively. The six month total weight distributions were estimated by using Crystal Ball to run a Monte Carlo simulation of the daily distributions of the ten product groups. The trials were grouped in six month increments and summed. The average production volume calculated for the first downstream remelter was 69,124 tons with a standard deviation of 1,483 tons. The average production volume calculated for the second downstream remelter was 9,582 tons with a standard deviation of 466 tons. The six month production distributions of the two plants were calculated separately to emphasize the independence of these facilities. The simulated production schedules support that a six month production schedule projection is characterized by uncertainty.

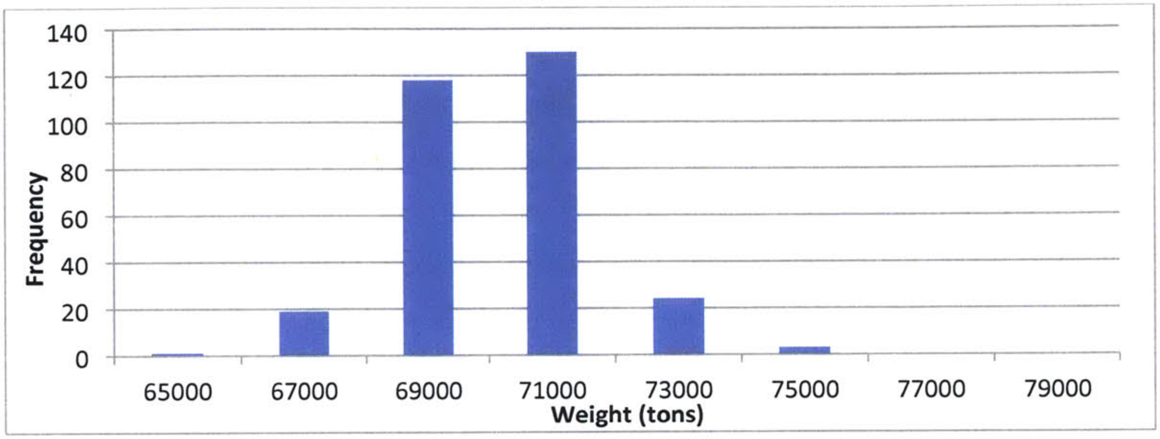

Figure 46. Estimated probability distribution of the total six month production of the first downstream remelter.

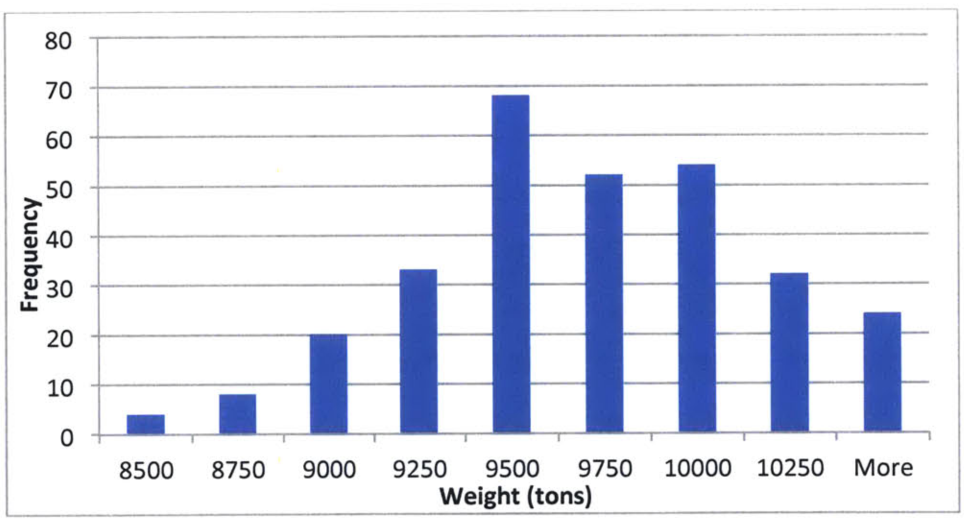

Figure 47. Estimated probability distribution of the total six month production of the second downstream remelter.

5.1.2 Initial estimate of the influence of downstream demand uncertainty on recycling center performance for three scenarios: one recycled product, 2 recycled products, and 8 recycled products

A linear recourse optimization model can provide an estimate for the impact of the previously quantified downstream remelter demand uncertainty on the performance of the recycling center. The recourse model calculates total recycled material delivered as liquid and the amount of residual recycled material cast as sows based on the recycled product characteristics including composition, volumes, and costs calculated using the long term recycling center production model (Brommer, Olivetti et al. 2011). This recourse model can be used to provide information about the recycling center performance based on a fixed set of recycled product characteristics, but cannot be used to inform the recycled product characteristics such as composition, volumes, and relative dross and scrap allocation. The recourse model used to provide information on the recycling center performance has 250 downstream production scenarios with equal probabilities embedded into the objective function to represent production uncertainty. The effect of downstream demand uncertainty on recycling center performance is expected to depend on the number of recycled products produced at the recycling center so to cover the solution space an 8 recycled products case, 5 recycled products case, and 1 recycled product case are explored (Brommer, Olivetti et al. 2011). The summary of the relative amount of recycled product calculated to be used as either liquid product or sow, the relative amount of recycled product expected to be delivered as liquid, the standard deviation of the liquid material used over the downstream production scenarios, and the amount of material expected to be cast as sow is included in Table XIX below. The significant proportion of recycled material purchased by the recourse model compared to the total available results from the modest penalty term in the objective function for casting the recycled products as sows. The modest penalty is intended to reflect the willingness of remelters to re-purchase their reprocessed aluminum dross. The range of the amount of recycled product delivered as liquid and incorporated into the downstream production plan is plotted in Figure 48. This plot reveals that demand uncertainty can reduce the ability of the recycling center to deliver liquid recycled products to the downstream remelters for certain scenarios. The performance risk associated with low downstream production scenarios is indicated by the large separation between the average liquid metal delivery rate and the minimum value.

Table XIX. Performance Summary of Recycling Center Production Plans for Downstream Uncertainty Scenarios

	8 Recycled Products	5 Recycled Products	1 Recycled Product
Estimated by Long Term Model (tons)	2991	2958	2054
Purchased by Recourse Model (tons)	2991	2958	2054
Liquid metal delivery (tons)	2876	2848	1973
Liquid metal delivery standard deviation (tons)	156	151	131
Cast sow (tons)	115	111	81

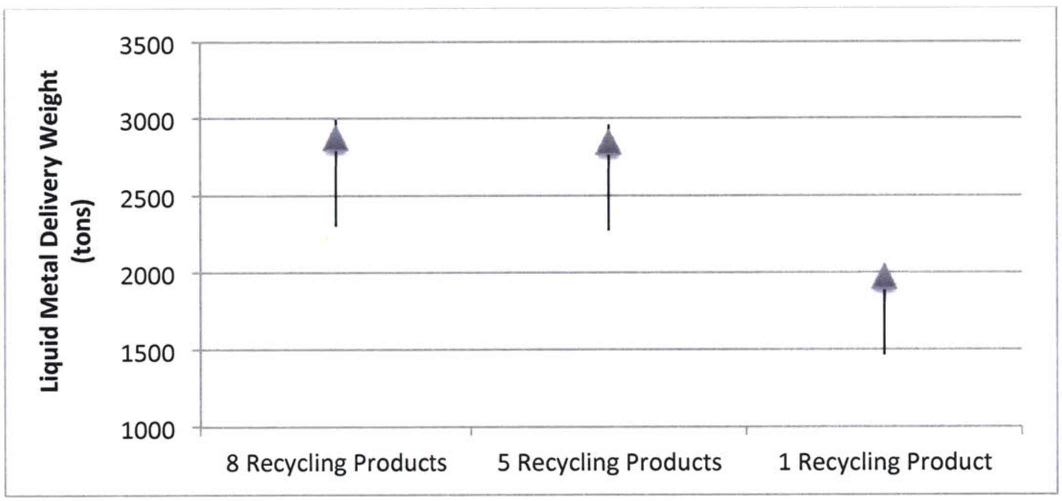

Figure 48. Liquid metal delivery weight in each of the three recycling center production scenarios (Brommer, Olivetti et al. 2011).

The recourse investigation on the influence of downstream demand uncertainty on recycling center performance reaffirms that producing more recycled products increases the amount of liquid metal delivery. In the case of downstream demand uncertainty, producing more recycled products offers more opportunities for substitution and increases the likelihood the recycled products can be incorporated into downstream production. The initial investigation using recourse modeling indicates that downstream production uncertainty can negatively impact recycling center performance. As a result, it is expected that recycling center performance can be improved by explicitly considering downstream remelter production uncertainty when calculating the long term recycling center production plan.

5.1.3 Applying design of experiments to structure demand uncertainty scenarios

The proposed recourse and pooling model formulations describing long term recycling center production can theoretically be used to explicitly incorporate the uncertain character of the downstream remelter production. The long term model with recourse incorporates probabilistic demand scenarios into the objective function; allowing the model to optimize the recycling product characteristics based on the uncertain character of production. The probabilistic demand distributions discussed in the previous section must be converted into demand scenarios to be incorporated into the long term production model with recourse. The principles of design of experiments can be applied to transform the uncertain character of the production into a discrete set of scenarios. A matrix of scenarios for a simple case of three production levels for each product group is proposed. Level 1 indicates a production level one standard deviation below the mean, level 2 indicates a production level equal to the mean, and level 3 indicates a production level one standard deviation above the mean. The formula for calculating the number of experiments required for a full-factorial experiment is given in Eq. 61 below.

$$l^n = x \qquad \textbf{Equation 61}$$

Where l is the number of values the design variables can have, n is the number of design variables, and x is the number of required experiments.

According to Eq. 1, the proposed simple case would require 3^{10} or 59,049 experiments because there are ten product groups which can take on three values. Many of the common techniques to reduce the number of required experiments rely on studying factors independently. Such techniques cannot be applied to the proposed recycling operation with great accuracy because of the interactive effects between finished alloys at the same remelting plant. For example, the total production of the downstream remelters are limited to the plant capacity. Thus, especially large production volumes of individual alloys require a corresponding small production volume of other alloys to avoiding exceeding the production capacity of the plants. Additional interactive effects between finished alloys are expected because deviations from the mean production volumes reflect changing economic conditions that could affect the production volumes of all the alloys. The other challenge to applying design of experiment strategies to reduce the total number of required experiments is preserving the shape of the probability distribution of the alloy production. Preserving the shape of the alloy production distribution is essential to calculating an optimal production plan that is robust to uncertainty and not individual events of production volume deviation. Along this reasoning, a significant number of scenarios are required to describe the stochastic production space of the downstream remelters.

5.1.4 Computational tractability of recourse pooling formulation

The challenge of representing the downstream remelter stochastic production space is explored by evaluating the computational burden as the number of demand scenarios increases. Table XX shows the approximate solving time and the number of iterations associated with each trial. The number of iterations is the most objective measure of computational burden because it is independent of processor speed. However, solving time gives a better representation of the feasibility of increasing the number of downstream demand scenarios input into the recourse model. Table XX demonstrates that the computational burden increases exponentially with increasing the number of demand scenarios. Seven downstream demand scenarios appears to be the limiting case for computational tractability. It is anticipated that seven scenarios is not a sufficient number of scenarios to represent the probability distributions characterizing the downstream production space.

Table XX. Associated Computational Burden for Varying Numbers of Downstream Demand Scenarios.

Number of Downstream Demand Scenarios	Solving Time	Number of Iterations
1	10 seconds	1,173
2	43 seconds	4,941
3	1 minute 55 seconds	12,018
4	6 minutes 45 seconds	42,657
5	13 minutes	156,893
6	13 minutes 30 seconds	150,999
7	32 minutes 17 seconds	62,842
8	> 48 hours 37 minutes and 13 seconds	>13,674,129

5.2 Recycling production plan hedged for long term downstream production uncertainty

The computational intractability of the long term recycling center production model with recourse has necessitated the use of alternative approximation techniques such as simulation methods to determine the effect of downstream demand uncertainty on the optimal production plan of the recycling center. The objective of the downstream production simulation is to determine recycling product specifications that are robust to uncertainty in downstream production but able to use a significant volume of recycled material. Additionally, the downstream production simulation can quantify the associated risk downstream production uncertainty poses to the recycling center performance. Further analyses on the effect of downstream production uncertainty on the optimal production plan of the recycling center can reveal strategies and insights to best hedge the recycling center production design for downstream demand uncertainty.

5.2.1 Purchasing strategy

Downstream remelter production uncertainty can affect recycling center performance because uncertainty can make long term planning decisions sub-optimal. The large tonnage of available recycled materials necessitates purchasing strategies with advanced planning. The six month production uncertainty simulation can reveal trends in recycled material consumption and potential issues that might be mitigated with an informed purchasing strategy.

The overall influence of uncertainty in downstream remelter production on the performance on the recycling center performance can be evaluated by looking at the resulting variation in material utilization, electrolysis, process scrap, and total recycled content. Figure 49 shows the weight ranges of electrolysis, process scrap, and recycled materials consumed over the course of the six month production simulation results using box and whisker plots. The weights calculated by the deterministic long term production model are included as blue diamonds on the plot. In the box and whisker plots, the top of the line indicates the maximum observed material used, the bottom of the line indicates the minimum observed material used, the top of the box indicates the upper quartile weight of material used, and the bottom of the box indicates the lower quartile weight of material used. The upper quartile required electrolysis weight is 7.4% larger than the weight predicted with the mean downstream production weight for the five recycled products case while the lower quartile required electrolysis weight is 2.8% larger. This asymmetry in the electrolysis weight used in downstream production suggests that downstream remelter production uncertainty poses a risk to the performance of the recycling center. Figure 49 supports that process scrap is a very attractive raw material across the six month production simulation because for the majority of the scenarios all 10,000 tons of available process scrap are purchased. Although purchasing more process scrap might be beneficial due to its relatively low cost and low alloying element concentrations, the supply is limited. The key performance metric for the recycling center is the total weight of recycled material incorporated into the downstream remelter production. Figure 49 indicates that downstream production uncertainty creates relatively minor variation in the total recycled material weight incorporated into production. The percent difference between the recycled materials incorporated into downstream production for the five recycled products mean case and the material incorporation for the uncertainty simulation is 1.5% for the upper quartile and 0% for the lower quartile. The percent difference between the deterministic recycled material incorporation and the maximum value observed during the uncertainty simulation is 4.3% and the minimum value is -4.2%. This limited variation in the total weight of recycled material included in production across the six month production scenarios suggests that the recycling center long term production plan is robust to downstream production uncertainty. In particular, the limited variation in the total recycled material incorporated into downstream production across the scenarios may be limited by the compositional diversity of the aluminum dross and post-consumed secondary materials. To evaluate the validity of this theory, the variation in consumption of individual recycled materials is explored below.

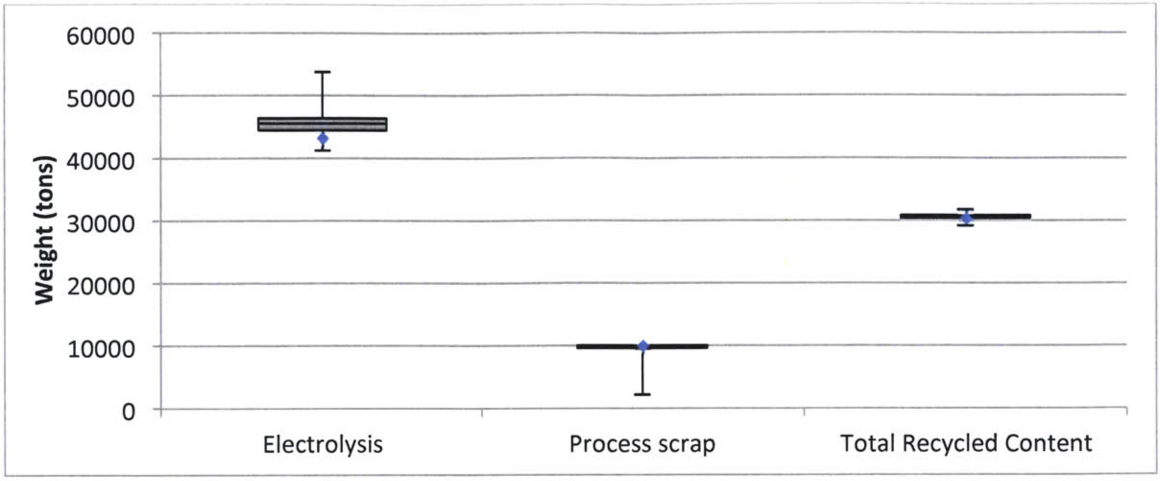

Figure 49. Box and whisker plots describing the electrolysis and process scrap used in the six month production simulation.

The downstream uncertainty production simulation revealed that the composition of several materials prohibits including these materials as liquid in downstream production. Figure 50 shows the fraction of recycled material incorporated into the downstream production to the total material available during the production uncertainty simulation. The relative recycled material utilizations calculated using the deterministic long term production model are included in blue. For the majority of the aluminum dross and post-consumed scrap materials, all of the available material is purchased and incorporated into production for every downstream production scenario in the uncertainty simulation. Several of the aluminum dross materials, D12, D15, D17, and D18 are not purchased and incorporated into production for any of the six month production scenarios. These dross materials were not able to be incorporated into the earlier deterministic long term model either. The limited utilization suggests that the current downstream production alloy portfolio cannot incorporate these materials and they should not be selected for liquid recycled product production until the downstream production portfolio is expanded to include new alloys. Introducing alternative alloys at the downstream remelters with broader compositional specifications that are more similar to the compositions of these aluminum dross could promote incorporating these materials as liquid into downstream production. Based on the present downstream remelting production schedule, the aluminum dross materials D12, D15, D17, and D18 should be segregated from the other recycled materials to promote individually reprocessing these materials and returning as sows to the suppliers.

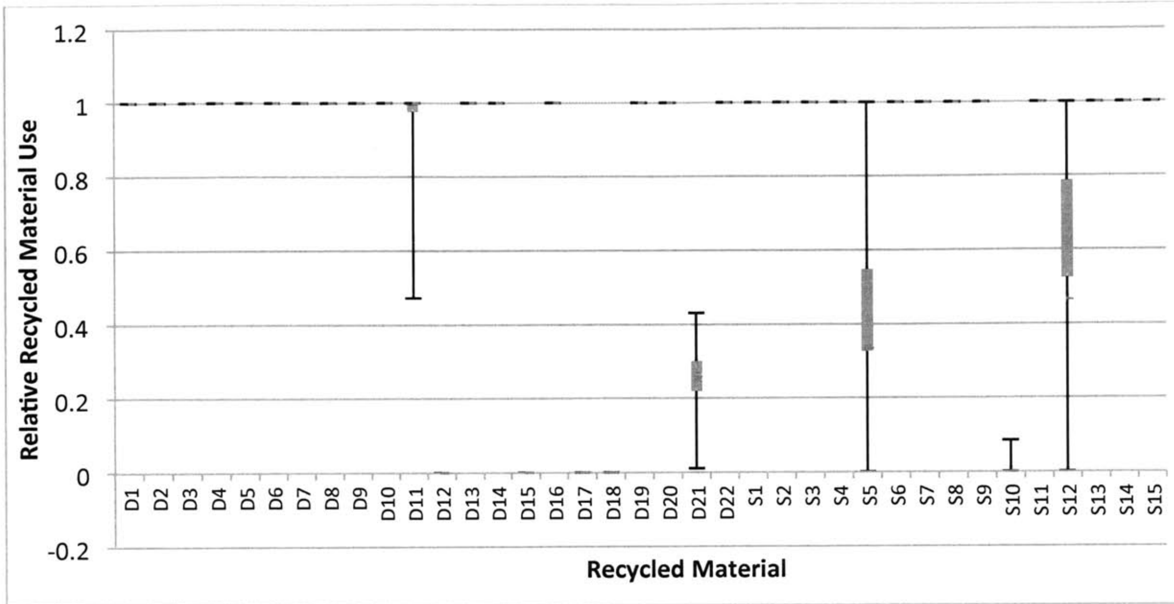

Figure 50. Box and whisker plots describing the relative raw material use for each recycled material during the six month simulation.

The downstream production uncertainty simulation revealed that four of the aluminum dross and post-consumed scrap materials, D21, S5, S10, and S12 are incorporated for only a selection of the six month production scenarios. The box and whisker plots demonstrating the variation in use of these recycled materials is included in Figure 50. For example, the incorporation of dross material D11 into downstream remelter production can vary between 47% and 100% of the total available depending on the downstream remelter production scenario. The recycling center should purchase these recycled materials with caution. Depending on macroeconomic factors, the recycling center may be able to deliver these recycled materials reprocessed as liquid to the downstream remelter. However, these recycled materials should be kept segregated, because light downstream remelting production could necessitate returning these reprocessed recycled materials to the supplier as cast sows.

Comparing the relative material incorporation during the six month downstream production scenarios reveals that several recycled materials have particularly favorable compositions that facilitate incorporation into downstream remelting production. Figure 50 shows that several recycled materials are incorporated into downstream remelter production at 100% of availability for every demand scenario. The six month production uncertainty simulation reaffirms the value of these recycled materials that was previously identified by the deterministic long term production model. Even in the case of downstream remelter production uncertainty; these recycled materials remain incorporated at rates of 100% of material availability. If possible, the recycling center should pursue strategies to increase the supply of these recycled materials or find recycled materials from other vendors with similar compositional specifications.

Reducing the required weight of alloying additions is an important advantage of using recycled materials and an important performance metric to evaluate the proposed recycling center. Figure 51 shows the variation in the weight of required alloying material additions for the six month production uncertainty simulation. The elemental compositional trends identified in the mean based long term deterministic study can be reaffirmed by Figure 51. Because of the high concentration of silicon in the aluminum dross and post-consumed scrap materials, silicon alloying material rarely needs to be purchased for any of the downstream remelter production scenarios. The low required weight for copper, chromium, and zinc alloying additions reflects partly the compositions of the aluminum dross and post-consumed scrap materials but is also a result of the sparse minimum required concentrations in the finished alloy production portfolio. Suggestions for future purchasing strategies can be inferred from Figure 51 based on the insufficient magnesium and manganese concentrations in the available aluminum dross and post-consumed scrap materials to meet the needs of the downstream remelters. Purchasing additional aluminum dross and post-consumed scrap materials with higher magnesium and manganese compositions could decrease the required alloying addition weight. Purchasing additional aluminum dross and post-consumed scrap materials with lower relative silicon compositions could increase the total weight of recycled material incorporated into downstream production.

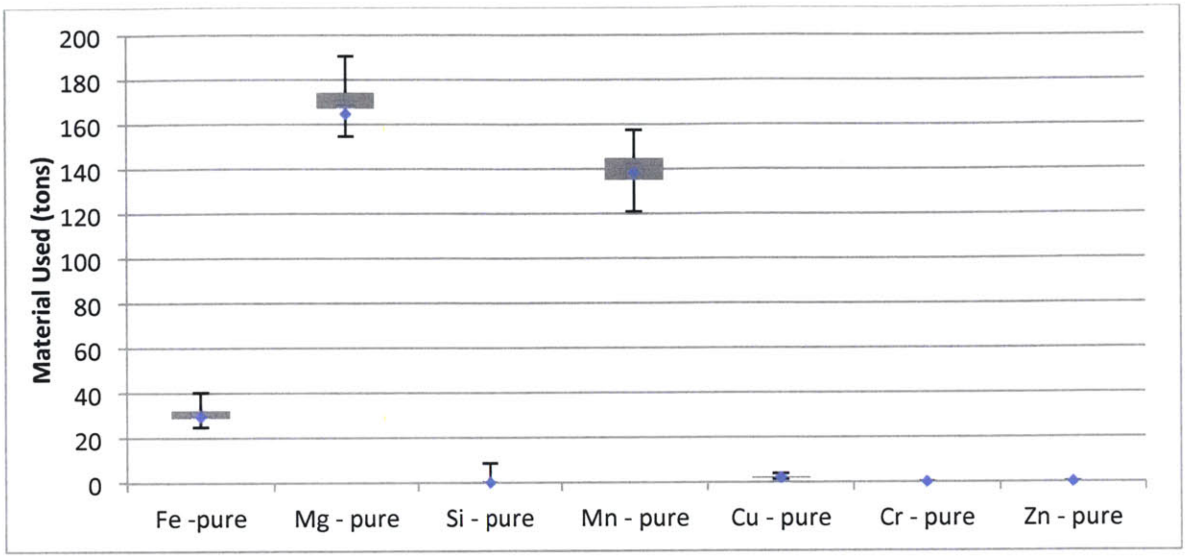

Figure 51. Box and whisker plots describing the alloying material consumption in the six month production simulation.

5.2.1 Variations in optimal recycling center production parameters observed from the uncertainty simulation

Probability distributions were fit to the historical production schedules of the downstream remelters in the previous section. Monte Carlo simulations were performed to generate daily production schedules for the downstream remelters. These daily simulations were aggregated into 296 six month production volumes and input into the long term production model to generate optimal recycling center product characteristics. The set of 296 recycling center production plans are compared to identify trends in the recycled product characteristics across the downstream production scenarios. K-means clustering was performed using the data analysis tool XLMiner to identify clusters in the simulation results. The calculated recycled product volumes and compositions from the simulation of 296 six month aggregated downstream production schedules were normalized according to Eq. 63 (Shmueli, Patel et al. 2010).

$$\hat{x} = \frac{x - \overline{x}}{\sigma} \text{(Shmueli, Patel et al. 2010)} \quad \textbf{Equation 62}$$

The product volumes and compositions were normalized to prevent the scale of individual parameters from dominating the analysis. The distances between the observations and the cluster centroid were calculated using Eq. 64 (Shmueli, Patel et al. 2010). The k-means clustering algorithm assigns observations to clusters with the closest centroid, recalculates the new cluster centroids, and iterates until the distance no longer decreases. This analysis iterated through the recycling center production data fifty times with a fixed start point.

$$d_{ij} = \sqrt{(x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + \mathrm{K} + (x_{ip} - x_{jp})^2}$$ (Shmueli, Patel et al. 2010)**Equation 63**

The k-means clustering technique requires the number of clusters to be pre-determined prior to the analysis. Ideally, there would be enough compositional and production volume similarities in the dataset to be able to identify only five clusters since this is the number of recycled products during the uncertainty simulation. To check the validity of that assumption k-means clustering was performed with four, five, and six clusters. An additional analysis decision must be made on which parameters to include when assigning the observations to clusters. In general, using more parameters to inform the cluster analysis provides more information. However, since in the uncertainty simulation the production volume of the downstream remelters is varied, including the production volume in the k-means clustering analysis might have a disproportionately large effect on the clustering results, since fluctuations in downstream production volumes more directly cause fluctuations in the recycling center production volumes. Additionally, unlike the compositional specifications of the recycled products, the production volume of the recycled products do not necessarily need to be identified in advance because the recycling center can adjust its production to meet the realized production schedule of the downstream remelters. It is suspected that including the calculated production volumes of the recycled products may introduce a bias in the compositional specification clusters and clusters are calculated including and excluding calculated production volume. To evaluate the extent of this bias, the average distance from the observation to the cluster center is calculated including the production volume parameter and excluding the production volume parameter.

The results of the four, five, and six cluster analyses are included in Table XXI, Table XXII, and Table XXIII below. Table XXI, Table XXII, and Table XXIII compare the number of observations assigned to each cluster and the average distance from the production simulation data to the cluster centroid when production volume is included as a parameter and when it is not. Table XXI shows that for the case of four clusters the allocation of observations to each cluster is more uniform when the production volume parameter is excluded. The overall average distance in the cluster is reduced when the production volume is not included as a parameter in the clustering analysis.

Table XXI. Average Distance of Observations from Cluster Center for a k-Means Clustering Analysis with Four Clusters

Cluster	Including Production Volume Parameter **Number of Observations**	Including Production Volume Parameter **Average Distance in cluster**	Excluding Production Volume Parameter **Number of Observations**	Excluding Production Volume Parameter **Average distance in cluster**
Cluster-1	473	0.883	531	1.135
Cluster-2	300	0.387	299	0.265
Cluster-3	650	2.404	344	0.816
Cluster-4	57	1.705	306	0.614
Overall	**1480**	**1.482**	**1480**	**0.777**

Table XXII lists the results of increasing the number of clusters to five and demonstrates a slightly more uniform allocation of the observations when production volume is excluded as a parameter in the analysis. In this case, the number of clusters is equal to the number of recycled products. Uniform allocation of observations across the five clusters supports the choice of five recycled products. The average distance in the cluster when the production volume parameter is included is very similar to the average distance in the cluster when the production volume parameter is excluded. However, the average distance in the cluster when the analysis is performed with five clusters is less than the average distance for the four cluster case. As a result, we can infer that five clusters is a more accurate description of the results and refrain from studying the four cluster case further.

Table XXII. Average Distance of Observations from Cluster Center for a k-Means Clustering Analysis with Five Clusters

Cluster	Including Production Volume Parameter **Number of Observations**	Including Production Volume Parameter **Average Distance in cluster**	Excluding Production Volume Parameter **Number of Observations**	Excluding Production Volume Parameter **Average distance in cluster**
Cluster-1	252	1.711	314	0.393
Cluster-2	301	0.405	294	0.341
Cluster-3	334	0.409	274	1.64
Cluster-4	294	0.342	297	0.233
Cluster-5	299	0.265	301	0.405
Overall	**1480**	**0.587**	**1480**	**0.584**

To further evaluate the accuracy of describing the results with five clusters and the characteristics of the five recycled products calculated using the uncertainty simulation, the k-means clustering analysis was performed for six clusters. It is expected that adding more clusters to describe the results reduces the average distance in a cluster because increasing the number of clusters increases the analysis' flexibility to assign observations to clusters. However, a significant reduction in the average distance in cluster would suggest that the six month production simulation should be repeated with six recycled products since the calculated recycled product characteristics are too distinct to be grouped into five clusters. Table XXIII demonstrates that the average distance in the cluster for the six cluster case is smaller than the five cluster case. Another difference from the five cluster case results is the less uniform allocation of observations. In both of the six cluster cases; including production volume as a parameter and excluding production volume as a parameter one of the clusters had a smaller number of assigned observations, 50 and 12 respectively. Since the number of observations is much smaller this suggests that there is not a uniform set of six clusters but rather five clusters with a set of outliers. Unlike the four and five cluster case, including the production volume parameter decreased the average distance in the cluster. As a result of this improvement, the clusters obtained excluding the production volume parameter are not examined further. Since the performance of the recycling center is measured by the recycled material incorporation and this performance metric is not included in the k-means clustering analysis, the compositional calculations for the five clusters including production volume case, five clusters excluding production volume, and the six clusters including production volume are further examined to evaluate the value of these recycled specifications in the context of recycling center performance.

Table XXIII. Average Distance of Observations from Cluster Center for a k-Means Clustering Analysis with Six Clusters

Cluster	Including Production Volume Parameter **Number of Observations**	Including Production Volume Parameter **Average Distance in cluster**	Excluding Production Volume Parameter **Number of Observations**	Excluding Production Volume Parameter **Average distance in cluster**
Cluster-1	201	1.147	305	0.381
Cluster-2	301	0.405	294	0.341
Cluster-3	50	1.772	271	1.334
Cluster-4	335	0.411	297	0.233
Cluster-5	294	0.342	301	0.405
Cluster-6	299	0.265	12	0.999
Overall	**1480**	**0.512**	**1480**	**0.528**

5.2.2 Recycled product compositional specifications

To translate the results of the k-means clustering analysis into compositional specifications of the recycled products, box and whisker plots were created for the three cases for each of the seven elements of interest, iron, magnesium, silicon, manganese, copper, chromium, and zinc in Figure 52, Figure 53, Figure 54, Figure 55, Figure 56, Figure 57, and Figure 58 respectively. The top of the line in the box and whisker plot indicates the maximum value of the elemental weight fraction in all of the observations assigned to the cluster and the bottom of the line represents the minimum elemental weight fraction. The top of the box represents the elemental weight fraction corresponding to the upper quartile of the results and the bottom of the box represents the elemental weight fraction corresponding to the lower quartile of the results. Thus, the weight fractions within the box represent 50% of the entire data set and can be used as the upper and lower compositional specifications of the recycled product. The tightness of the clusters can be estimated from the width of the boxes. When comparing the weight fraction cluster results for the three cases, it is important to remember that the order of the clusters is determined arbitrarily during the k-means clustering analysis.

Figure 52 includes the box and whisker plots of the iron weight fraction for the three clustering cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. A degree of weight fraction overlapping occurs for each of the cases because the k-means clustering analysis was performed for eight compositional parameters adding multi-dimensional complexity to the weight fraction results space. The analysis shows a tendency to create a cluster with a relatively low iron weight fraction and a cluster with a relatively high iron weight fraction. For example, in the five clusters excluding production volume case, cluster one is a relatively tight cluster characterized by low iron weight fraction and cluster five is characterized by a relatively high iron weight fraction. Each case has a cluster with a wider box than the other clusters, suggesting that this cluster may not be as accurately defined by the analysis. In the case of five clusters including production volume, this wider cluster is cluster one, in the case of five clusters excluding production volume, this wider cluster is cluster three, and in the case of six clusters including production volume this is cluster one.

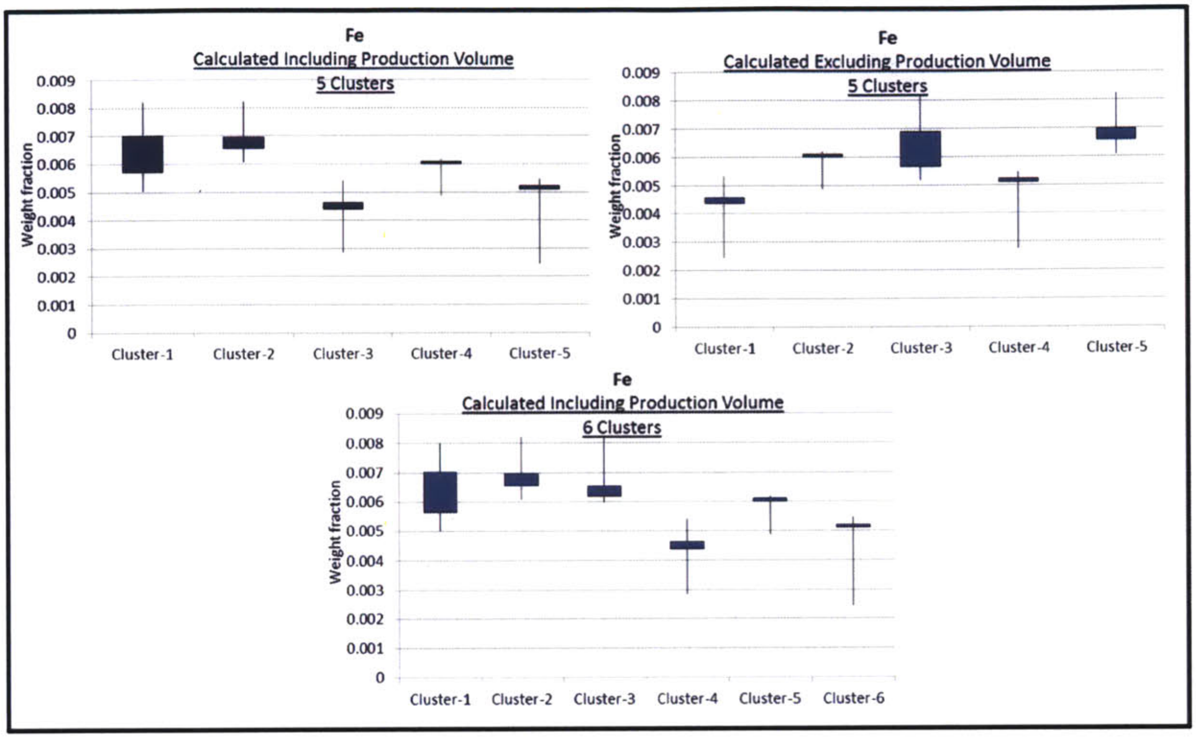

Figure 52. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile iron compositions of the k-means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

Figure 53 shows the box and whisker plots for the magnesium weight fraction of the three cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. Although the weight fractions of the clusters in the three cases exhibit a degree of overlap, the amount of overlap is reduced from Figure 52. In each of the three cases, one of the clusters is defined to have a significantly larger magnesium content than the other clusters identified as cluster 5, cluster 4, and cluster 6 in the three respective cases. The clusters identified as having the widest range for the iron weight fraction also have the widest range for the magnesium weight fraction supporting that these clusters may not be as accurately described by this cluster. Several of the boxes have widths less than three percent of the value of the upper quartile, suggesting that the six month production simulation generated consistent magnesium compositions for a few of the recycled products.

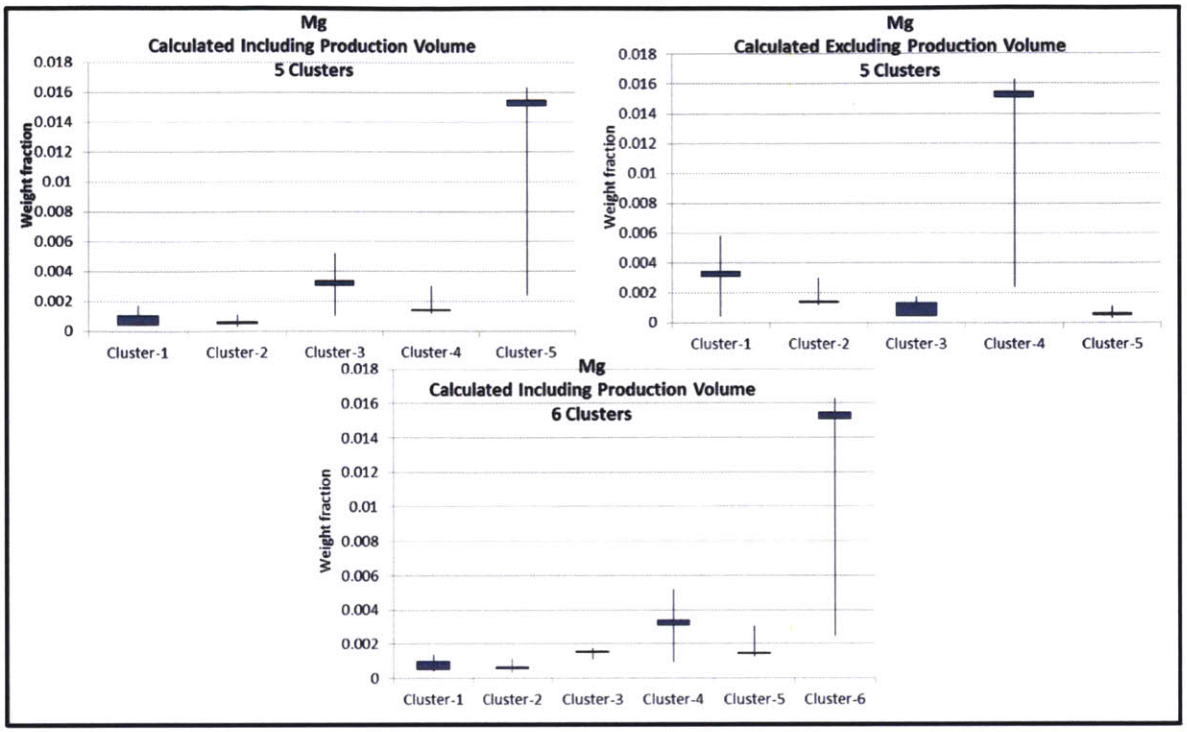

Figure 53. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile magnesium compositions of the k-Means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

Figure 54 shows the box and whisker plots for the silicon weight fraction of the three cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. The plots demonstrate the large variability of silicon weight fraction in the calculated clusters. Each of the three cases includes a cluster with a much higher silicon weight fraction, approximately 3% and two other clusters with a low silicon weight fraction < 0.4%. Several of the low silicon weight fraction clusters are characterized by very narrow boxes, widths less than 1%, suggesting that more of the observations should be incorporated into the compositional specifications to improve model flexibility. As a result of the large range of silicon weight fractions there is limited overlap in the calculated clusters. The box and whisker plots for each of the cases support the previously observed trend of certain clusters having a wider box than the other clusters and the wider clusters identified for the silicon weight fractions are the same as those previously identified. In the six cluster case including production volume cluster three also has a wide silicon weight fraction.

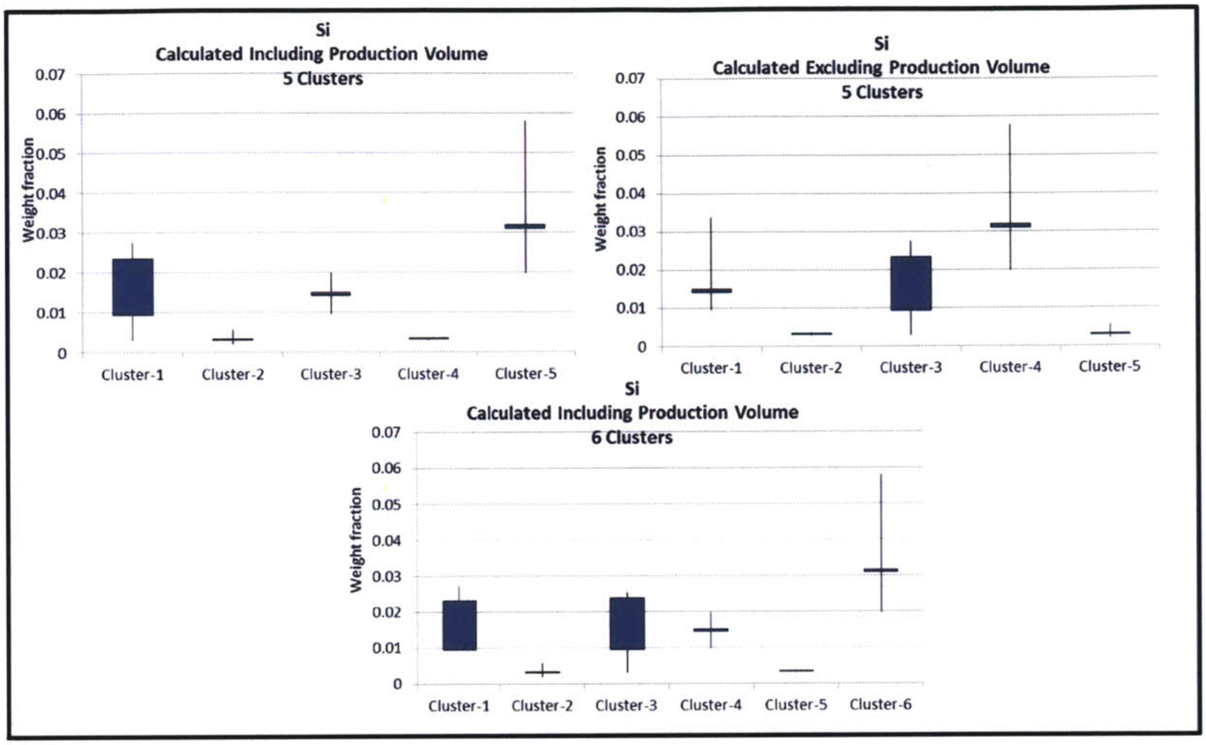

Figure 54. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile silicon compositions of the k-Means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

Figure 55 shows the box and whisker plots for the manganese weight fraction of the three cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. The clusters are widely separated when plotted against manganese weight fraction. In all three cases, a cluster having an upper limit of 0.94% emerges with at least two other clusters having upper limits of 0.12%. The large separation between the manganese weight fractions of these clusters suggests that there is a strong tendency for the recycled products to produce a high manganese recycled product and segregate the low manganese aluminum dross and post-consumed scrap materials into low manganese recycled products. The box and whisker plots describing the manganese weight fractions for the three cases support that cluster one, in the case of five clusters excluding production volume, cluster three, and in the case of six clusters including production volume, cluster one are the least accurate clusters describing the six month simulation results.

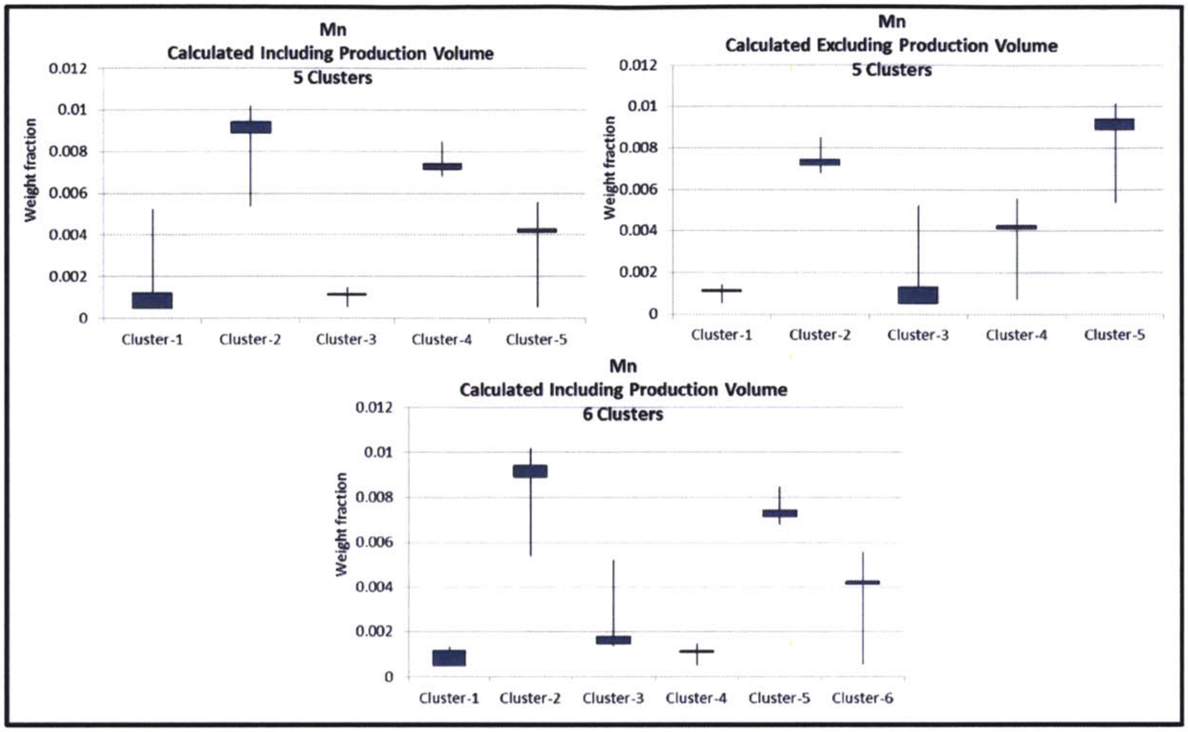

Figure 55. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile manganese compositions of the k-Means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

Figure 56 shows the box and whisker plots for the copper weight fraction of the three cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. The clusters plotted against copper weight fraction demonstrate a significant degree of overlap, suggesting that there is limited variation in the copper concentration of the aluminum dross and post-consumed scrap materials or in the minimum product specifications of the downstream remelters. In each of the three cases, a high copper weight fraction emerges with an upper copper specification of 0.15%. The wide separation between the upper quartile and the lower quartile for cluster one, in the case of five clusters excluding production volume, cluster three, and in the case of six clusters including production volume, cluster one is also demonstrated for the copper weight fractions. In the six cluster case including production volume two boxes have large widths; 36% in the cluster one and 26% in cluster three.

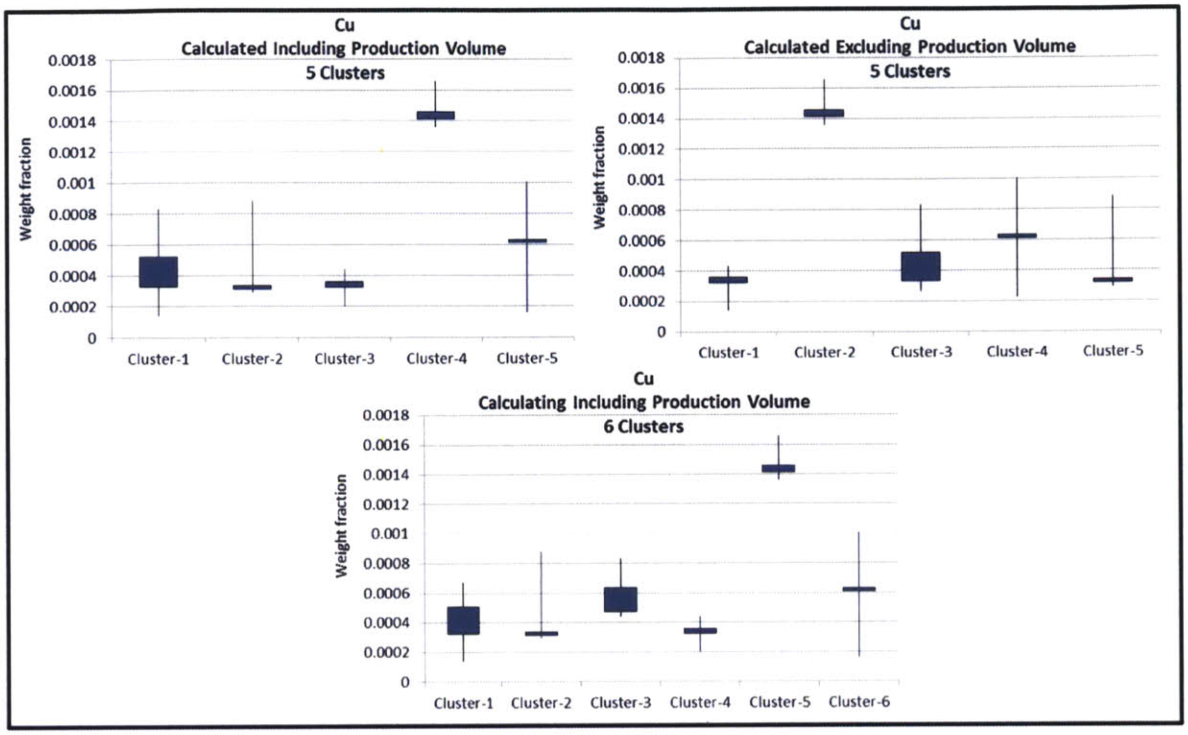

Figure 56. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile copper compositions of the k-Means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

Figure 57 shows the box and whisker plots for the chromium weight fraction of the three cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. The three cases demonstrate limited variation across the chromium weight fraction within the boxes, although the lines indicate that several observations contained large chromium weight fractions. When the k-Means clustering was performed with six clusters, cluster three was created having a larger weight fraction than the other five clusters. In each of the three cases, a cluster was determined to have a smaller chromium weight fraction and narrower box width than the other clusters, with a maximum chromium weight fraction of 0.0001. Contrary to the previously described trend in iron, magnesium, silicon, manganese, and copper of having a cluster with a much wider spread between the upper and lower specification, the clusters when plotted against chromium weight fraction indicate three boxes with significant spread between the upper and lower compositions. In all three cases examined there are three clusters with greater than 21% difference between the upper and lower chromium weight fraction. This suggests that the variation in chromium content in the recycled products is influencing the identification of cluster with large relative differences between the upper and lower compositional specifications.

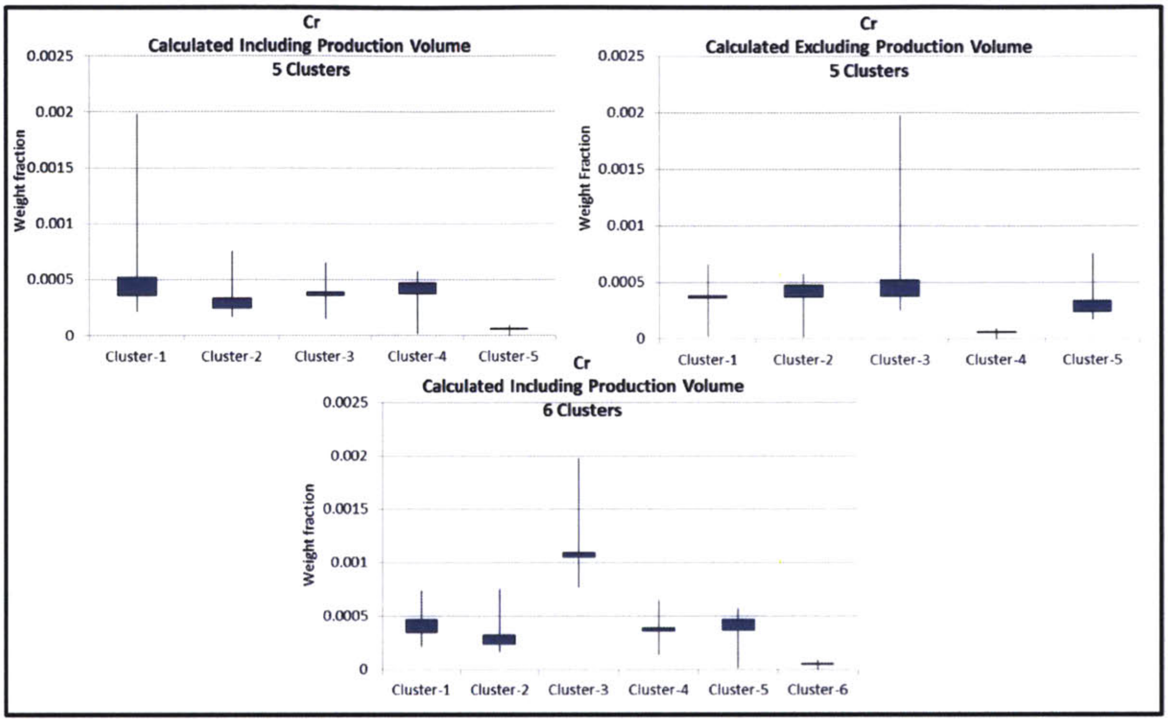

Figure 57. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile chromium compositions of the k-Means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

Figure 58 shows the box and whisker plots for the zinc weight fraction of the three cases; five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. The clusters in the five clusters including production volume and five clusters excluding production volume cases exhibit no overlap in the specified zinc weight fractions. The overlap in the six clusters including production volume is a result of two clusters three and five having identical zinc weight fraction compositional specifications. In all three cases a low zinc weight fraction can be identified as having a maximum zinc weight fraction of 0.0002. The five clusters including production volume and five clusters excluding production volume both include a high zinc weight fraction cluster having a maximum specification of 0.0008. In the six clusters case including production volume there are two clusters with a maximum zinc weight fraction of 0.0008. Similar to the previously identified trend in chromium, plotting the clusters against zinc weight fractions reveals that the relative widths of the boxes are more uniform than in the case of iron, magnesium, silicon, manganese, and copper. The percent difference between the upper quartile and the lower quartile in the five clusters including production volume case is less than 16% while in the case of five clusters including production volume the percent differences are even smaller, all less than 15%. In the case of six clusters including production volume the percent differences between the upper quartile and lower quartile is less than 13%. The more uniform box widths for the chromium and zinc cluster weight fractions compared to the iron, magnesium, silicon, manganese, and copper box widths suggest that these elements are influencing the k-means clustering algorithm to identify more widely spaced clusters. Despite the relatively low concentration of chromium and zinc in the recycled materials, normalizing the data ensures that all elements have an equal impact on identifying the clusters.

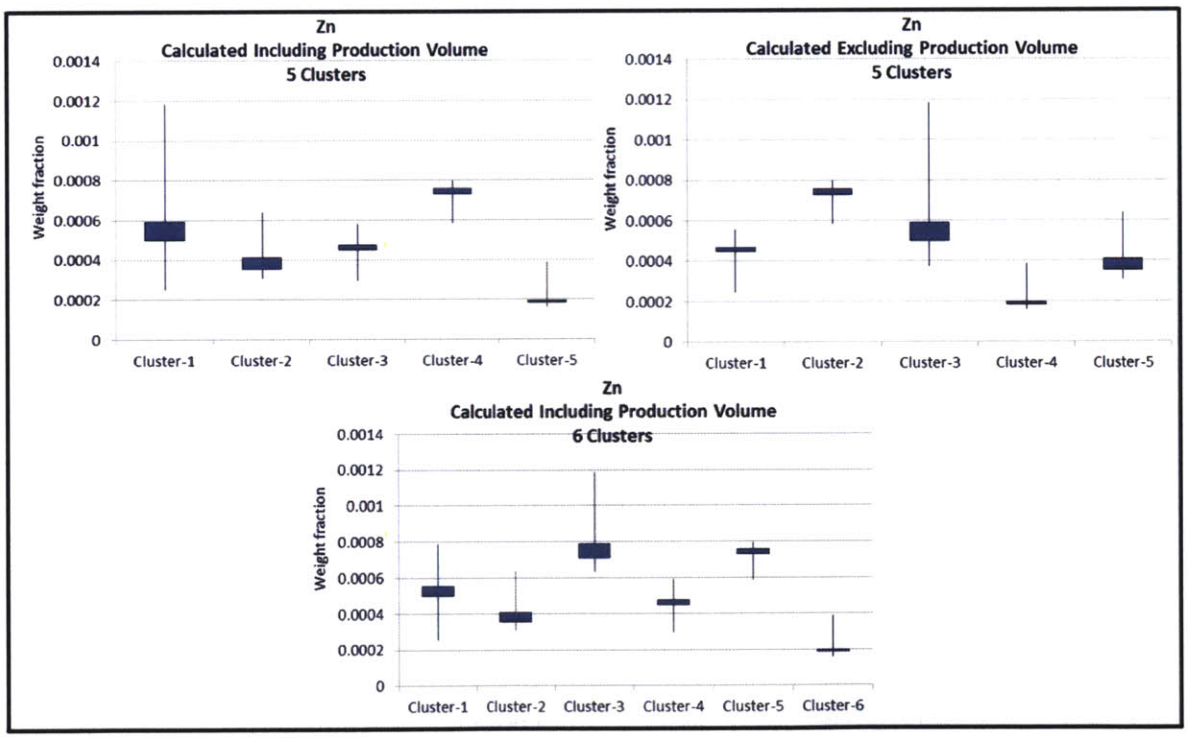

Figure 58. Box and whisker plots representing the maximum, minimum, lower quartile, and upper quartile zinc compositions of the k-Means clustering analysis using five clusters including production volume, five cluster excluding production volume, and six clusters including production volume.

The k-means clustering analysis has generated three sets of potential compositional specifications for the recycled products. The main limitation of the k-means clustering analysis was the equal weighting of each compositional element and the inability to include the performance metric of the recycling center, which is the ability to incorporate recycled material into the downstream production plans of the downstream remelters. To begin the refinement of the three potential compositional specifications for the recycled products, the subsequent section explores the variation of the dross and scrap material consumption for the 296 six month production schedules.

5.3 Short term downstream production variability

This chapter explored the effect of long term downstream remelter production uncertainty on the recycling center performance. The long term production model calculated the optimal recycling center production parameters for varying downstream production plans. Several trends were identified in the recycled product compositional specifications and optimal combinations of recycled materials. Simulating several six month downstream remelter production plans allowed resolution of the potential variation of the estimated material flows in the previous chapter. Although many insights can be gained by studying the performance of the recycling center from a long term perspective, it is crucial to study the recycling operation at a shorter time scale, particularly at a daily operational level. Modeling the recycling operation at a daily level allows operational constraints to be explicitly considered that cannot be resolved in the long term production model. In particular, the shorter term model calculates the daily recycling center production including constraints on the operational limits of the recycling center, such as daily plant capacity and furnace volume. Comparing the recycling center daily production plan calculated with the longer term production model to the recycling center daily production plan calculated explicitly considering daily operation constraints may reveal limitations of the longer term production model. Additionally, studying the recycling operation at a daily timeframe provides a method to explore the value of providing flexibility to the recycling center to plan production according to its own operational constraints. The longer term production model implicitly assumes perfect coordination between the recycling center and the downstream remelters because no daily production level constraints are included. Thus, comparing the recycling center production plan calculated by the long term production model to the production plan calculated by the daily production models provides a method to quantify the value of coordination between the recycling center and the downstream facilities.

The main benefits of flexibility for the recycling center are expected to result from the recycling center's ability to decide its production based on the daily production plan at the downstream remelters. Such flexibility is expected to be valuable only in downstream production scenarios which include more alloys than the recycling center has production capacity to meet. Further complexity that is not incorporated into the long term production model is the variability of the downstream remelter production schedules; the alloys produced vary each day and the production of the two plants is independent. Table XXIV shows a few example daily production plans from the downstream remelters to demonstrate the variability characteristic of the production schedules. This variability is difficult to translate into the long term production model because decision rules that describe the recycling center production are difficult to define. As a result, a separate set of optimization models that can endogenously optimize daily recycling center production is necessary. The subsequent chapter uses the daily operational model formulations to evaluate the value of coordination between the recycling center and the downstream remelters.

Table XXIV. Four Example Downstream Remelter Daily Production Plans

1/1/2011										
Product Group	**Group C1**	**Group C2**	**Group C3**	**Group C4**	**Group C5**	**Group C6**	**Group R1**	**Group R2**	**Group R3**	**Group R4**
Total Charges	1	0	5	3	0	0	1	0	0	0
1/2/2011										
Product Group	**Group C1**	**Group C2**	**Group C3**	**Group C4**	**Group C5**	**Group C6**	**Group R1**	**Group R2**	**Group R3**	**Group R4**
Total Charges	0	0	6	2	0	2	2	0	0	0
1/3/2011										
Product Group	**Group C1**	**Group C2**	**Group C3**	**Group C4**	**Group C5**	**Group C6**	**Group R1**	**Group R2**	**Group R3**	**Group R4**
Total Charges	0	1	5	2	0	1	1	0	0	0
1/4/2011										
Product Group	**Group C1**	**Group C2**	**Group C3**	**Group C4**	**Group C5**	**Group C6**	**Group R1**	**Group R2**	**Group R3**	**Group R4**
Total Charges	2	0	5	0	0	1	2	0	0	0

Chapter 6. Evaluating the Value of Coordination and Flexibility

The previous chapters have proposed recycling center production plans based on long term production parameters and constraints. Long term production planning is essential to embedding insights into the initial recycling center production design to manage potential challenges later in operation, but the proposed recycling center production designs must also be balanced with short term production constraints. To determine the optimal level of coordination between the recycling center and the downstream remelting facilities and the optimal level of operational flexibility to provide to the recycling center, a recycling center production simulation must be performed using historical downstream remelter production data. The principal objective of the dynamic simulation is to evaluate the performance of the long term production model solution in the context of daily downstream remelter production patterns. In order to perform the daily production simulation, the mean based and uncertainty derived long term production plans must be transformed into daily production plans. The daily recycling center dynamic simulation can calculate the performance of each recycling center production design and can inform the recycling center's decision on the optimal level of flexibility to allow daily operations to deviate from the calculated long term production plan. The optimal degree of operational flexibility is enforced at the recycling center by implementing the daily optimization tool corresponding to the desired daily operational model formulation. The optimal degree of coordination is enforced at the recycling center by calculating the long term production plan according to the desired number of recycled products.

The daily operational model formulations require different combinations of production inputs calculated by the long term production models, resulting in different levels of operational flexibility at the recycling center. This chapter evaluates the performance of the recycling center production plans calculated for the varying levels of flexibility and coordination. This chapter also makes recommendations for the optimal recycling center production design, degree of coordination between the recycling center and the downstream remelting facilities, and level of flexibility to provide to the recycling center to modify production according to daily operational constraints including short term variations in downstream remelting production.

6.1 Balancing short term and long term constraints

There is an inherent mismatch between recycling center production plans calculated using the long term model formulation and those calculating using the daily operational model formulation. The schematic in Figure 59 lists the decisions the recycling center must make each day based on the downstream remelter's daily production plan. The long term model allocates aluminum dross and post-consumed secondary materials across the recycled products based on the long term recycled material availability and long term aggregate downstream production volumes. The daily operational model formulations optimize recycling center production either in terms of the relative production of each recycled product or by pooling the dross and post-consumed secondary materials into the recycled products based on daily production constraints including; rotary furnace volume, charge capacity of the rotary furnace, and the daily production volumes at the downstream remelters. The principal advantage of the daily recycling center operational model formulations over the long term production model is the ability of the daily formulations to modify production from the long term plan according to temporal variations in downstream remelter production. The effect of the following daily operational parameters on recycling center performance is explored: 1) downstream demand variation, 2) furnace capacity mismatch, 3) recycling center production capacity, 4) recycled material management or stock depletion. The principal advantage of the long term production model formulation is the ability to allocate the aluminum dross and secondary materials according to the long term availabilities and finished alloy production schedule at the downstream remelters. As a result, the long term production model is better able to allocate aluminum dross and post-consumed secondary materials over an extended period and avoids depleting the highest quality secondary materials which hinders the ability to meet recycled product compositional specifications later on. To determine the optimal recycling center production design, including the optimal degrees of coordination and flexibility, the performance of twelve recycling center production designs are quantified using a dynamic production simulation.

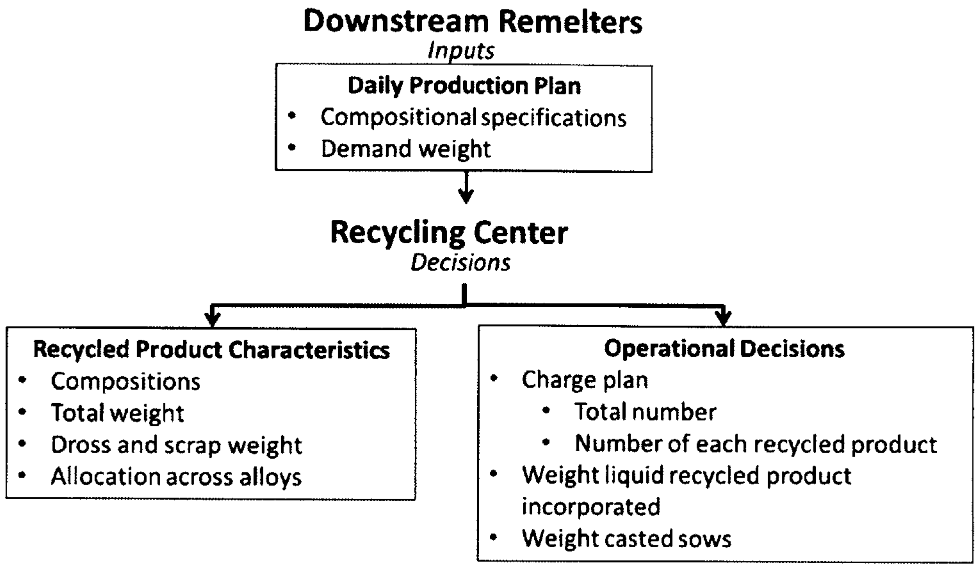

Figure 59. Mapping of the daily decisions the recycled center must determine based on the daily downstream remelter production plan.

6.1.2 Recycled material management or stock depletion

Stock depletion of the aluminum dross and post-consumed secondary materials is an important effect that could significantly decrease performance at the recycling center without proper mitigation strategies. Previous research on the effect of misallocating secondary materials during aluminum recycling by optimizing production over a short time frame has been shown to reduce overall secondary material utilization (Brommer, Olivetti et al. 2012). Figure 60 shows the challenge of incorporating secondary materials into aluminum alloy products when the products are optimized one at a time over a sequence (Brommer, Olivetti et al. 2012). The plot includes two optimization approaches, an integrated approach which optimizes the aluminum alloy charge plans simultaneously for all of the alloys and a sequential approach which progressively optimizes the charges in order of increasing content of element X (Brommer, Olivetti et al. 2012). The sequence of increasing content of element X is a heuristic based on the plant manager's concerns with this specific element (Brommer, Olivetti et al. 2012). The recycled fraction indicates the relative amount of recycled material included in the charge to the total amount of material included. Aluminum dross and post-consumed secondary material stock depletion results from the inherent difference in the value of the materials and their relative ability to be incorporated into the tight compositional specifications of aluminum alloy products (Brommer, Olivetti et al. 2012). As the recycler progressively optimizes the aluminum alloy products in the sequence, the cleanest and highest quality secondary materials are depleted and the final alloys in the sequence cannot incorporate as much recycled content as the charges optimized using the integrated method (Brommer, Olivetti et al. 2012). Figure 61 further explains this trend by plotting the percent difference between the integrated recycled fraction and the sequential recycled fraction over the sequence progression (Brommer, Olivetti et al. 2012). The effects of stock depletion are also expected to influence recycled material utilization at the recycling center, resulting in aggressive initial recycled material incorporation and limited recycled material incorporation towards the end of the sequence.

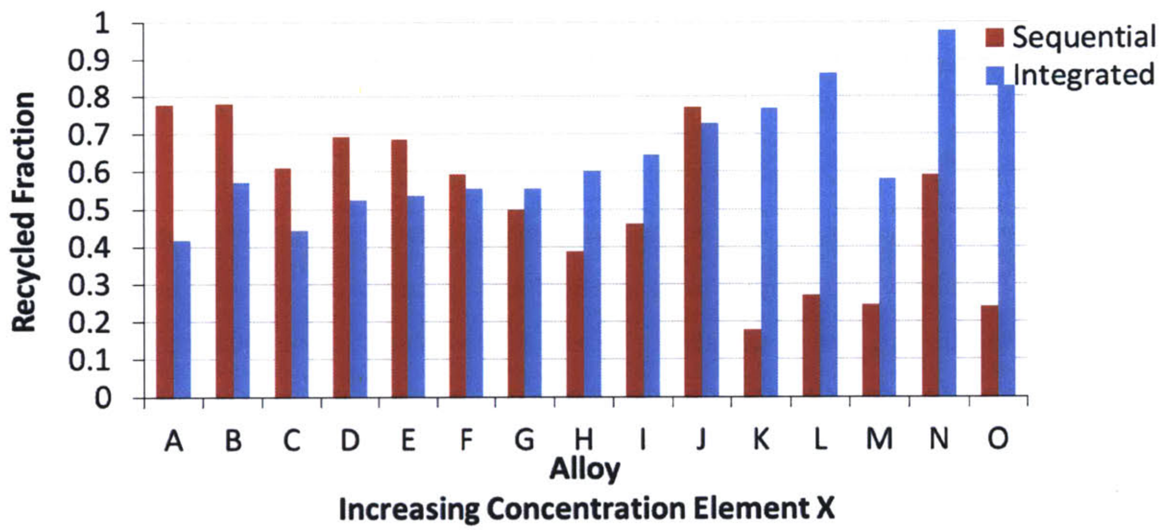

Figure 60. Stock depletion of cleaner recycled materials as aluminum alloy products are sequentially optimized (Brommer, Olivetti et al. 2012).

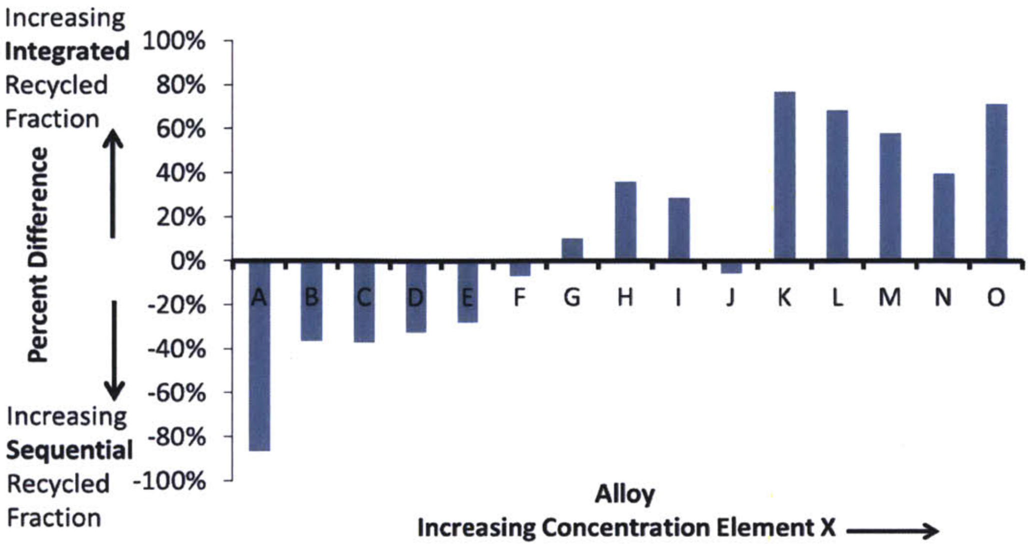

Figure 61. Percent difference between the recycled fraction incorporated into the integrated approach and the recycled fraction incorporated into the sequential approach (Brommer, Olivetti et al. 2012).

Blending models that optimize over periods shorter than the secondary material shipment frequency are subject to stock depletion because the models do not have an incentive to allocate raw materials for future charge plans because the models have no knowledge of future production plans. Since the negative effects of stock depletion in aluminum recycling operations over short time frames have been modeled and documented, this research proposes intermediate strategies to prevent stock depletion, while maintaining sufficient flexibility at the recycling center to adjust production to meet downstream remelter production variation. The intermediate strategies involve embedding varying degrees of information about long term production constraints of the recycling center into the daily model formulations which have varying degrees of flexibility. Embedding long term production information into the daily operational model formulations requires additional calculations because the aluminum recycling production plans calculated using the long term production model must be converted into daily production plans.

6.2 Daily recycling center production dynamic simulation according to the 12 design plans

The varying degrees of flexibility built into the daily recycling center operational models are aimed at incorporating the material allocation advantages of an integrated approach in aluminum recycling while providing the recycling center with the ability to react to variations in the downstream remelter production plans. Table XXV which compares the types of flexibility imbedded into the four daily operational model formulations is included again below where the models increase in flexibility from left to right. There are two approaches to calculating the recycled product compositional specifications models pursued in this research; a deterministic approach calculated by the mean historical downstream alloy production volumes and a simulation optimization approach calculated by simulating several downstream alloy production volume scenarios to calculate uncertainty aware variables that are input into the long term production optimization model. Further study of the simulation optimization method will follow in subsequent sections. The deterministic approach calculates the optimal recycling center production plan; the allocation of the recycled products for each aluminum alloy product group explicitly. The deterministic approach also explicitly calculates the optimal recipe or the relative amount of aluminum dross and post-consumed secondary material in each recycled product as included previously in Figure 32 and Figure 36. The calculated production plan and recycled material allocation across the finished alloys can be easily scaled to daily levels. The composition of each recycled product is also explicitly calculated by the long term model as seen previously in Table XIV and Table XVII.

Table XXV. Parameters Included in the Four Recycling Center Daily Operation Optimization Models

	Fixed recipe with fixed production	**Fixed recipe with fixed production**	**Flexible recipe with fixed production**	**Flexible recipe with flexible production**
Flexible production plan		X		X
Flexible secondary material allocation			X	X
Flexible specification				

The value of coordinating the recycling center production with the downstream remelter production is explored by comparing the performance of the recycling center for three cases of recycling center coordination at four levels of daily operation flexibility. A summary of the 12 recycling center production designs and the associated levels of coordination and flexibility cases are included in Table XXVI below. Three levels of coordination are examined, high coordination corresponding to nine recycled products, middle coordination corresponding to five recycled products, and low coordination corresponding to two recycled products. Producing more recycled products at the recycling center requires more coordination with the downstream production facilities because there is a greater need for the recycling center to schedule production more closely to the downstream production schedule. Since there are more recycled products at the recycling center, there is a greater likelihood that a recycled product could be required that is not presently reprocessed and ready for delivery to the downstream remelters. In order to prevent such missed opportunities for production, the recycling center must coordinate rotary furnace operation closely with the expected demands of the downstream remelters. A high degree of coordination also poses risks to the recycling center performance including the potential for a scheduling delay to cause a recycled product to be reprocessed too late to be incorporated into the downstream production. Such an event could result in lost revenue if the recycled product could not be incorporated into a subsequent alloy and had to be cast as a sow. For each level of coordination between the recycling center and the downstream facilities, four levels of flexibility are included.

Table XXVI. Table of Recycling Center Production Plan Designs Based on Downstream Production Volumes

Level of Coordination

9 Recycled Products	5 Recycled Products	2 Recycled Products
• *High coordination*	• *Middle coordination*	• *Low coordination*

Level of Daily Operational Flexibility

Fixed recipe with fixed production	Fixed recipe with flexible production	Flexible recipe with fixed production	Flexible recipe with flexible production
• *Low flexibility*	• *Mid-low flexibility*	• *Mid-high flexibility*	• *High flexibility*

The levels of flexibility are enforced by the structure of the daily model formulation using the combination of variables and fixed inputs. The four daily model formulations can be subdivided into two groups; the set of daily model formulations with fixed raw material recipes and the set of daily models with flexible raw material recipes. The daily model formulations with fixed raw material recipes are pre-pooled; the optimal allocation of recycled materials across the recycled products calculated with the long term model formulation is enforced in the daily model formulations eliminating recipe flexibility to the operators. However, in the daily model formulations with flexible raw material recipes, the model pools the recycled materials into recycled products based on the daily production of the downstream remelters and the daily availabilities of the recycled materials. Therefore, the four daily model formulations can be alternatively subdivided into two groups; the set of pre-pooled daily model formulations and the set of dynamically pooled daily model formulations. The level of flexibility within the model subgroups is increased by allowing the model to calculate the optimal daily production plan and not enforcing the production plan calculated by the long term model. The subsequent section explores the performance of the recycling center production designs calculated using deterministic downstream remelter production volumes at different levels of coordination and flexibility. The following section establishes a baseline production for a deterministic case in which downstream production is fixed at the mean values over the interval examined.

6.2.1 Deviation in recycling center recycled product allocation from the long term production model calculated by the dynamic simulation

In this section, the recycling center production plan calculated using the long term production model is compared to the recycling center production calculated using the six shipment period dynamic simulation. Differences in the calculated recycling center production are expected to result from the inability of the long term recycling center production model to explicitly incorporate the effects of downstream remelter production variation into the optimal production plan calculations. The 84 day dynamic recycling center production simulation revealed that downstream production variation decreases total liquid recycled material incorporated and causes the recycling center to deliver a different amount of each liquid recycled product than the previously calculated baseline value and the estimates using the long term production model. The effect of downstream production variation and operational factors on recycling center performance for the low coordination case is shown in Figure 62. The percent difference between the liquid recycled product weights incorporated into downstream production for the dynamic simulation and the long term model estimate for the low coordination case. below. A positive percent difference indicates that more recycled products are incorporated into downstream production in the long term model calculation. A negative percent difference indicates that the dynamic simulation incorporated more recycled material into downstream production than the long term model calculation. The first and second recycled products are incorporated less in the dynamic simulation for each of the daily operational model formulations than the predicted incorporation in the long term model formulation. The liquid recycled product incorporation for recycled product two is very similar to the predicted weight from the long term production model for the fixed raw material recipe with fixed and flexible production. The liquid recycled product incorporation for both recycled products for the fixed recipe with fixed production is very similar to the calculated weights using the long term production model. The liquid recycled product incorporation for the flexible recipe models with fixed and flexible production demonstrates the most deviation from the weights calculated with the long term production model.

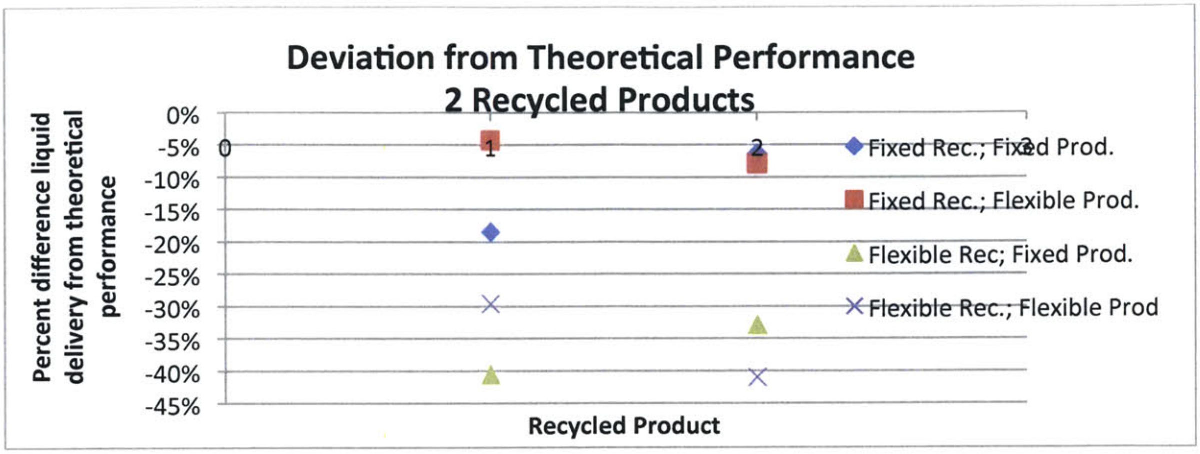

Figure 62. The percent difference between the liquid recycled product weights incorporated into downstream production for the dynamic simulation and the long term model estimate for the low coordination case.

The deviation in the recycling center production for the medium coordination case from the optimal production plan calculated with the long term production model is included in Figure 63. The percent difference between the liquid recycled product weight incorporated into downstream production for the dynamic simulation and the long term estimate for the middle coordination case. below. Comparing Figure 62 with Figure 63 reveals that increasing the coordination between the recycling center and the downstream remelting facilities increases the overall deviation in the amount of liquid metal incorporated in the dynamic simulation from the amount calculated by the long term model. The least flexible daily model formulations, the fixed recipe with fixed and flexible production incorporate less liquid into the downstream production of each recycled product than the weight predicted by the long term production model because the total volumes of the recycled products incorporated into the downstream production by the long term production model serve as the upper availability limits. However, the total amount of liquid recycled product one produced in the flexible recipe with fixed and flexible production model formulation during the dynamic simulation exceeds the amount allocated by the long term production model. The amount of recycling product four incorporated as liquid during the dynamic simulation for the flexible recipe with flexible production model formulation is less than the amount estimated by the long term model by 160%. The results of the dynamic simulation for the medium coordination case demonstrate that daily operational factors and variation in the downstream remelter production can cause significant deviations from the estimated recycling center production and such deviation is particularly large in the flexible recipe model formulations.

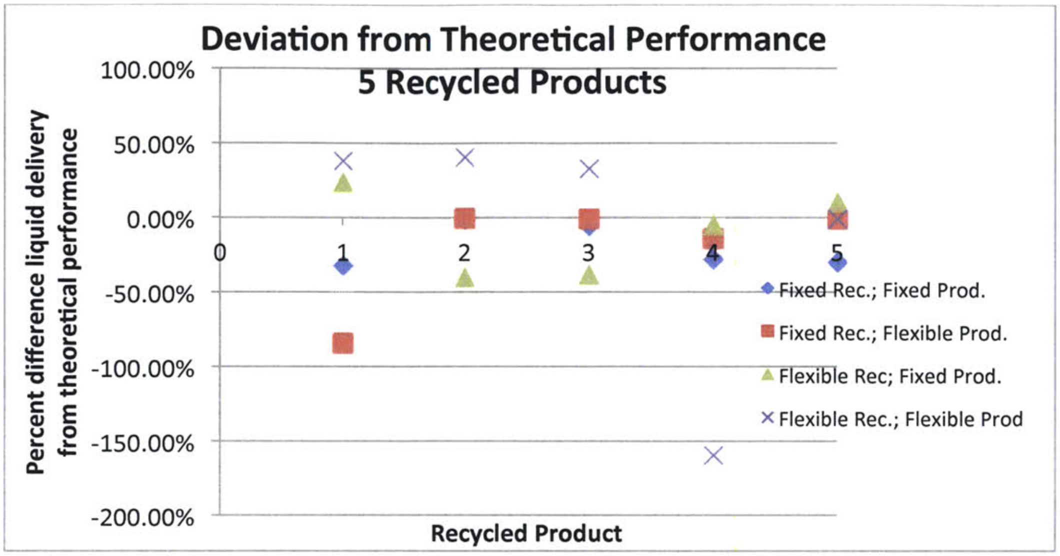

Figure 63. The percent difference between the liquid recycled product weight incorporated into downstream production for the dynamic simulation and the long term estimate for the middle coordination case.

The deviation from theoretical performance of the high coordination case is more pronounced than the middle and low coordination cases, as can be seen by comparing Figure 61, Figure 63, and Figure 64. The overall increase in the deviation from the theoretical liquid delivery values with increasing coordination between the recycling center and the downstream remelting facilities, results from the challenge of enforcing the optimal recycling center production plan calculated by the long term model over a greater number of recycled products. Although in the high coordination case, the recycled products are tailored for specific alloy products, substitution opportunities exist and downstream variation can promote such opportunities. Recycled product substitution causes significant deviation from the theoretical recycling center performance because the recycled product allocation across the alloy products is not as rigidly enforced. The flexible recipe with fixed and flexible production model formulations produced more of certain recycled products than the long term model estimation because of opportunities for recycled product substitution resulting from downstream demand variation and daily operational constraints. For example, the flexible recipe with fixed production formulation produced 94% more recycled product one and 75% more recycled product nine than the estimated volumes predicted by the long term production model. The significant deviation from the theoretical performance estimated by the long term production model caused by downstream production variation and daily operational factors for the high coordination case supports that quantifying the optimal level of flexibility to provide daily operators at the recycling center to modify charges to meet downstream production variation is essential to optimizing the performance of the recycling center.

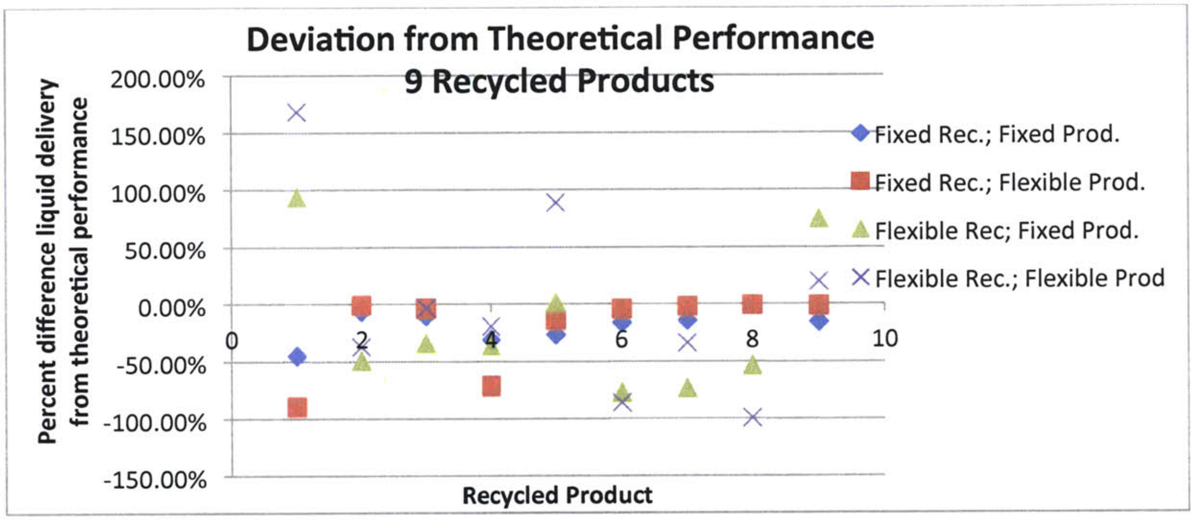

Figure 64. The percent difference between the liquid recycled product incorporated into downstream production for the dynamic simulation and the long term estimate for the high coordination case.

6.2.2 Recycling center production design performance at varying levels of coordination and flexibility

A dynamic simulation of the optimal recycling center production in response to the 84 day historical downstream remelter production is performed to evaluate the performance of the 12 proposed recycling center production designs. The performance of the low coordination case across the flexibility levels is included in Figure 65 and Table XXVII below. The negative effect downstream production variation and daily operational factors has on performance can be confirmed by the significant amount of theoretical stocks for each recycled product which indicates the difference between the long term production model's liquid weight incorporation and the liquid weight incorporated in the dynamic simulation.

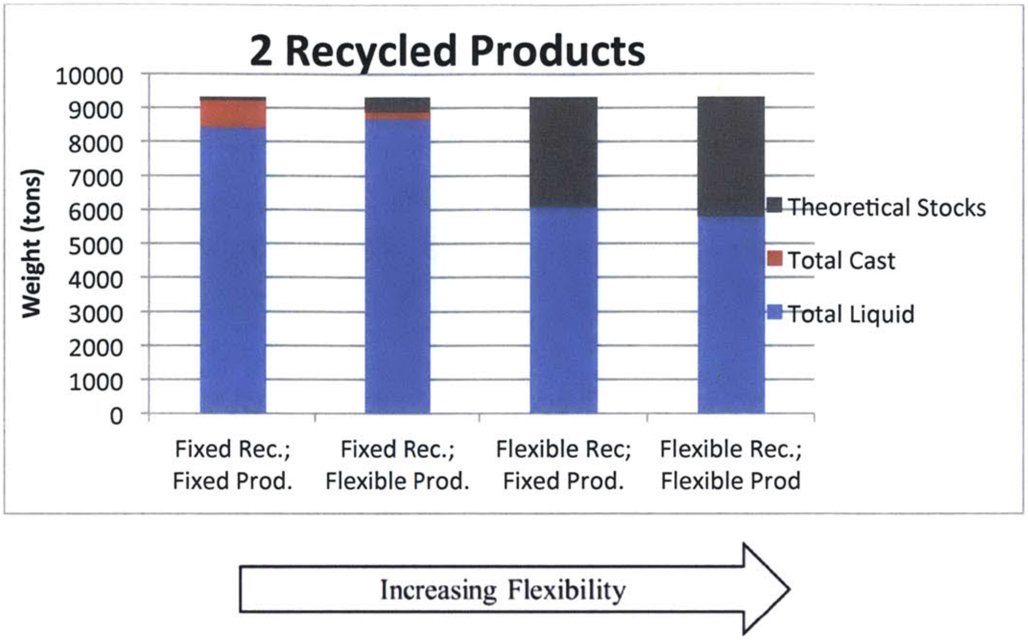

Figure 65. Low coordination case performance across different levels of flexibility.

Table XXVII. Low Coordination Case Performance Including Cast Weight, Liquid Weight Incorporated, Theoretical Stock Weight, and the Percent Difference with the Long Term Model.

	Total Cast (tons)	Total Liquid (tons)	Theoretical Stocks (tons)	Percent Difference to Theoretical
Fixed recipe with fixed production	797.8	8430.5	103.6	-9.66%
Fixed recipe with flexible production	204.2	8686.0	441.7	-6.92%
Flexible recipe with fixed production	6.4	6065.8	3259.7	-35.00%
Flexible recipe with flexible production	6.2	5795.2	3530.5	-37.90%

The cast recycled material weight included in red on Figure 65 also indicates performance limitations because this material was produced by the recycling center but unable to be incorporated into the downstream alloy production. The generation of cast sow material is minimized by a penalty term in the objective function of all four of the daily operation models. Despite the penalty coefficient, sow generation can be determined favorably by a model formulation when it is accompanied by a significant amount of incorporated liquid content. The cast sow weight is largest for the fixed recipe with fixed production model formulation because there is the least flexibility in this model formulation because of the fixed production plan and the pre-pooled recycled materials. Thus, the fixed recipe with fixed production model formulation is the least able to adjust its production to minimize sow generation that results from downstream production variation. The recycled product production plan is calculated by an independent algorithm that prioritizes enforcing the long term production plan. For the case of low coordination, the maximum liquid metal incorporated corresponded to the fixed recipe with flexible production model formulation which incorporated 8,686 tons of liquid recycled products into the downstream production. By embedding knowledge of the optimal recycled material allocation across the downstream alloys and recycled material compositional specifications calculated using the long term production model while providing flexibility to adjust recycling center production to meet downstream production variation, the fixed recipe model with flexible production incorporated more liquid recycled products into the downstream production. The flexible recipe with flexible production is the worst performing model formulation for the low coordination case incorporating only 5,795 tons of liquid recycled material into downstream production. The poor performance of the most flexible daily operation model results from the inability of this model formulation to allocate recycled material for later production causing stock depletion and the inability to blend recycled materials to meet recycled product specifications later on in the shipment period. The percent differences between the theoretical liquid metal incorporated by the long term production model and the liquid metal incorporated by the dynamic simulation are significantly larger for the flexible recipe model formulations than the fixed recipe model formulations. This effect suggests that providing more daily operational flexibility can manifest more deviation from the theoretical performance of the recycling center.

To evaluate the robustness of the hypothesis that the fixed recipe model with flexible production incorporates the most liquid recycled product into downstream production during the 84 day dynamic simulation, the performance of each daily operational model formulation is compared for two shipment period sub-intervals. The total liquid weight incorporated and the total recycled product cast in each sub-interval is included in Figure 66 and Figure 67 respectively. Figure 66 demonstrates that pre-pooling the recycled materials generates production plans that are better able to incorporate liquid recycled products into downstream remelter production in each of the three sub intervals. The flexible recipe with fixed production model formulation incorporates more liquid recycled product into downstream production for each sub-interval than the flexible recipe with flexible production model formulation. The fixed recipe with flexible production model formulation incorporates more liquid recycled product into the downstream production than the other model formulations for every sub-interval except for the third. However, the performance of the fixed recipe with fixed production requires casting more recycled products as sows than the other daily operational model formulations as demonstrated in Figure 67. Customers exist for the cast sows but the selling price of these materials is significantly less than the liquid value. Additionally, managing casting operations during liquid recycled product production and delivery presents significant operational challenges that also have associated costs. As a result, the value of the recycling center production plan calculated using the fixed recipe with fixed production must be assessed not only based on the liquid recycled product incorporation but also the significant weight of cast sows. As a result, for the low coordination case, the optimal performance is achieved with the fixed recipe with flexible production model formulation.

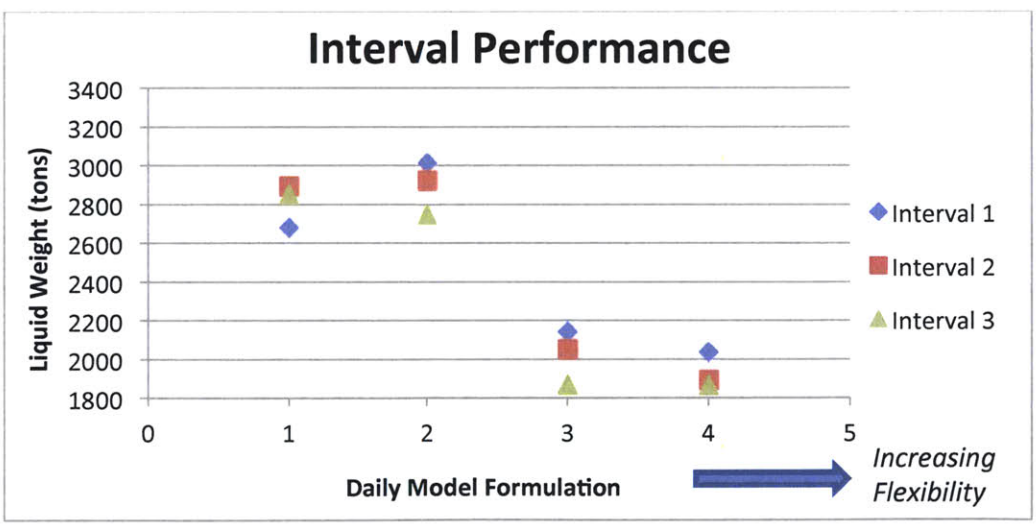

Figure 66. Robustness of the performance of the four daily model formulations across the three sub-intervals in the dynamic production simulation for the low coordination case.

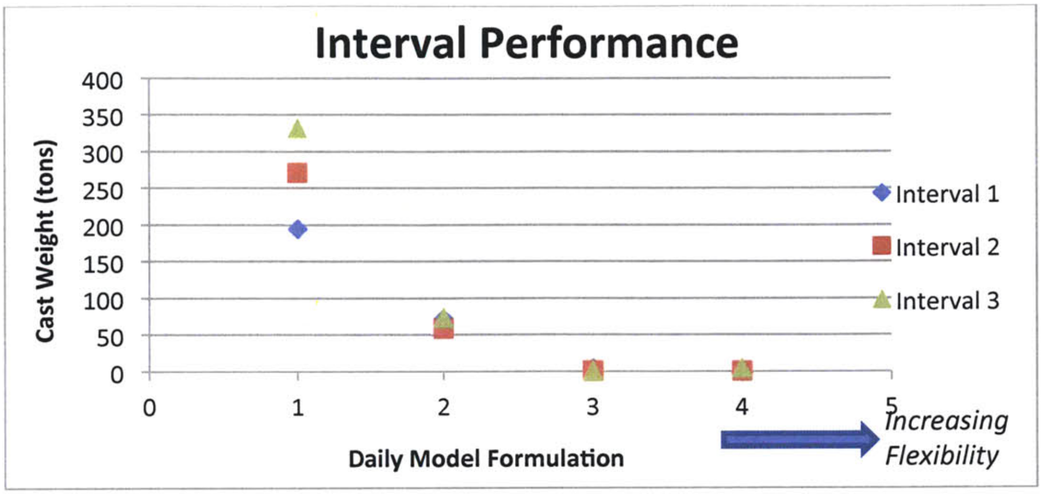

Figure 67. Comparison of the cast weight resulting from each daily model formulation across the three sub-intervals in the dynamic production simulation for the low coordination case.

The performance difference between the flexible recipe model formulations can be explained by comparing the calculated daily recycling center production. The number of charges produced each day for the first shipment period in the flexible recipe daily model formulations is included in Figure 68 below. One of the biggest differences between the rotary furnace operation is the more conservative production of recycled product one initially by the fixed production model formulation which allows it to continue to produce recycled product one when the flexible production model no longer can towards the end of the shipment period. One example of the flexible production model more aggressively producing the first recycled product occurs on the second day when the flexible production model produced three charges of recycled product one while the fixed production model does not produce any. The improved recycled material management achieved by fixing production based calculations from the long term model causes the flexible recipe with fixed production model to outperform the flexible production model for the low coordination case.

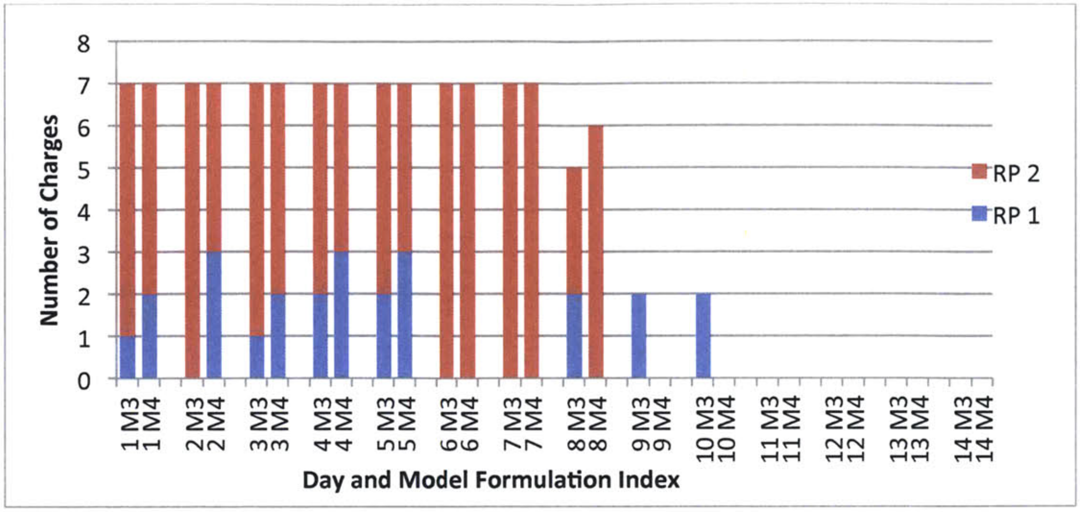

Figure 68. Comparison between the recycling center production plans between the flexible recipe with fixed and flexible production model formulations for the low coordination case.

Increasing the degree of coordination between the recycling center and the downstream remelting facilities from low to medium increases the total liquid recycled product incorporated into downstream production across the flexibility levels. The results of the middle coordination case are included in Figure 69 and Table XXVIII below. Several of the previous observations for the low coordination case remain valid when the degree of coordination is increased. For example, the largest cast sow weight is generated by the fixed recipe with fixed production daily operational model formulation. Additionally, the most liquid recycled product, 9,551 tons is incorporated into the fixed recipe with flexible production daily operational model formulation. One difference between the low coordination and middle coordination case results is that increasing the degree of coordination between the recycling center and downstream remelting facilities causes the flexible recipe model formulation with flexible production to incorporate more liquid recycled material than the flexible recipe model formulation with fixed production; 8,711 tons vs. 8,233 tons. Increasing the level of coordination between the recycling center and the downstream remelting facilities increases the percent difference between the theoretical liquid metal weight incorporated by the long term production model and the liquid metal weight incorporated by the dynamic simulation for the fixed recipe models. However, increasing the level of coordination between the recycling center and the downstream remelting facilities decreases the percent difference between the theoretical liquid metal weight incorporated by the long term production model and the liquid metal weight incorporated by the dynamic simulation for the flexible recipe models. This effect suggests that increasing the number of recycled products can mitigate some of the negative impacts on performance of extreme daily operational flexibility.

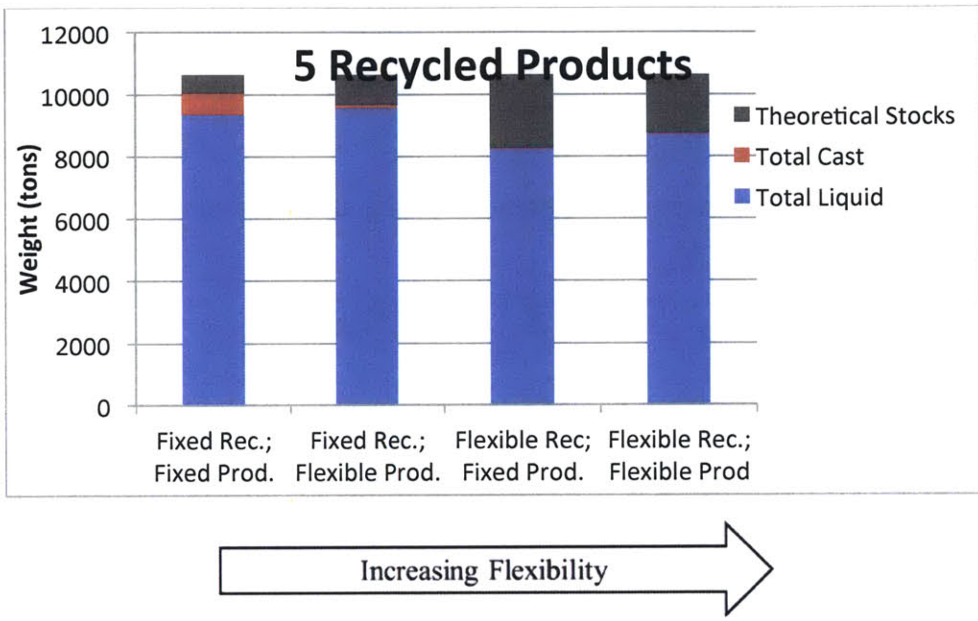

Figure 69. Medium coordination case performance across flexibility levels corresponding to the four daily operational model formulations.

Table XXVIII. Middle Coordination Case Performance Including Cast Weight, Liquid Weight Incorporated, Theoretical Stock Weight, and the Percent Difference with the Long Term Production Model.

	Total Cast (tons)	Total Liquid (tons)	Theoretical Stocks (tons)	Percent Difference to Theoretical
Fixed recipe with fixed production	664.8	9356.1	608.9	-11.98%
Fixed recipe with flexible production	119.9	9550.7	959.2	-10.15%
Flexible recipe with fixed production	26.9	8232.6	2370.3	-22.55%
Flexible recipe with flexible production	24.9	8710.6	1894.4	-18.06%

The robustness of the performance observations for the different daily operational model formulations with varying levels of flexibility is evaluated by comparing the performance across three sub-intervals corresponding to two shipment periods. The total liquid weight incorporated by each daily operational model formulation for each sub-interval is included in Figure 70 and the corresponding weight of cast sow is included in Figure 71. The fixed recipe with flexible production incorporates more liquid recycled product that the other daily operational model formulations for every sub-interval with the exception of the second interval in which the fixed recipe with fixed production incorporates 3,244 tons of liquid recycled product compared to 3,240 tons in the flexible production case. The large cast recycled product weight associated with the fixed recipe with flexible production operational model formulation is reaffirmed in Figure 71. The flexible recipe with flexible production incorporated more liquid metal than the fixed production counterpart for every sub-interval in the dynamic simulation.

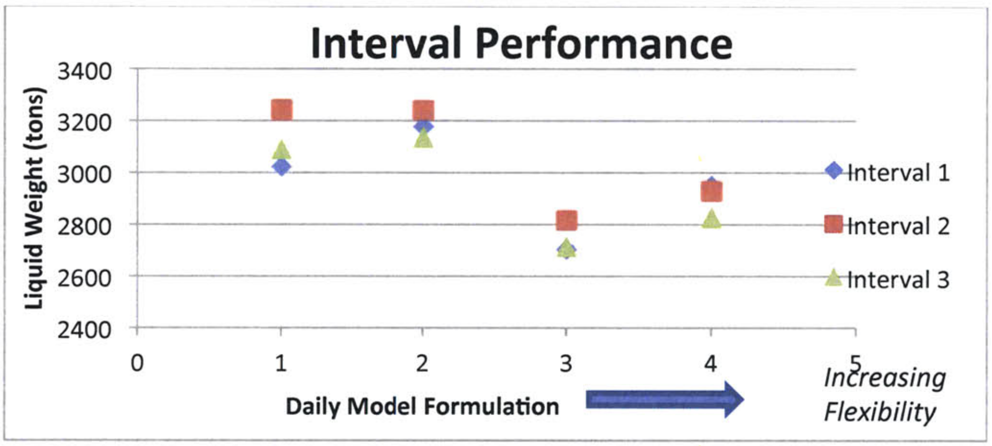

Figure 70. Robustness of middle coordination results determined by dividing the dynamic simulation into three sub-intervals.

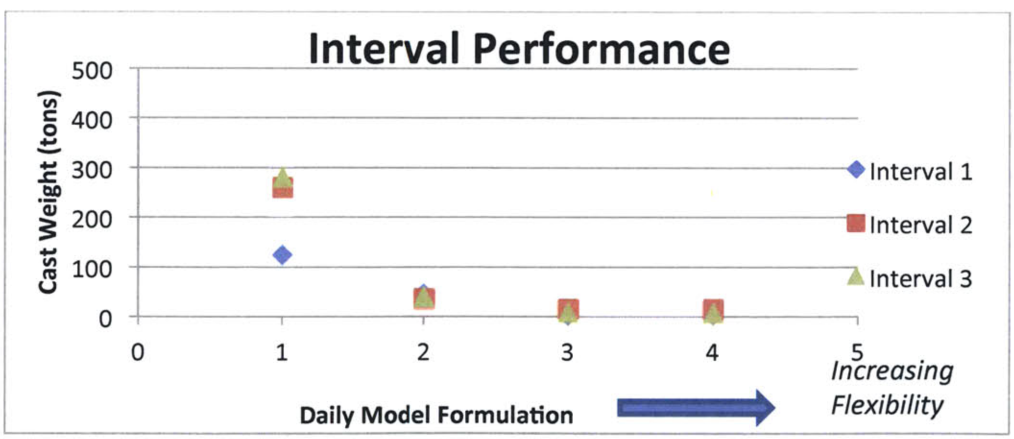

Figure 71. Robustness of the middle coordination results determined by dividing the dynamic simulation into three sub-intervals.

The difference in the ability of the fixed recipe with flexible production and the flexible recipe daily operational models to incorporate liquid recycled products into the downstream remelter production can be explained by comparing the rotary furnace production in the middle coordination case. Figure 72 compares the number of rotary furnace charges produced for the middle coordination case with the fixed recipe with flexible production model formulation and the flexible recipe with fixed and flexible production model formulations for two shipment periods. Figure 72 supports that fixed recipe with flexible production can incorporate more liquid recycled product into the downstream remelter production because of the more uniform rotary furnace operation across the two shipment period. The flexible recipe daily model formulations are particularly susceptible to stock depletion as indicated by the inability of these model formulations to maximize rotary furnace production towards the end of the shipment period. The flexible recipe model formulations have more flexibility to selectively deplete certain recycled materials that have particularly favorable compositional specifications which can maximize the incorporation of liquid recycled products. This flexibility can maximize liquid recycled product incorporation and minimize sows initially but makes meeting recycled product compositional specifications more challenging later in the shipment period as material availability decreases. In this particular two shipment period, it appears that stock depletion limits the performance of the flexible recipe model formulation with fixed production more than the flexible production model formulation.

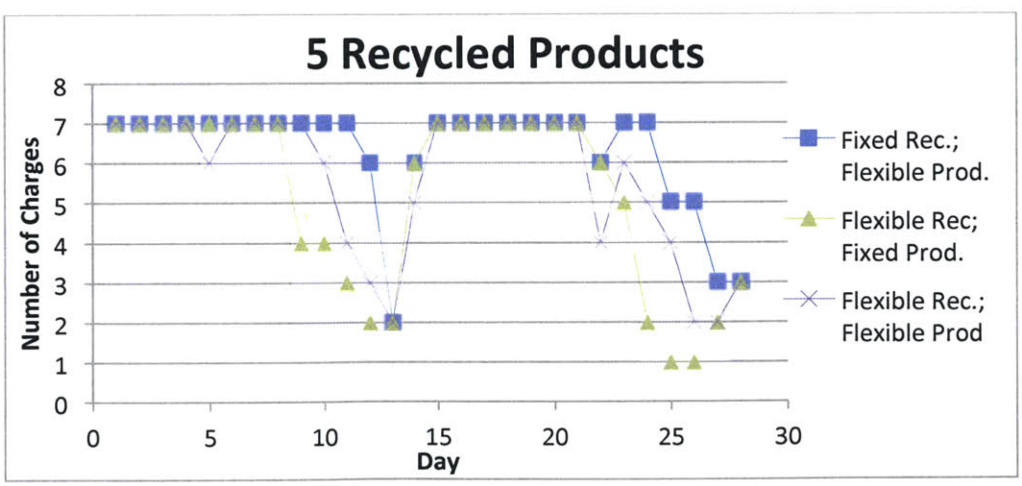

Figure 72. Number of rotary furnace charges across the two shipment interval for the fixed recipe with flexible production model formulation and the flexible recipe production model formulation with fixed and flexible production.

The difference in liquid recycled product incorporation between the two flexible production model formulations can be explored by comparing the number of charges of each recycled product calculated to be produced by the model formulations for a sub-interval of the dynamic simulation. Figure 73 shows the optimal recycling center production plan calculated using the flexible recipe with fixed and flexible production model formulations for the first shipment period in the dynamic simulation. Although the flexible recipe with flexible production does not have any embedded knowledge of the optimal long term allocation of recycled products across finished alloys, the calculated production plans are quite similar. For example, the second day recycling center production plan is identical for both model formulations. Figure 73 indicates that there are many opportunities for recycled product substitution in the middle coordination case. Recycled product substitutions that can be seen in Figure 73 include, recycled product four and recycled product three, recycled product five with recycled product three, and recycled product one with recycled product four. In the previously examined low coordination case, opportunities for recycled product substitution were more abundant because the compositional specifications of the recycled products were more similar. In the case of middle coordination, the compositional specifications of the recycled products are more distinct and more customized to particular alloys although similarities remain. In the flexible recipe, fixing the optimal production plan calculated using the long term model without limiting stock depletion of certain recycled materials limits the ability of this formulation to incorporate liquid recycled products into downstream production. The increased flexibility of the flexible recipe with flexible production model delivers improved performance because this formulation is better able to modify production according to demand variation.

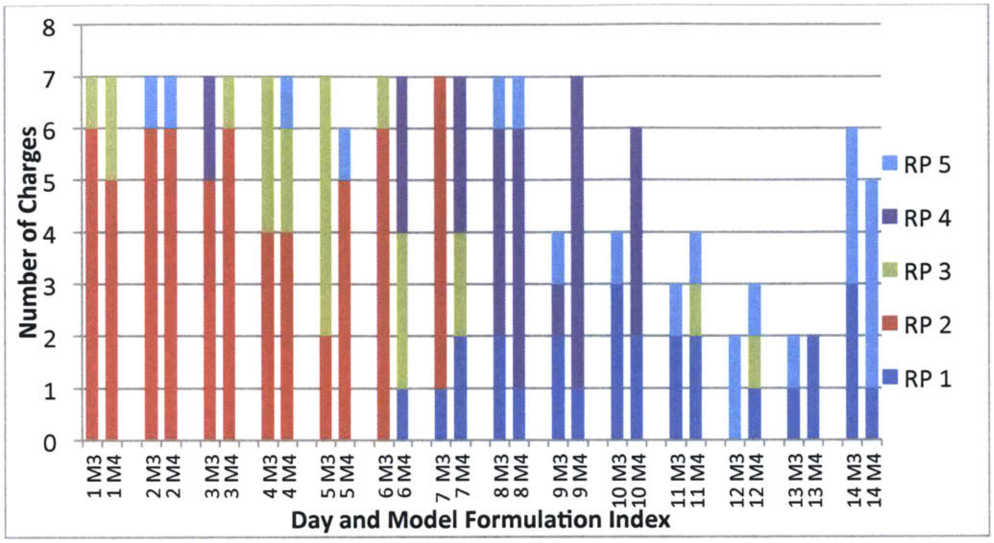

Figure 73. Comparison of calculated rotary furnace operation by the flexible production with fixed and flexible production model formulations for the first shipment period.

The performance of the highest degree of coordination between the recycling center and the downstream remelting facilities for the four daily operational models at different levels of flexibility is included in Figure 74 and Table XXIX below. As in the low and middle coordination cases, the fixed recipe with flexible production also incorporates the most liquid recycled material during the 84 day dynamic simulation, 9,596 tons. Unlike in the middle coordination case, increasing the level of coordination between the recycling center and downstream remelting facilities caused the flexible recipe with fixed production model formulation to incorporate more liquid recycled product than the flexible production model formulation; 7,734 tons vs.7,608 tons. As determined in the middle coordination case, increasing the level of coordination between the recycling center and the downstream remelting facilities increases the percent difference between the theoretical liquid recycled product weight incorporated by the long term production model and the liquid metal recycled product weight incorporated by the dynamic simulation for the fixed recipe models. Increasing the level of coordination between the recycling center and the downstream remelting facilities from the middle coordination case to the high coordination case increases the percent difference between the theoretical liquid recycled product weight incorporated by the long term production model and the liquid product weight incorporated by the dynamic simulation for the flexible recipe models.

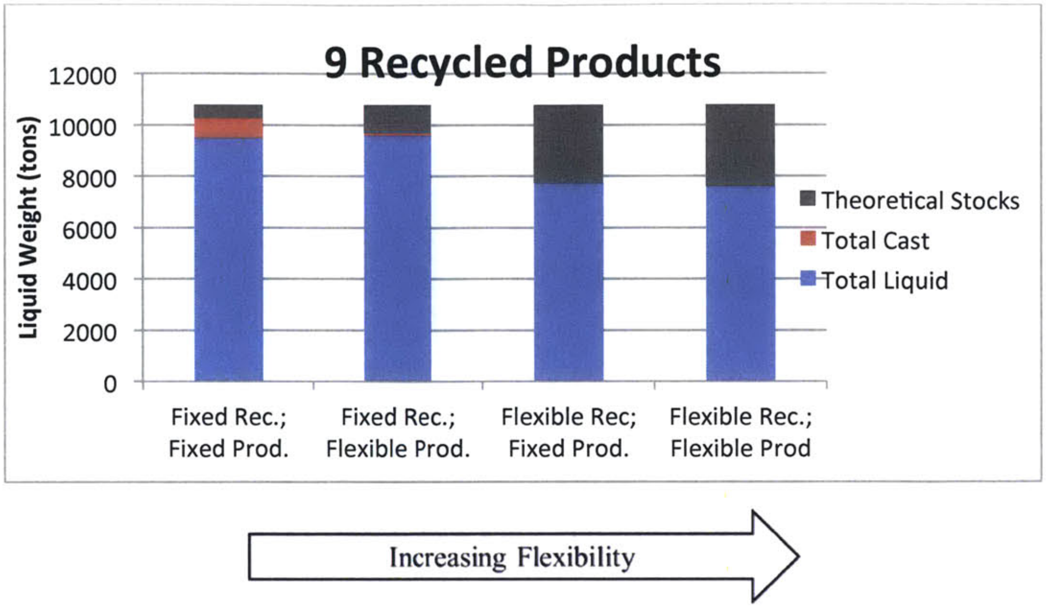

Figure 74. High coordination case performance across the different flexibility levels corresponding to the four daily operational model formulations.

Table XXIX. High Coordination Case Performance Including Cast Weight, Liquid Weight Incorporated, Theoretical Stock Weight, and the Percent Difference with the Long Term Model.

	Total Cast (tons)	Total Liquid (tons)	Theoretical Stocks (tons)	Percent Difference
Fixed recipe with fixed production	759.1	9500.7	543.0	-12.05%
Fixed recipe with flexible production	97.5	9596.1	1109.1	-11.17%
Flexible recipe with fixed production	1.7	7734.0	3067.0	-28.41%
Flexible recipe with flexible production	1.8	7607.5	3193.4	-29.58%

The performance of the high coordination case is evaluated for three sub-intervals within the 84 day dynamic simulation to ensure the robustness of the conclusions regarding the optimal level of flexibility. The liquid recycled product incorporated weight and the cast sow weight across the flexibility levels are included in Figure 75 and Figure 76 respectively. As observed previously in the low and middle coordination cases, the pre-pooled model formulations incorporate more liquid recycled product into downstream remelter production. The fixed recipe with flexible production incorporates more liquid recycled product into downstream production for each sub-interval with the exception of the third interval. Although the fixed recipe with fixed production is able to incorporate more liquid recycled product for this particular sub-interval it has higher associated cast sow weight. As identified previously, the more flexible model formulations are able to better adjust recycling center production to minimize cast sow weight.

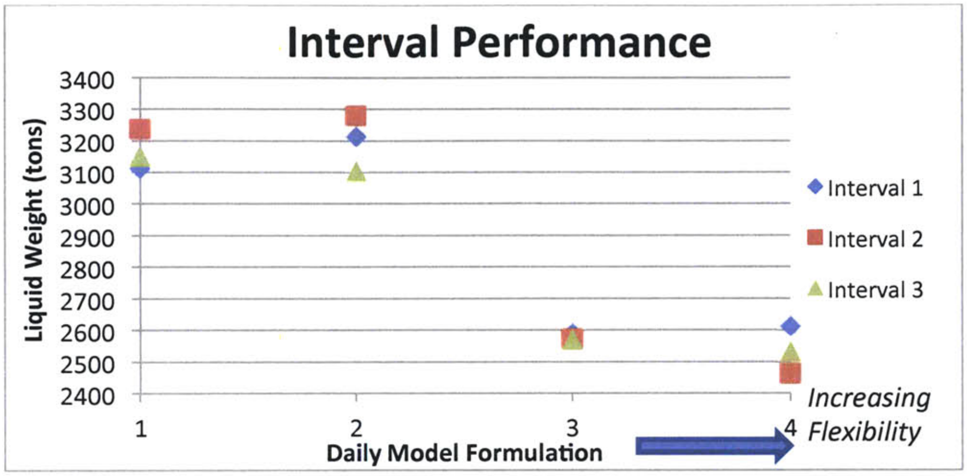

Figure 75. Recycled product liquid weight incorporated into downstream production for each daily operational model formulation in the case of high coordination in each two shipment period interval during the dynamic simulation.

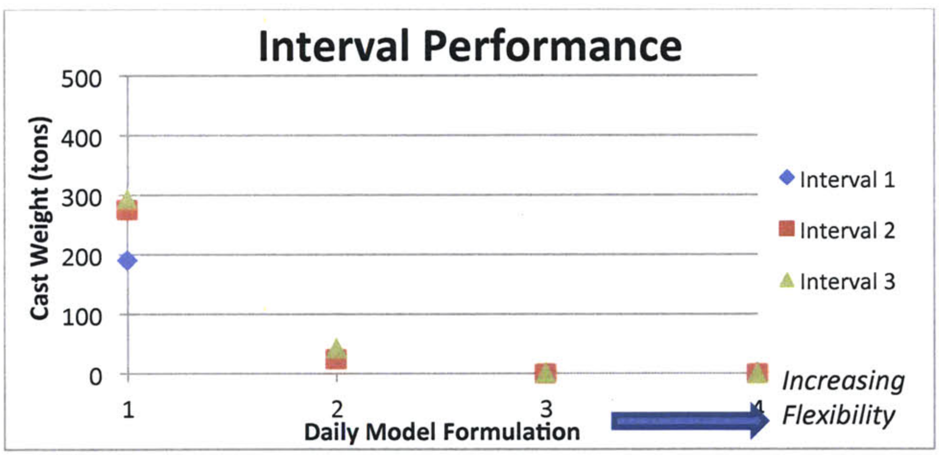

Figure 76. Recycled material cast weight resulting from each daily operational model formulation in the case of high coordination in each two shipment period interval during the dynamic simulation.

The performance difference between the flexible recipe models can be better understood by examining the rotary furnace production for the first shipment period in the dynamic simulation in the high coordination case as included in Figure 77. The recycling center production calculated using the flexible production model formulation demonstrates many differences from the fixed production counterpart. Increasing the number of recycled products produced at the recycling center increases the customization of the recycled products for particular finished alloys. In the case of flexible production, the model searches for a recycling center production plan that minimizes both sow creation and the need to use alloying elements in downstream remelter production. As a result of this objective function formulation, the model does not perceive any benefit to adding recycled materials that exceed the minimum compositional specifications of the alloy products unless sow generation is minimized as a result. Thus, although each recycled product may have been designed to match the compositional specifications of a particular finished alloy, overlap between the compositional specifications promotes material substitution that deviates from the preferred allocation. The flexible recipe with fixed production model formulation outperforms the flexible recipe with flexible production model formulation because it is able to find combinations of recycled materials that can meet recycled product specifications and incorporate into downstream remelter production.

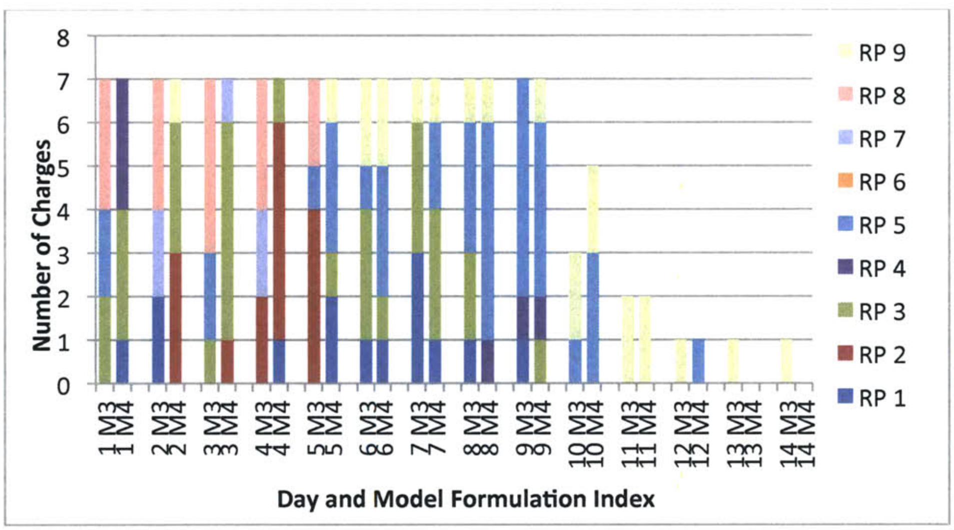

Figure 77. Stock depletion in the high coordination case over the first two weeks of production.

To inform the optimal production plan design of the recycling center, the performance of 12 recycling center designs were evaluated. A color coated diagram comparing the liquid recycled product weight incorporated into downstream production for each recycling center design is included in Figure 78. Pre-pooling the recycled materials improves recycling center performance because the total liquid recycled weight incorporated into downstream production by these model formulations is larger than the total liquid recycled weight incorporated into downstream production by the flexible recipe daily operational model formulations. Examining the portion of the figure with fixed recycled product recipe indicates that increasing the degree of coordination between the recycling center and the downstream remelting facilities increases the total liquid recycled product weight incorporated into downstream remelter production. Increasing operational flexibility within the fixed recipe optimization models increases the total liquid recycled product incorporated. This effect suggests that providing operational flexibility to respond to variation in downstream remelter production improves performance when the recycled materials are pre-pooled according to the long term model formulation.

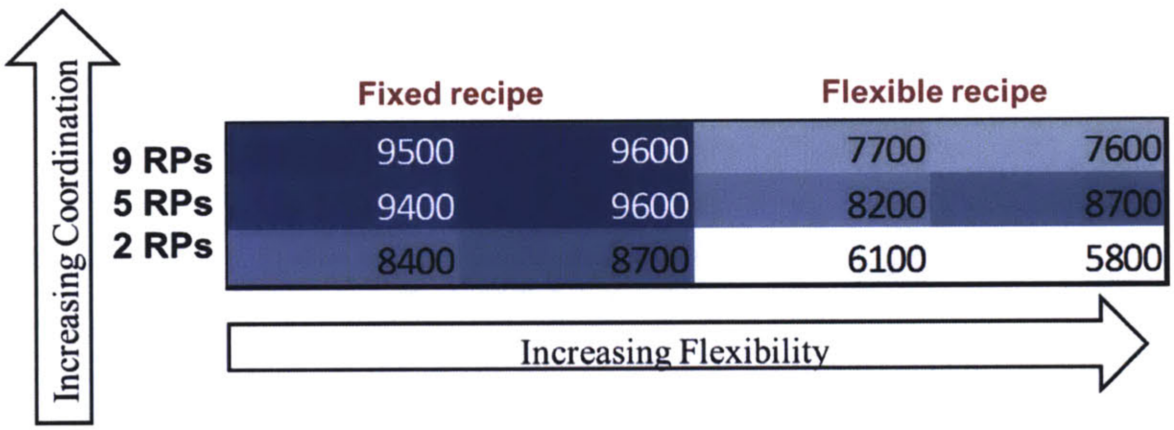

Figure 78. Color mapping of the performance in terms of total liquid recycled products incorporated into production of the twelve recycling center production plan designs.

The relationship between recycling center performance, coordination, and flexibility is less straightforward when the recycled product recipe is flexible. When the recycled product recipe is flexible, the optimal liquid recycled product weight incorporated into downstream production corresponds to the middle coordination case. Increasing the level of coordination beyond five recycled products actually decreases the ability of the recycling center to incorporate liquid recycled products into downstream production. Additionally, increasing the level of operational flexibility for the flexible recipe model formulations decreases the incorporated liquid recycled product weight for the low and high coordination cases but increases the incorporated liquid recycled product weight for the middle coordination case. Previous plots on the calculated rotary furnace operation at the recycling center revealed that the flexible recipe model formulations are particularly susceptible to stock depletion because of the added flexibility of these model formulations allow the model to selectively deplete certain recycled materials with particularly favorable compositions. In the low and high coordination cases, increasing the level of flexibility makes the effects of stock depletion more pronounced and the model is unable to find combinations of recycled materials that can meet the recycled product specifications. In the case of two recycled products, the compositional specifications are very similar and opportunities for substituting the recycled products are abundant. In the case of nine recycled products, the compositional specifications are more diverse and without enforcing the recycled product volumes calculated by the long term production model the daily operational model is unable to maintain proper production levels of recycled products. The middle coordination case represents a balance of recycled products that are intended to be incorporated into multiple finished alloys and recycled products that are customized for specific finished alloys. As a result, the flexible production case is able to resolve a balanced allocation of recycled products across the finished alloys while maintaining sufficient flexibility to respond to downstream production variation. The performance difference between the middle and high coordination cases can be further resolved by comparing the average silicon composition in the recycled products.

Previous sections explored the challenge of incorporating recycled materials into downstream production because of the compositional mismatch between the recycled materials and the specifications of the finished alloy products. The high silicon composition of the recycled materials is particularly limiting to increasing recycled material incorporation. One metric to distinguish the middle coordination and high coordination performance in the flexible recipe model formulations the silicon composition in the total recycled product weight. Since the system is characterized by having a surplus of silicon, the model formulation that delivers the most silicon to the downstream remelting facilities should perform best over time. Figure 79 and Figure 80 show the silicon composition in the recycled products over time for the middle coordination and high coordination cases respectively. In the middle coordination case, it appears the flexible production model formulation incorporates more silicon content on average than the fixed production model formulation. However, in the high coordination case, it appears the fixed production model formulation incorporates more silicon content on average than the flexible production model formulation. The ability to incorporate more silicon in the recycled products may explain the improved performance of the flexible production model formulation in the middle coordination case and the improved performance of the fixed production model formulation in the high coordination case.

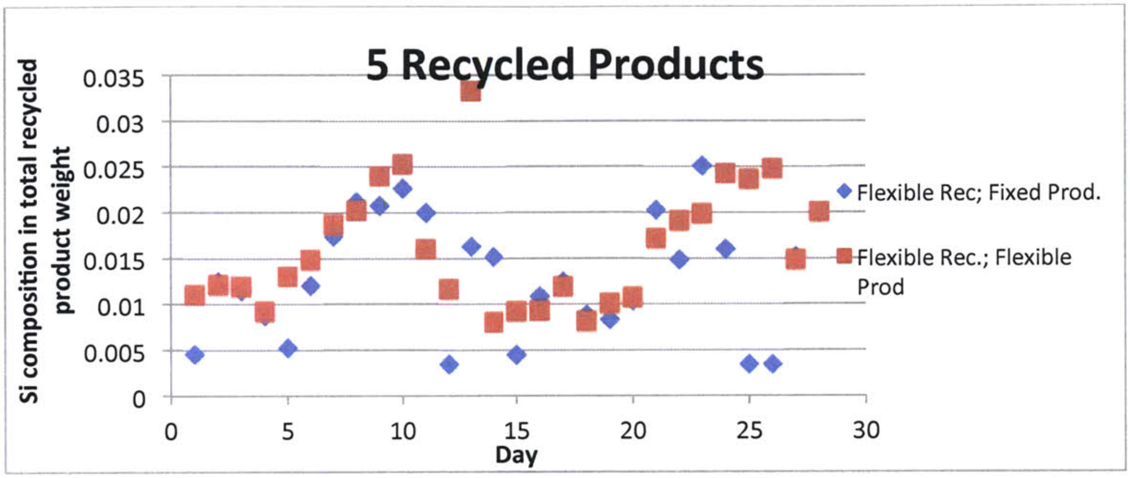

Figure 79. Silicon composition in the total weight of liquid recycled products for the middle coordination case across the first two shipment periods.

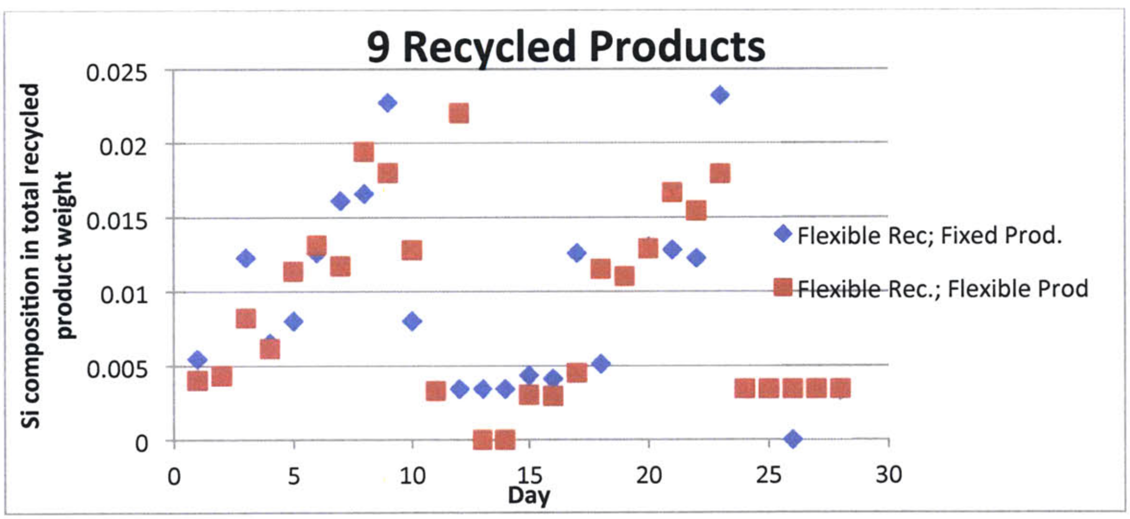

Figure 80. Silicon composition in the total weight of liquid recycled products for the high coordination case across the first two shipment periods.

Comparing the performance of each of the twelve recycling center production designs revealed that the fixed recipe with flexible production outperforms the other daily operation model formulations for each level of coordination. The optimal performance of the low, middle, and high coordination case is included in Figure 81 and the optimal performance for each sub-interval is included in Figure 82. Increasing the coordination between the recycling center and the downstream remelting facilities increases the total liquid weight incorporated into downstream remelter production. However, the increase in the amount of liquid weight incorporated when moving from low coordination to middle coordination is larger than the increase when moving from middle coordination to high coordination. The amount of liquid recycled product incorporated into downstream production by the middle coordination case is similar to the high coordination case as supported by Figure 82 which shows that for the third interval the middle coordination case was able to incorporate more liquid recycled product into downstream production than the high coordination case.

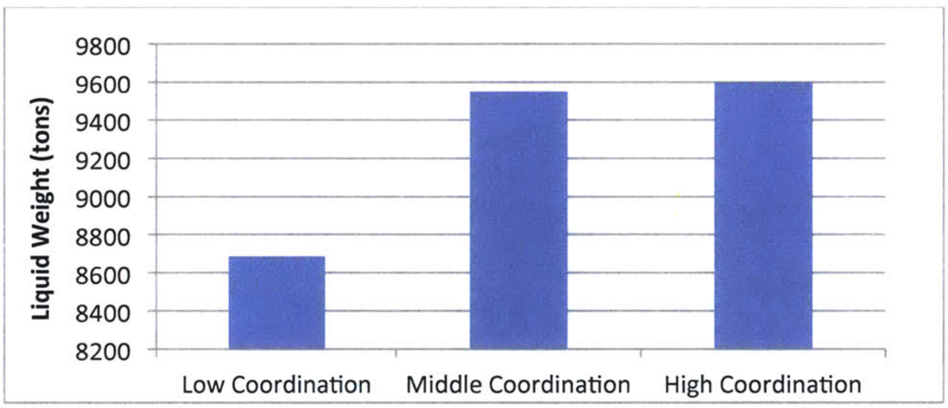

Figure 81.Comparison of the optimal performance obtained with each level of coordination.

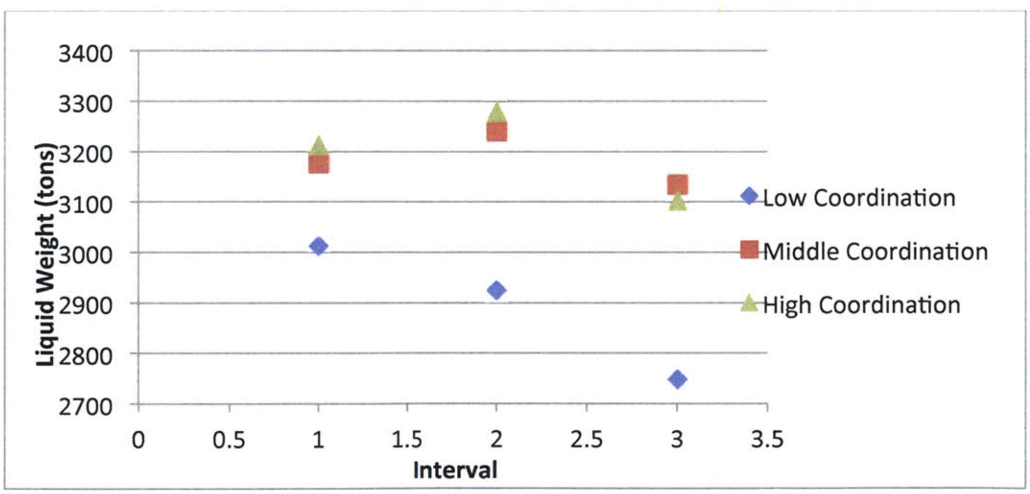

Figure 82. Robustness of the performance of the fixed recipe with flexible production model formulation at each level of coordination, low, middle, and high.

Resilience to recycled product stock depletion is one of the advantages of the fixed recipe with flexible production model formulation. The liquid recycled product weight incorporated across the first two shipment periods is shown in Figure 83 below. An analogous plot showing the total number of rotary furnace charges at the recycling center for the same period is included in Figure 84 below. Material yield effects introduce volatility into Figure 83 that is removed by converting the liquid weight into an equivalent number of charges. The recycled product with flexible production model formulation is able to produce some volume of liquid recycled product weight into downstream production for every day during the first two shipment periods. The middle and high coordination cases are particularly robust to stock depletion towards the end of the shipment period.

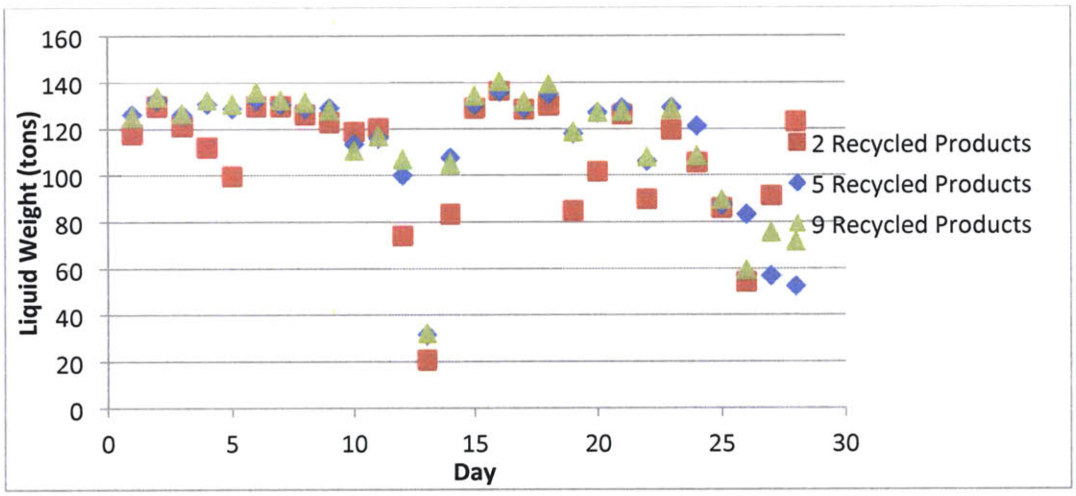

Figure 83. Liquid weight produced at the recycling center and incorporated into the downstream remelter production through two shipment periods for the fixed recipe with flexible production model formulations at low, medium, and high levels of coordination.

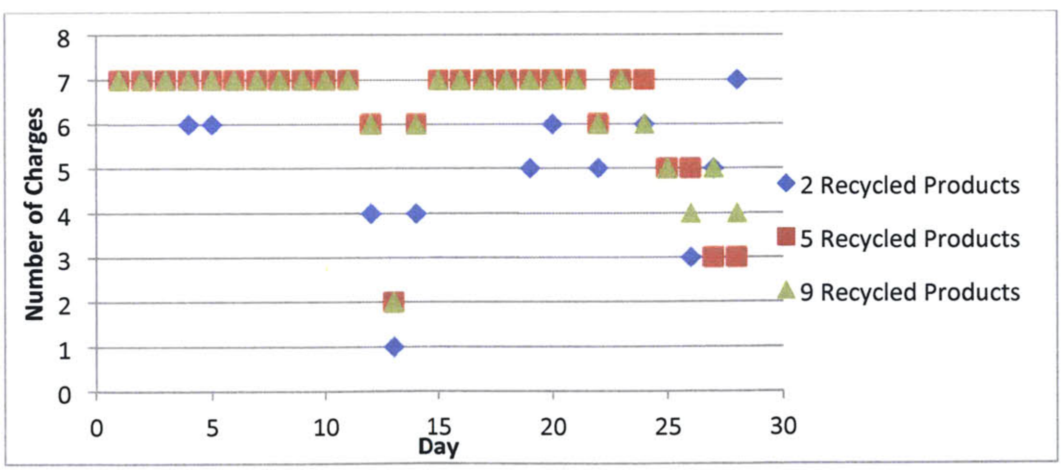

Figure 84. Number of charges produced at the recycling center through two shipment periods for the fixed recipe with flexible production model formulations at low, medium, and high levels of coordination.

6.2.3 Recycling center production design performance at varying levels of coordination and flexibility calculated using simulated downstream production volumes

The recycling center production design recommendations given previously were determined using historical production volumes at the downstream remelters. The robustness of the previous recommendations was explored by evaluating the performance for sub-intervals within the 84 day dynamic simulation. To further scrutinize the accuracy of the recycling center production design recommendations, the probability distributions for each alloy at the downstream facilities characterized in chapter six were used as the basis of a Monte Carlo simulation to generate daily charge plans at the downstream remelters. The performance of the twelve proposed recycling center production designs was evaluated using the simulated downstream production volumes.

The total liquid recycled product incorporated into downstream production for each of the twelve recycling center production designs is included in Figure 85 below. In the case of simulated downstream production, the fixed recipe model formulations incorporate the most liquid recycled product into the downstream production. Increasing flexibility within the fixed recipe model formulations increases the total liquid recycled product delivered by allowing the daily operational models to modify production to respond to downstream demand variation. These results are consistent with those observed with the dynamic simulation using historical data. Similar trends are also observed for the flexible recipe results including, increasing flexibility for the low and high coordination case decreases the total liquid recycled product weight incorporated into downstream production. The optimal liquid recycled product weight incorporated corresponds to the middle coordination case with flexible production. The consistency of these observations using simulated production volumes supports that providing flexibility to pre-pooled recycled materials limits stock depletion. The results also support that for the flexible recipe model formulations, the middle coordination case provides the optimal liquid recycled product incorporation by balancing recycled product substitution with recycled product customization.

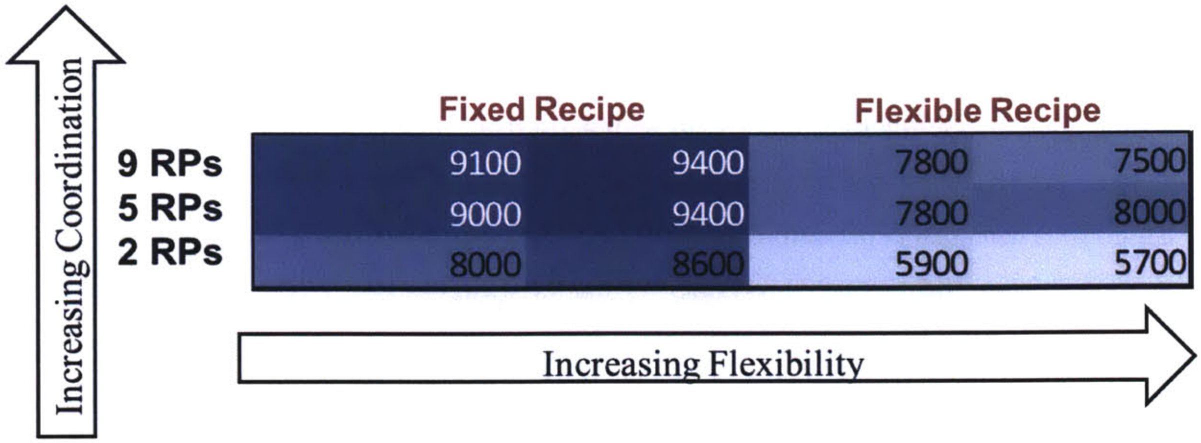

Figure 85. Color mapping of the performance in terms of total liquid metal incorporated into production of the twelve recycling center production plan designs resulting from the production generated from Monte Carlo simulation.

6.3 Comparison recycling center performance calculated by long term production model versus performance calculated by dynamic simulation

The output of the long term production model studied in chapter four was calculated using historical production data and can be considered a theoretical estimation of the recycling center performance excluding operational constraints. The dynamic simulation presented in this chapter studied the performance of the long term production model calculations in daily operational context. Converting the total weight of aluminum dross and post-consumed scrap estimated by the long term production model performance estimate from a six month time horizon to an 84 day time horizon estimated 13,986 tons of recycled material incorporated into downstream remelter production. The optimal recycling center production design incorporated 12,391 tons of aluminum dross and post-consumed scrap during the 84 day dynamic simulation. The percent difference between the simulated performance and the theoretical performance based on historical data is 11.4%. Since the theoretical performance was calculated using downstream remelter production volumes describing earlier production, the long term production model was recalculated using the aggregated production volumes from the 84 day period in early 2011. Re-calcuating the long term production model for the same production volumes observed in the 84 day historical production values incorporated 14,420 tons of dross and scrap into the downstream remelter production. In this case, the percent difference between the theoretical recycling center performance and the simulated performance including operational constraints is 14.1%. However, comparing the simulated performance to the theoretical performance calculated with the long term production model using the same production volumes neglects a substantial practical challenge that is inherent to designing the optimal production plan of the recycling center; the recycling center must determine the recycled product characteristics without having knowledge of the future downstream remelter production. The recycling center must calculate the recycled product characteristics based on historical downstream production volumes or projected downstream remelter production volumes based on historical data. Ignoring the uncertainty characterizing downstream remelter production volumes and calculating the recycling center performance based on future volumes and ignoring operational constraints using the long term production model provides an idealized performance estimate that is not practically realizable.

6.4 Impact of daily production factors on recycling center performance

The difference between the liquid recycled product incorporated into downstream remelter production weight calculated by the long term production model and the weight corresponding to optimal recycling center production design during the dynamic simulation demonstrates opportunity for improvement. The inability of the optimal recycling center production design during the dynamic simulation to incorporate as much liquid recycled product indicates that daily production factors negatively impact recycling center performance. In this section, the relative impact of the daily production factors, 1) downstream demand variation, 2) furnace capacity mismatch, 3) recycling center production capacity, and 4) recycled material management on performance. Identifying the most significant daily production factors limiting recycling center performance can provide insights on strategies to improve recycling center production design.

6.4.1 Impact of downstream demand variation: recycling center performance calculated with deterministic downstream demand

The motivation for developing four daily model formulations is to provide varying levels of flexibility to operators at the recycling center to adjust production plans according to daily variation in downstream remelting production because it is assumed the daily production variation negatively impacts the performance of the recycling center. To test the validity of this assumption, a baseline downstream remelter production case was developed that includes only the deterministic mean daily productions of each alloy for the 84 day production period. 84 days of recycling center production were simulated using the fixed raw material recipe with fixed and flexible production daily model formulations with low coordination. A low coordination case is selected for this study to reduce the impact of material substitution, or deviations from the optimal allocation of recycled products across the downstream alloys as calculated by the long term production model. Since the point of this study is to establish a baseline case without production variability, limiting opportunities for material substitution maintains emphasis on operational limitations on recycling center performance. The results of the simulations are included in Figure 86, Figure 87, and Table XXX. The fixed recipe with fixed production model uses nearly all of the available materials to produce either liquid recycled products or cast sow. Material is left over because it has insufficient volume to maximize the capacity of the rotary furnace which is a constraint in the model formulation. The fixed recipe with flexible production model formulation is able to deliver 94.9% of the available material as liquid recycled products and incorporate into the production of the downstream remelters. The fixed recipe with flexible production model incorporates the first recycled product to the maximum capacity of the recycling center because the remaining stocks are insufficient to fill the rotary furnace. This model formulation uses less recycled products than the fixed production formulation because of the large penalty associated with casting materials as sows. However, the fixed recipe with flexible production model formulation is able to incorporate more liquid recycled product than the fixed recipe with fixed production model formulation, 8,855 tons vs. 8,659 tons. The performance difference between the two baseline production cases with deterministic downstream production volume can be better explained by considering the dynamic liquid recycled product incorporation for the first two shipment periods.

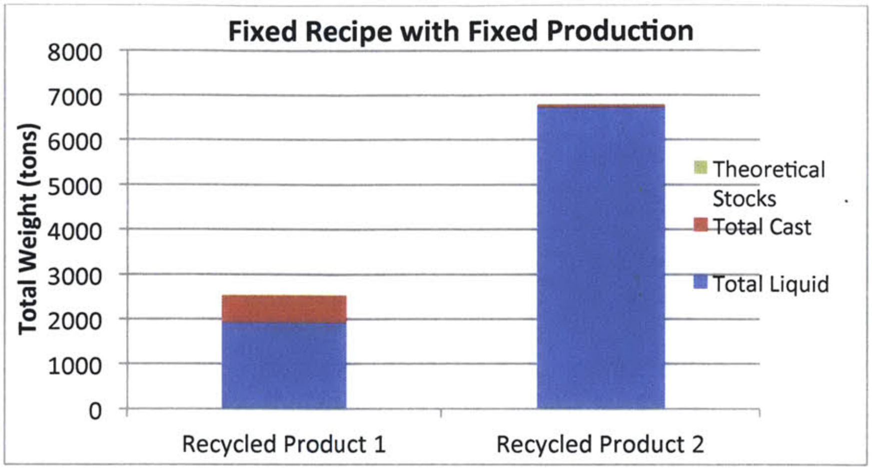

Figure 86. The weight of the theoretical stocks, total cast, and total liquid resulting from the deterministic recycling center production simulation for the fixed recipe with fixed production model formulation.

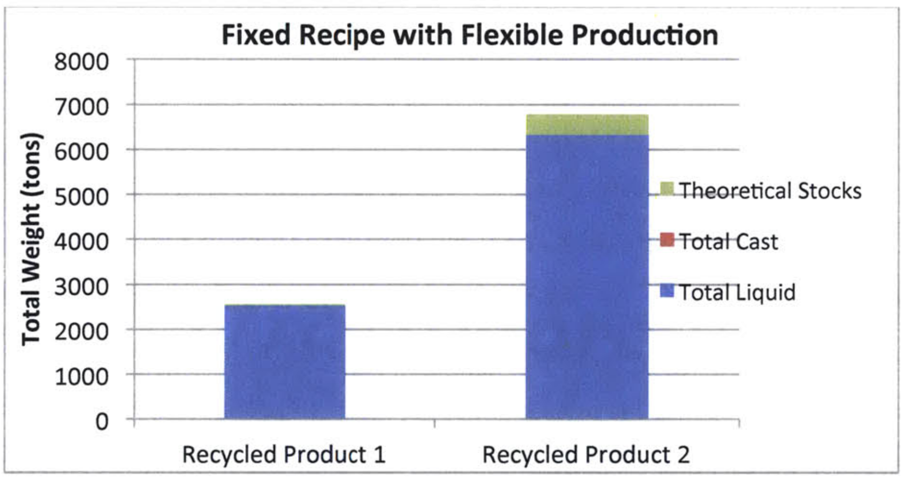

Figure 87. The weight of theoretical stocks, total cast, and total liquid resulting from the deterministic recycling center production simulation for the fixed recipe with flexible production model formulation.

Table XXX. Summary of the Recycling Center Performance for the Fixed Recipe with Fixed Production and Fixed Recipe with Flexible Production Model Formulations

	Total Liquid (tons)	Total Cast (tons)	Total Used (tons)	Total Allocated (tons)	Percent difference (tons)
Fixed recipe with fixed production	8658.78	653.10	9311.87	9331.88	-0.21%
Fixed recipe with flexible production	8854.99	0.00	8854.99	9331.88	-5.11%

The ability of the fixed recipe with flexible production model formulation to incorporate more liquid recycled product into the downstream production schedule than the fixed recipe with fixed production results from improved rotary furnace operation during the daily production sequence. Figure 88 shows the progression of liquid recycled product incorporation into downstream production for the two model formulations and Figure 89 shows the corresponding progression of the number of charges for the same 28 day production period. The fixed recipe with fixed production model aggressively operates the rotary furnace at the recycling center initially, depleting the supply of recycled products and limiting the ability to incorporate liquid recycled products into the downstream production near the end of the raw material shipment period. The fixed recipe with flexible production model more conservatively operates the rotary furnace initially, allowing more liquid recycled products to be incorporated into downstream production toward the end of the shipment period. Comparing the performance of the two model formulations suggests that forcing production plans based on the long term model calculations forces the recycling center to operate more aggressively promoting stock depletion and sow generation. Allowing the recycling center to adjust production to more closely match downstream production levels improves recycled material stock management and limits sow generation.

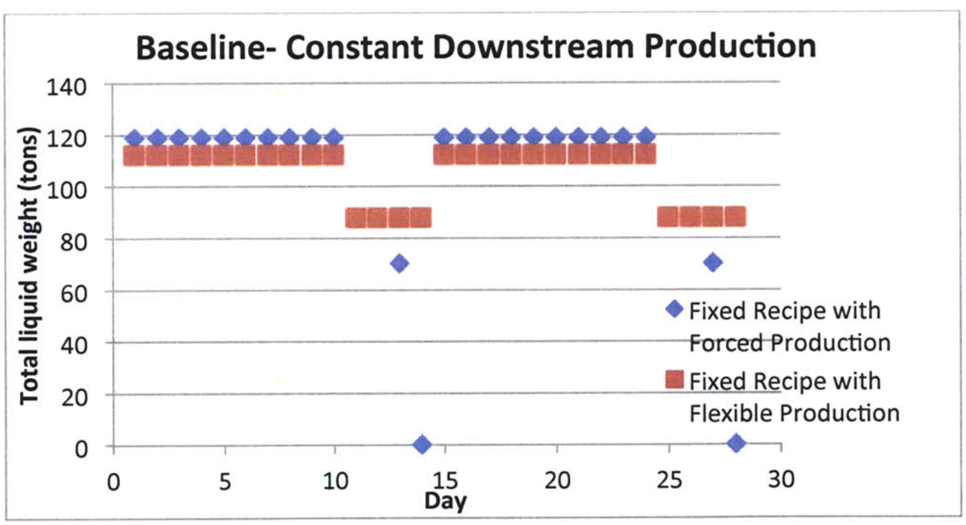

Figure 88. The total liquid recycled product weight incorporated into the downstream production schedule for the fixed recipe with fixed and flexible production for the first 28 days in the production simulation.

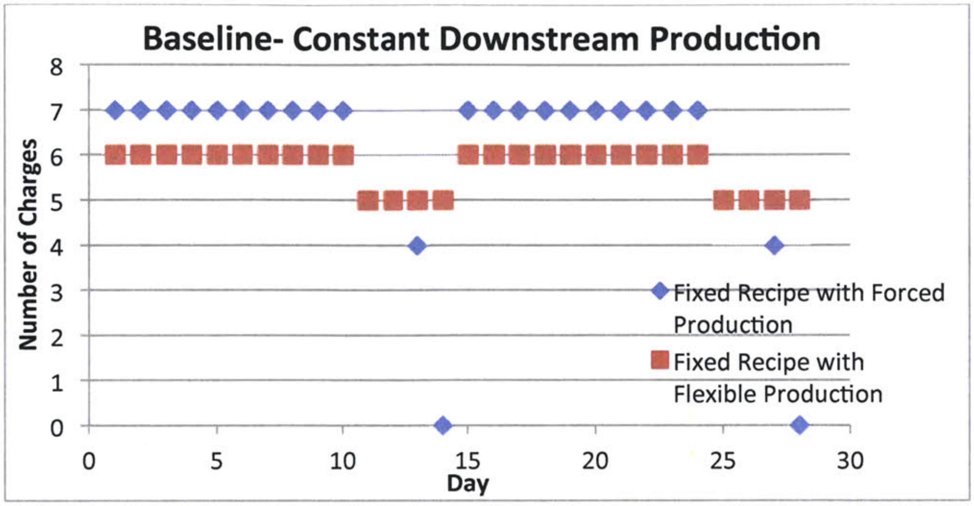

Figure 89. The number of rotary furnace charges performed at the recycling center for the fixed recipe with fixed and flexible production for the first 28 days in the production simulation.

6.4.2 Impact of rotary furnace and recycling center production capacity on performance

The presented analysis was performed using a fixed rotary furnace capacity determined by the plant manager in advance based on cost and operational factors. The rotary furnace capacity, 24 tons selected for the recycling center is a relatively large rotary furnace capacity which improves energy efficiency. A smaller furnace capacity was expected to bring advantages including the option to produce a greater number of recycled products on a particular day while maintaining the same overall production volume. Although increasing the furnace capacity was expected to bring further gains in energy efficiency, a larger furnace would limit the number of recycled products that can be produced in a day given constant recycling center capacity. To evaluate the validity of these assertions, a sensitivity analysis was performed to determine the influence of the rotary furnace capacity on the total liquid recycled product weight incorporated. Table XXXI shows the liquid weight incorporated and the percent difference to the baseline value for five different furnace capacities. Decreasing the rotary furnace capacity offers moderate gains in liquid recycled product incorporation by providing the recycling center with more precision to meet the production needs of the downstream remelters and minimize sow generation. Increasing the rotary furnace capacity decreases the liquid recycled product incorporation by limiting the number of recycled products that can be produced in a day. For example, to maintain equivalent recycling center production capacity with an 84 ton rotary furnace a maximum of two different recycled products can be produced in a day. As a result, 13.8% less liquid recycled products can be incorporated into downstream remelter production. It is worth noting that an 84 ton rotary furnace is quite large and is probably not a realistic size for this application. Because decreasing the rotary furnace capacity offered moderate gains in performance, another sensitivity analysis on the total recycling center capacity was performed.

Table XXXI. Effect of Changing the Furnace Capacity on the Total Liquid Weight Incorporated into Downstream Production.

Furnace capacity (tons)	Liquid weight incorporated (tons)	Percent difference to baseline
6	9630	0.80%
12	9573	0.20%
24	*9551*	*Baseline*
42	9299	-2.70%
84	8231	-13.80%

The effect of increasing the maximum number of rotary furnace charges per day at the recycling center on liquid recycled product incorporation is included in Table XXXII below. Increasing the recycling center capacity to eight charges per day provided the most improvement in performance by increasing the liquid recycled product weight incorporated by 1.5%. Increasing the recycling center capacity beyond eight charges per day led to decreasing liquid recycled product incorporation from the eight charges per day case because of the effects of stock depletion. Increasing the recycling center production capacity allows the recycling center to produce more in the beginning of the shipment period which can promote the negative effects of stock depletion. The results suggest that the limiting liquid recycled product weight incorporated as the recycling center production capacity approaches infinity for the optimal production design is 9,668 tons in this 84 day production period.

Table XXXII. Effect of Changing the Recycling Center Capacity by Increasing the Maximum Number of Charges per Day on the Total Liquid Weight Incorporated into Downstream Production.

Maximum number of charges per day	Liquid weight incorporated (tons)	Percent difference to baseline
7	*9551*	*Baseline*
8	9694	1.50%
9	9679	1.30%
10	9668	1.20%
11	9668	1.20%

6.4.3 Impact of recycled material management on recycling center performance

Recycled material management or mitigating stock depletion is another daily production factor that is expected to limit liquid recycled product incorporation into downstream production. The remaining recycled materials or stock weight for the fixed recipe with flexible production model formulation during the dynamic simulation for the first shipment period is included in Figure 90. The preference of this model formulation for recycled product two is indicated by the depletion on day nine. Similarly, recycled product four is depleted on day 11 and recycled product three is depleted on day 13. Depleting these recycled products early on indicates that the recycled products are sub-optimally allocated across the shipment period. The recycling center maximizes production in the beginning of the shipment period and struggles to incorporate liquid recycled products into downstream production later in the shipment period when fewer recycled products are available. Because of the sub-optimal performance, the later part of the shipment period is an opportunity for improvement. Improving the compositional specifications of recycled products one and five may lead to improved performance in the later part of the shipment period. Calculating the recycled product compositions explicitly considering downstream demand uncertainty using simulation optimization may provide more flexible compositional specifications that can improve recycling center performance.

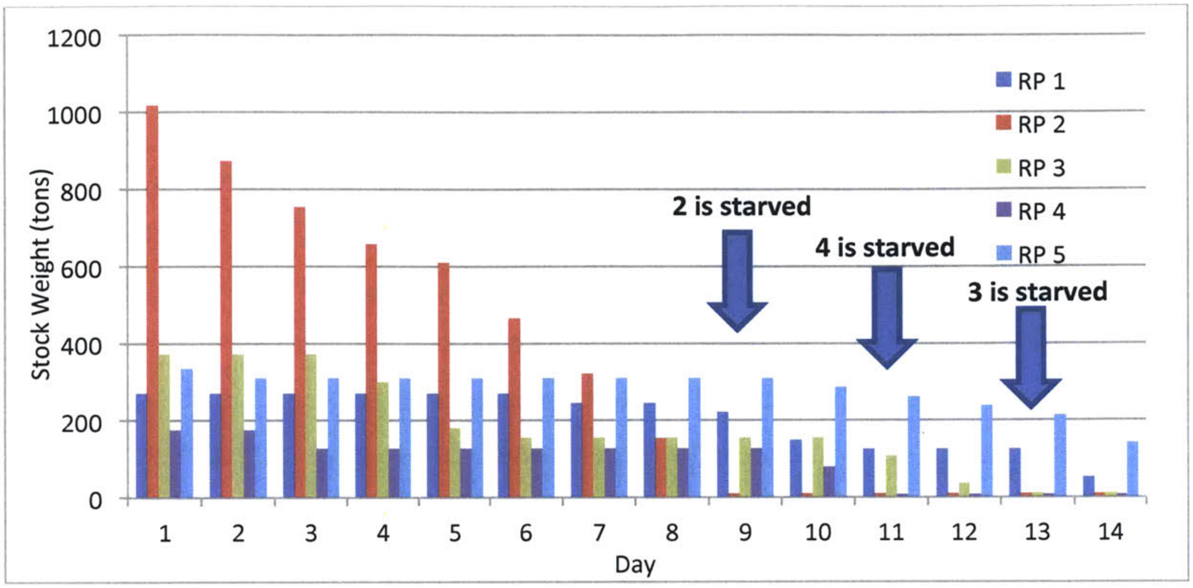

Figure 90. Weight of remaining raw recycled materials over the first shipment period for the middle coordination with fixed recipe and flexible production daily operational model formulation.

6.5 Simulation optimization results for the fixed recipe flexible daily operational model formulations

A simulation optimization method was implemented as a strategy to improve recycling center performance. Calculating the recycled product characteristics explicitly incorporating the impact of downstream production volume uncertainty is expected to improve the flexibility and robustness of the recycled product compositional specifications in the presence of daily downstream production variation. K-means clustering analysis is used to convert the production plans calculated by the stochastic optimization into inputs for the daily production models. In chapter five, k-means clustering was used to determine compositional clusters of the five recycled product case including the maximum, upper quartile, lower quartile, median, and minimum composition in the cluster. The associated recycling center production plan including the recycled material recipes are calculated by inputting the recycled material compositions determined by clustering into the long term production optimization model.

6.5.1 Optimal k-means clustering parameters

The k-means clustering analysis was performed based on three different combinations of input parameters and it is necessary to evaluate the input combination that generates the optimal recycled product characteristics. The optimal combination of input parameters is determined by the performance of the calculated specifications during actual daily production conditions. The case of the five recycled products recycling production plan hedged for long term demand uncertainty is used to evaluate the performance of the different clustering analysis setups. In particular, the validity of setting the number of clusters equal to the number of recycled products and including the production volume in the k-means clustering analysis is examined. The recycled product compositions were calculated in the following three ways: five clusters including production volume, five clusters excluding production volume, and six clusters including production volume. The recycled product specifications for each k-means clustering result was used as in input for daily model formulation four which provides the most flexibility to the recycling center. The results of the 90 day dynamic simulation are shown in Table XXXIII. The case of five clusters excluding the production volume parameter incorporated the most liquid product into the production at the downstream remelting facilities. Thus, for the subsequent daily production simulations, the recycling center production plans hedged for long term downstream demand uncertainty are calculated using k-means clustering excluding production volume and setting the number of clusters equal to the number of recycled products.

Table XXXIII. Comparison of Performance of the Calculated Recycling Product Compositional Specifications

Clustering Inputs	Total Weight Cast (tons)	Total Weight Liquid (tons)	Percent Difference with Maximum Liquid Delivery
5 Clusters Excluding Production Volume	49.9	11542.1	-
5 Clusters Including Production Volume	47.1	10944.9	5.2%
6 Clusters Including Production Volume	64.8	11263.2	2.4%

6.5.2 Simulation optimization performance

The methods described above were used to perform simulation optimization to calculate recycling center production plans according to different recycled product characteristics. To evaluate the effect of the recycled product compositions on the performance of the recycling center design, the recycled product compositions corresponding to the 40th percentile, median, 60th percentile, and upper quartile positions in the uncertainty simulation results were calculated and input into the long term production model. The optimal recycling center production plan calculated by the long term production model corresponding to the recycled product compositions was evaluated with the dynamic simulation tool using the fixed recipe with fixed and flexible production daily operation model formulations. The performance of the fixed recipe daily operational model formulations is studied because of the ability of these model formulations to incorporate more liquid recycled products into downstream remelter production than the flexible recipe daily operational model formulations as demonstrated previously. The recycling center production designs calculated using the simulation optimization tool are referred to as uncertainty aware designs because of their embedded knowledge of the impact of downstream production variation on the optimal recycled product compositional specifications. The main risk downstream production variation poses to the recycling operation is increasing the inaccuracy of the recycling center production parameters calculating using the long term production model to describe the optimal daily production because of a large difference between the historical and realized downstream production variation. Such inaccuracies in the calculated recycling center production parameters are expected to manifest economic losses to the proposed recycling operation. The performance of the deterministic and uncertainty aware model formulations was compared by estimating the associated profit with each recycling plan accounting for revenue from the liquid and cast recycled products and the cost associated with purchasing recycled materials that are not able to be incorporated into downstream remelter production.

The previous section examined the opportunity to improve the performance of the optimal recycling center design. Stock depletion which refers to the preferential consumption of certain recycled products causing leftover recycled product stocks that are not incorporated into downstream remelter production was identified as a significant factor limiting performance. It was proposed that recalculating the recycled product compositional specifications using the simulation optimization technique could provide compositional specifications that were better suited for recycled product substitution especially towards the end of the supply shipment period where the biggest opportunity for performance improvement exists. Additionally, calculating the recycled product compositions in the context of the impact of downstream production uncertainty may also help improve the recycled material allocation across the recycled products by allowing the long term production model to allocate more recycled materials to recycled products with preferential compositions and less recycled materials to recycled products with more customized compositions. The validity of these assertions is evaluated by calculating the performance of the deterministic and uncertainty aware recycling center production plans with the dynamic simulation tool for three downstream remelter production cases.

There are three potential relationships between the production volume input to the long term production model and the production volume realized in the dynamic simulation. The production volume input to the long term production model can be less than, equal to, or greater than the production volume realized in the dynamic simulation. To represent these downstream remelter production cases, the realized downstream remelter production was projected to six month volumes and decreased by ten percent, preserved, and increased by ten percent to represent case one, case two, and case three respectively. The previous section characterized the performance according to historical data which can be categorized as case one because the production volume input to the long term production model from the previous year was less than the production volume realized in the subsequent year. In order to evaluate the simulation optimization technique's ability to increase profitability, the total weight of incorporated liquid recycled product into downstream remelter production, the total weight of remaining recycled product stocks, and the total weight of cast sows is calculated for each of the three potential production cases.

Table XXXIV lists the weight of liquid recycled product incorporated into each of the cases for the deterministic and uncertainty aware fixed recipe with fixed production daily operation model formulations. In production case one, the deterministic recycling center production design incorporates the most liquid recycled product into downstream remelter production, 9,576 tons. However, in case two, the simulation optimization technique with compositions determined at the 40^{th} percentile incorporates the most liquid recycled product and in case three, the simulation optimization technique with compositions determined at the 60^{th} percentile incorporates the most liquid recycled product into downstream remelter production. As a result of the variation in performance of the techniques across the downstream remelter production cases, determining the optimal method to calculate the recycling center production plan depends on the relationship between the historic downstream remelter production volume input into the long term production model and the realized production volume in the dynamic simulation. In addition to the weight of incorporated liquid recycled product, the performance of the recycling operation also depends on the weight of allocated but unused recycled material stocks and the weight of sows calculated to be cast during the dynamic simulation. Table XXXV lists the total weight of recycled material stocks that were allocated by the long term production model to be incorporated as liquid recycled products, but were unable to be incorporated during the dynamic simulation. In the deterministically determined recycling center production plan, the stock supply of recycled materials in case one which is characterized by having a lower production volume input to the long term production model than the production volume realized in the dynamic simulation is smaller than the stock supplies in cases two and three which have larger production volumes input to the long term production model than realized in the dynamic simulation. This difference in recycled material stock supplies across the cases for the deterministically determined recycling center production plan is especially pronounced when compared to the difference in the recycled material stock supplies across the downstream production cases for the recycling center production plan determined by the proposed 40th percentile, media, 60th percentile, and upper quartile methods. This behavior suggests that the deterministic model formulation has a tendency to more aggressively allocate recycled materials for recycled products than the uncertainty aware recycling production plans. As discussed in the previous sections, the fixed recipe with fixed production model formulation tends to cast a greater proportion of the recycled products as sows as a result of the embedded fixed production plan algorithm. The total weight of recycled products allocated to be cast as sows for the proposed recycling center production designs is included in Table XXXVI below. With the exception of the upper quartile recycled product characteristics, the total recycled product weight cast as sow is similar for each case across the methods used to calculate the recycled products. This uniform allocation of recycled products for casting suggests that the relative weight of cast sows may not be an influential factor in differentiating the proposed methods to calculate recycling center production plans.

Table XXXIV. Total Liquid Recycled Product Weight Incorporated Into Downstream Production for the Fixed Recipe with Fixed Production Model Formulation for the Deterministic and Uncertainty Aware Recycled Product Compositions and Production Plans.

	Deterministic (tons)	40th Percentile (tons)	Median (tons)	60th Percentile (tons)	Upper Quartile (tons)
Case 1	9,576	9,433	9,364	9,322	7,982
Case 2	9,574	9,643	9,612	9,612	8,021
Case 3	9,407	9,578	9,651	9,683	8,193

Table XXXV. Total Weight of Recycled Material Stocks Corresponding to the Fixed Recipe with Fixed Production Model Formulation for the Deterministic and Uncertainty Aware Recycled Product Compositions and Production Plans.

	Deterministic (tons)	40th Percentile (tons)	Median (tons)	60th Percentile (tons)	Upper Quartile (tons)
Case 1	488	190	277	288	54
Case 2	906	262	517	524	57
Case 3	1,374	406	445	332	57

Table XXXVI. Total Weight of Recycled Products Allocated to be Cast by the Fixed Recipe with Fixed Production Model Formulation for the Deterministic and Uncertainty Aware Recycled Product Compositions and Production Plans.

	Deterministic (tons)	40th Percentile (tons)	Median (tons)	60th Percentile (tons)	Upper Quartile (tons)
Case 1	504	668	650	637	572
Case 2	754	768	763	745	626
Case 3	1,114	731	776	812	454

The results of the fixed recipe daily operational model formulation with flexible production are presented in Table XXXVII, Table XXXVIII, and

Table XXXIX below. In the flexible production model formulation, the deterministically determined recycled product compositions incorporated more liquid recycled product into downstream production than the uncertainty aware recycled product compositions for cases one and two with 9,619 tons and 9,748 tons respectively. The recycled product compositions calculated by the 60th percentile of the uncertainty simulation incorporated the most liquid recycled product into downstream remelter production for case three with 9,604 tons. The deterministic method's outperformance for cases one and two suggests that the uncertainty aware recycled product compositional specifications may not facilitate recycled product substitution at the end of the shipment period enough to offer significant performance improvements. Recycled product substitution opportunities at the beginning of the shipment period may not be realized because of the recycling center's flexibility to choose the daily production schedule. The higher liquid recycled product incorporation into downstream production calculated in the fixed recipe with fixed production for cases two and three suggests that the full benefits of the uncertainty aware recycled product compositions may not be realized without the fixed production algorithm. Table XXXVIII listing the recycled material stocks associated with each model formulation supports the previously seen result that the deterministic method more aggressively allocates recycled materials across the recycled products. As a result of the aggressive allocation, for each case the deterministic method has the largest recycled material stock weight. The leftover stocks are the largest for the third production case which realizes a smaller downstream remelter production volume than input into the long term production model. The larger downstream remelter production volumes input to the long term production model causes all of the model formulations to allocate a larger proportion of recycled materials to the recycled products than can be consumed during the dynamic simulation.

Table XXXVII. Total Liquid Recycled Product Weight Incorporated Into Downstream Production for the Fixed Recipe with Flexible Production Model Formulation for the Deterministic and Uncertainty Aware Recycled Product Compositions.

	Deterministic (tons)	40th Percentile (tons)	Median (tons)	60th Percentile (tons)	Upper Quartile (tons)
Case 1	9,619	9,387	9,419	9,439	7,939
Case 2	9,748	9,482	9,539	9,604	7,963
Case 3	9,527	9,506	9,539	9,604	7,963

Table XXXVIII. Total Weight of Recycled Material Stocks Corresponding to the Fixed Recipe with Flexible Production Model Formulation for the Deterministic and Uncertainty Aware Recycled Product Compositions.

	Deterministic (tons)	40th Percentile (tons)	Median (tons)	60th Percentile (tons)	Upper Quartile (tons)
Case 1	992	1,102	1,045	912	798
Case 2	1,626	1,462	1,669	1,508	897
Case 3	2,574	1,462	1,669	1,508	897

Table XXXIX. Total Weight of Recycled Products Allocated to be Cast by the Fixed Recipe with Flexible Production Model Formulation for the Deterministic and Uncertainty Aware Recycled Product Compositions.

	Deterministic (tons)	40th Percentile (tons)	Median (tons)	60th Percentile (tons)	Upper Quartile (tons)
Case 1	165	123	110	133	131
Case 2	193	147	113	139	138
Case 3	170	125	113	139	138

The total liquid recycled product weight incorporated into downstream production, the recycled material stock weight, and the cast sow weight are important metrics for differentiating the performance of the deterministic and proposed simulation optimization method but do not provide an objective measure to determine the model formulation to calculate the optimal recycling center production design. In order to identify the correct model formulation to implement, the relative profitability of the deterministic and uncertainty aware methods for the fixed recipe daily operational model formulations is defined according to Eq. 64.

$$P_T = \sum_{i=1}^{3} \alpha_i (L_i + P_R C_i - P_C S_i) \qquad \textbf{Equation 64}$$

Where P_T is the total profit, i is an index representing the case, α_i is the probability of realizing case i, L_i is the total weight of liquid recycled product incorporated into downstream production, P_R is the relative profit of selling cast sows in reference to the profit of selling liquid recycled products, C_i is the total weight of cast sows, P_C is the relative cost of purchasing recycled materials compared to the profit resulting from selling liquid recycled products, and S_i is the stock weight.

Calculating the relative profit of each recycling center production design required the introduction of a few parameters that are presently unknown for the proposed recycling operation, α_i, P_R, and P_C. The recycling production design profit is expected to depend on the values of these parameters and to ensure the robustness of the conclusions, sensitivity analyses on the impact of the probability of realizing the production cases and the relative cost of purchasing recycled materials compared to the profit resulting from selling liquid recycled products or the cost coefficient are performed. The relative profit of selling cast sows in reference to the profit of selling liquid recycled products is fixed to 0.3 and a sensitivity analysis is not performed because of the relatively small cast sow weights compared to the liquid recycled product and stock weights. Figure 91 shows the calculated profit as a function of the cost coefficient relating the relative profit of liquid recycled products incorporated into downstream production to the cost of purchasing the recycled materials for the fixed recipe with fixed production daily operational model formulation. The upper quartile recycled product characteristics were excluded from the profitability calculations because of the poor performance demonstrated in the previous tables. The probability of realizing each production case is 1/3. Figure 91 indicates that the uncertainty aware recycled product compositions calculated using the 40^{th} percentile point from the uncertainty simulation have the largest associated profit for every cost coefficient examined with the fixed parameters. The increased profitability of the uncertainty aware model formulations results from the more conservative allocation of recycled materials across the recycled products calculated by the long term production model. Although in the event of realizing a larger downstream remelter production than expected, the uncertainty aware model formulation does not perform as well as the deterministic model formulation, calculating the profit including the other two downstream remelter production cases causes the uncertainty aware method to have a larger expected profit. The relative profitability of the uncertainty aware model formulation compared to the deterministic model formulation increases with increasing cost coefficient because of the increasing penalty of purchasing and allocating recycled materials to recycled products that are not able to be incorporated into downstream remelter production.

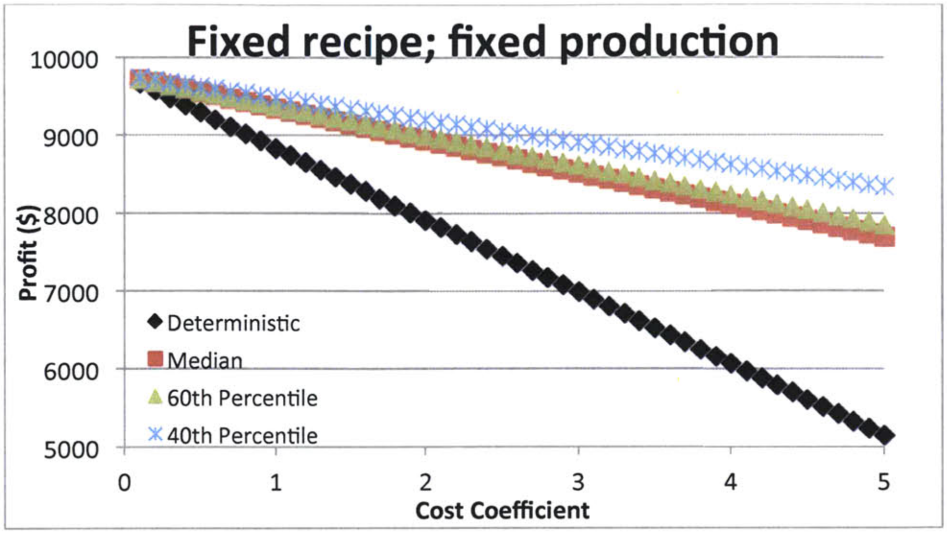

Figure 91. The profit corresponding to the fixed recipe with fixed production deterministic and uncertainty aware model formulation for various cost coefficients.

The profit of the uncertainty aware and deterministic methods is also calculated for the fixed recipe with flexible production daily model formulation and included in Figure 93. The deterministic method is more profitable for cost coefficients less than 0.5 and the uncertainty aware method with compositions determined at the 60th percentile is the most profitable for cost coefficients greater than 0.5. This behavior is consistent with the previously identified advantages of the uncertainty aware method for increasing cost penalties for allocating recycled materials to recycled products that are not able to be incorporated into downstream production. The improved profitability for the uncertainty aware method is not as pronounced for the flexible production daily operational model formulation as demonstrated previously in the fixed production formulation. This behavior suggests that the ability of the uncertainty aware recycling center production plan to mitigate recycled material stock depletion is greater than the ability of uncertainty aware recycled product compositional specifications.

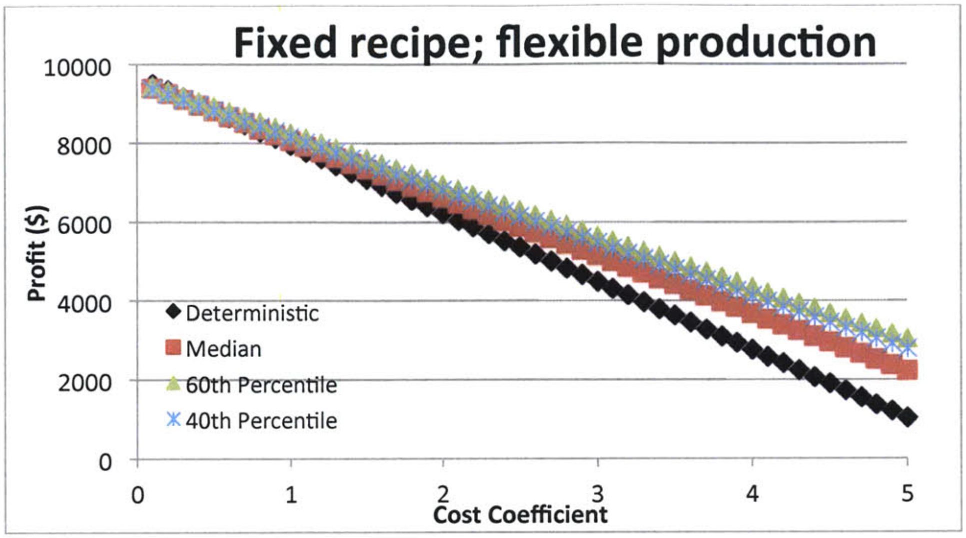

Figure 92. The profit corresponding to the fixed recipe with flexible production deterministic and uncertainty aware model formulation for various cost coefficients.

The increased profitability associated with the uncertainty aware method largely results from an allocation of recycled materials across the recycled products that is more robust to downstream demand uncertainty. However, reducing the uncertainty surrounding downstream demand production uncertainty reduces the gains provided by the uncertainty aware method. To evaluate the sensitivity of the profit increase provided by the uncertainty aware method, a sensitivity analysis on the effect of the probability of realizing the downstream production cases is performed. A triangle distribution is used to describe the probabilities of cases one, two, and three, where the probability of realizing case one equals the probability of realizing case three. The profitability of the deterministic and uncertainty aware model formulations for the fixed recipe with fixed production daily operational model formulations as a function of the probability of realizing the second downstream demand production case is included in Figure 93 below. The cost coefficient was fixed to 2.5 to generate the plot because this is in the center of the range explored in the previous sensitivity analysis. The uncertainty aware model formulation with recycled product compositional specifications determined at the 40th percentile location in the uncertainty simulation results produces the largest profit across the probabilities of realizing the second case downstream production scenario. The increase in profit resulting from the uncertainty aware recycling center production plan decreases as the probability of case two increases, supporting the assertion that the uncertainty aware method provides the largest gains when the downstream remelter production uncertainty is greatest.

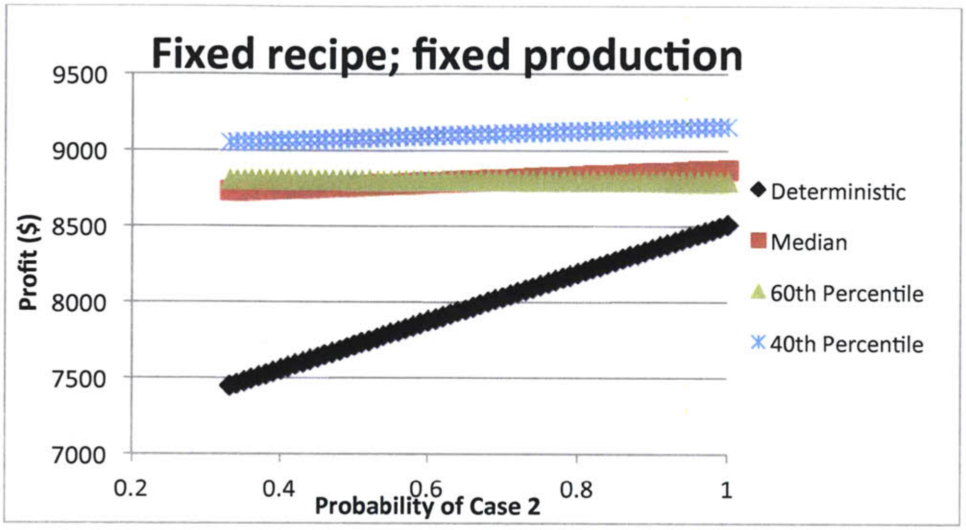

Figure 93. The profit corresponding to the fixed recipe with fixed production deterministic and uncertainty aware model formulations for various probabilities of realizing equal downstream production values as the historical data.

The profit as a function of the probability of realizing case two for the fixed recipe with flexible production daily operational model formulation is included in Figure 94 below. The largest profit is achieved by using the recycled product compositions determined at the 60th percentile in the uncertainty simulation results for the various probabilities of realizing downstream remelter production volumes equal to the production input to the long term production model. The profit achieved with the deterministic method approaches the profit achieved with the 60th percentile recycled product compositions as the probability approaches one. Figure 94 supports the previous finding; the value of the simulation optimization method decreases as the degree of downstream remelter production uncertainty decreases.

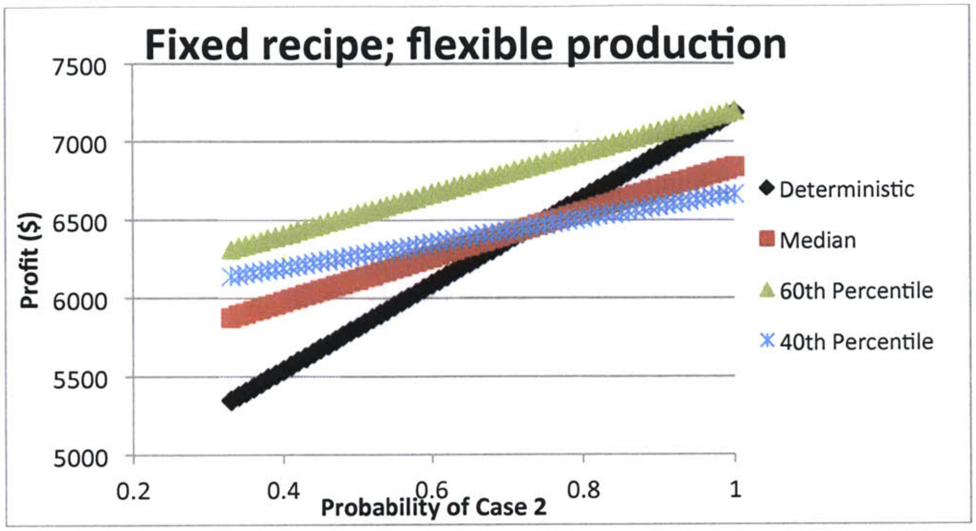

Figure 94. The profit corresponding to the fixed recipe with flexible production deterministic and uncertainty aware model formulations for various probabilities of realizing equal downstream production values as the historical data.

The previous section identified the fixed recipe with flexible production model formulation as the optimal daily operational model formulation because of its ability to incorporate the most liquid recycled products into the downstream remelter production. However, the results of this section indicate that the fixed recipe with flexible production daily operational model formulation may not perform as well as the fixed production formulation in situations with large financial penalties for purchasing recycled materials that are not incorporated into the downstream remelter production and situations that are characterized by substantial uncertainty and variation in downstream remelter production volumes. For example, in the event of varying cost coefficient, the relative profitability of the optimal fixed recipe with fixed production daily operational model formulation varies from $9,740 to $8,338 while the range of the relative profitability of the optimal fixed recipe with flexible production formulation is $9,511 to $3,045. Thus, expensive stock penalties pose more significant risks to the fixed recipe with flexible production formulation. Similarly, in the event of varying the probability of realizing equal downstream remelter production for the optimal fixed production model formulation the relative profitability varies from $9,158 to $9,052 while the range of the relative profitability of the optimal flexible production formulation is $6,313 to $7,200.

The simulation optimization method can be implemented to provide more profitable recycling center production designs than deterministically determined recycling center production plans. The optimal recycling center performance for the fixed recipe with fixed production model formulation corresponds to the simulation optimization method with recycled product compositions determined at the 40th percentile. The optimal recycling center performance for the fixed recipe with fixed production model formulation corresponds to the simulation optimization method with recycled product compositions determined at the 60th percentile. The simulation optimization method provides improved performance in the event of downstream remelter production uncertainty and expensive financial penalties for allocating recycled materials to recycled products that cannot be incorporated into the downstream production.

6.6 Recommended recycling center production design based on dynamic simulation results

The performance of 12 recycling center production designs during the 84 day dynamic simulation of recycling center production in response to historical and simulated downstream remelter production values was evaluated. Variation in downstream production negatively affected recycling center performance but providing flexibility to the recycling center to modify production can mitigate the negative effects. However, increasing operational flexibility at the recycling center to a large extent can promote stock depletion which negatively affects recycling center performance. For all levels of coordination, fixing the allocation of recycled materials across the recycled products increased liquid recycled product incorporation into downstream remelter production. The fixed recipe with flexible production model formulation maximized liquid recycled product incorporation into downstream production across the degrees of coordination. The optimal liquid recycled product incorporated in the high and middle coordination cases were very similar; the high coordination case incorporated 45 tons of additional liquid recycled products. Since high coordination between the recycling center and the downstream remelting facilities presents several logistical challenges, including tighter scheduling requirements and more complex stock management, the minor increase in liquid recycled product incorporated is outweighed by the risk. Thus, the recommended recycling center production design is characterized by middle coordination between the recycling center and downstream remelting facilities and follows a daily operational optimization model in the fixed recipe with flexible production. The performance of the proposed dynamic simulation method for the middle coordination case with the fixed recipe with fixed and flexible production was evaluated for three downstream remelter production cases. The dynamic simulation method provided improved profitability of the fixed recipe daily operational model formulation in the case of large financial penalties for allocated recycled materials that were not incorporated into downstream remelter production and in the presence of significant downstream remelter production uncertainty. Thus, the recommended recycling center production design should be calculated with the simulation uncertainty method in the event of expensive aluminum dross and post consumed secondary material costs and significant uncertainty in the production volumes of the downstream remelters.

Chapter 7. Conclusions

Growing aluminum consumption presents a significant environmental burden that researchers must identify strategies to mitigate. Although reducing global aluminum consumption would provide the most dramatic reduction in environmental impact, such an approach is especially challenging because of the growing global population. One alternative strategy that can reduce environmental impact while meeting the material needs of the global population is to use secondary materials to produce aluminum alloys. The growing popularity of producing aluminum alloys using secondary materials has constrained conventional secondary material supplies and motivated research on strategies to incorporate lower quality secondary materials, such as post-consumed scrap and aluminum dross.

The variable and uncertain character of post-consumed scrap and aluminum dross are the primary challenges to recycling these materials. Aluminum remelters can avoid plant contamination from these materials by reprocessing post-consumed scrap and aluminum dross in separate facilities. The variable and diverse compositional characteristics of these materials also necessitate long term planning at the recycling center to avoid depleting the most compositionally favorable secondary materials. The significant energy requirement to reprocess post-consumed scrap and aluminum dross motivates research on the potential to deliver re-processed liquid post-consumed scrap and aluminum dross directly to remelters. The delivery of re-processed liquid post-consumed scrap and aluminum dross or recycled products implicitly requires coordination between the secondary material re-processor and the aluminum remelter to avoid substantial energy costs to maintain molten recycled products. In this context, a decision emerges for the recycling center to determine the optimal degree of coordination to maintain with the downstream remelting facilities and the optimal level of flexibility to allow the recycling center operators to adjust production based on short term constraints.

A modeling framework describing the recycling center production was developed to quantify the optimal degree of coordination with the downstream remelting facilities and the optimal level of operational flexibility at the recycling center. A pooling optimization model that describes the long term recycling center production in response to the aggregate production volumes at the downstream remelters was formulated. Batch fitting analysis and Monte Carlo simulations were performed to evaluate the robustness of the long term recycling center production plan for aggregate downstream production uncertainty. Four daily scale recycling center operational optimization models of varying levels of flexibility were formulated. These daily operational models were used in a dynamic simulation to evaluate the recycling center production in response to historical production volumes at the downstream remelters.

The long term production model was used to determine the theoretical viability of the two stage post-consumed scrap and aluminum dross recycling operation. The economic viability of the recycling center requires the ability to incorporate large volumes of liquid recycled products into downstream production. However, a long term production optimization model was required to calculate the theoretical material utilizations because of the large concentrations of alloying elements in the recycled materials. In the high coordination case with an equal number of recycled products and finished aluminum alloys, 17,615 tons or 79% of available aluminum dross and 13,162 tons or 85% of available post-consumed secondary materials were incorporated into downstream production. Decreasing the degree of coordination between the recycling center and the downstream facilities limits the ability of the long term production model to customize recycled products to finished alloys. Reducing the number of recycled products to five decreases the theoretical total recycled material incorporated by 1.3%. Reducing the number of recycled products to one decreases the theoretical total recycled material incorporated by 33.7%. The initial recycled material consumption estimates were determined to be economically viable and the robustness of the estimates was explored using uncertainty simulations.

The recycled material consumption estimates calculated with the long term production model used the aggregate historical production mean volumes. The downstream production volumes were determined to strongly influence the recycling center's ability to incorporate recycled materials into downstream production. Simulating the long term production model with uncertainty revealed that the total recycled material consumption for the middle coordination case is relatively robust because the percent difference between the upper quartile recycled material consumed and the lower quartile is 1.4%. The uncertainty simulation revealed that the aluminum dross materials D12, D15, D17, and D18 should not be purchased or reprocessed individually and returned to the supplier as sows because these materials were not incorporated into any of the six month production scenarios. The uncertainty simulation also demonstrated that the ability of D21, S5, S10, and S12 to be incorporated into downstream production varies depending on the downstream production scenario and these secondary materials should be purchase with caution. The robustness of the calculated long term recycling center material consumption values demonstrates the validity of this approach to arriving at initial performance estimates. The charges produced by the downstream remelter production vary depending on the customer orders for that particular day.

The value of enforcing recycling center production parameters calculated using the long term production model during daily operations at the recycling center was evaluated using a dynamic simulation of historical production in 2011. The objective of the dynamic simulation was determine the influence of daily production factors including, downstream demand variation, furnace capacity mismatch, recycled material perishability, and recycled material management on the ability of the recycling center to incorporate liquid recycled products into downstream production. The dynamic simulation revealed that removing downstream demand variation allows the fixed recipe with flexible and fixed production models to consume 0.21% and 5.11% of the recycled products allocated by the long term production model. The fixed recipe with flexible production daily model formulation incorporated the most liquid recycled products for each level of coordination, high, middle, and low incorporating 9,600 tons, 9,600 tons, and 8,700 tons respectively. The proposed optimal recycling center production design is the middle coordination case operated with pre-pooled recycled products and flexible production. This recycling center production design incorporates nearly all of the allocated recycled material into liquid recycled products incorporated by the high coordination case with reduced scheduling constraints. Additionally, the proposed level of flexibility allows the recycling center to have freedom to adjust production to meet downstream demand variation with operational constraints limited to binning recycled materials together upon arrival. A simulation optimization method was demonstrated to improve recycling center profitability for the fixed recipe daily operational model formulations. The most significant improvements in recycling center profitability achieved by the simulation optimization method correspond to situations with substantial financial penalties for allocating recycled materials that cannot be incorporated into downstream remelter production and significant uncertainty characterizing the expected downstream remelter production volumes.

This investigation has attempted to calculate the optimal recycling center production design based on practical constraints limiting aluminum dross and post-consumed secondary material recycling. However, assumptions and simplifications were made to ensure the computational tractability of the model formulations. Proposed improvements and further analyses are explored in the subsequent chapter.

Chapter 8. Future Work

Several opportunities for further work persist to better quantify the challenges associated with operating a two-step aluminum dross and post-consumed secondary material recycling operation. The optimization and simulation tools describing the aluminum recycling operation rely on empirical data to determine the composition and material yield of the aluminum dross and post-consumed scrap after reprocessing. Replacing the deterministic factors relating material properties of the recycled materials to those of the reprocessed materials with functional relationships based on thermodynamic factors and interactive effects between recycled materials during reprocessing could improve model accuracy. Another potential strategy to improve model accuracy is to expand the scope of the daily recycling center operation models beyond a single day, providing the recycling center with the option to embed more long term planning into daily operations. One of the inherent challenges associated with long term planning is the need to make long term decisions with imperfect knowledge of the future. The impact of downstream demand uncertainty has been studied in the presented research, but further opportunities exist to quantify the impact of raw material compositional uncertainty on recycling center performance.

8.1 Additional thermodynamic, storage, and operational factors in aluminum dross and post-consumed secondary material reprocessing

The recycling operation proposed in this work involves reprocessing several types of aluminum dross at high temperatures in rotary furnaces. Combining several types of aluminum dross during reprocessing reduces cost because of economies of scale considerations and the high temperatures required to remelt entrapped metal. Such high temperatures are sufficient to promote oxidation of the entrapped metal. Currently, the material yields of the reprocessed aluminum dross are the empirical results of previous reprocessing operations. Future work could involve expressing the dross material yield as a function of the rotary furnace temperature and interactive effects resulting from the presence of other aluminum dross materials. Relating reprocessed aluminum dross material properties to the properties of the original aluminum dross and rotary furnace conditions was originally explored experimentally by (Tzonev and Lucheva 2007). One particularly interesting result observed by (Tzonev and Lucheva 2007) is the nonlinear relationship between entrapped metal recovery rate and the rotary furnace rotation speed. As a result of the nonlinear relationship, the optimal furnace rotation speed is a function of the dross and scrap characteristics. Additionally, further research on interactive effects between elements that occur during reprocessing operations could reveal elemental losses. A limitation of the presented research is the assumption that metal recovery is independent of the reprocessing production parameters and the material properties of the dross and scrap combination in the rotary furnace. Embedding a functional relationship for the material recovery as a function of the dross characteristics and reprocessing parameters into the long term production model could reveal insights regarding the optimal combinations of dross and scrap materials and improve model accuracy. Accurate functional forms for metal recovery that account for thermodynamic effects on material and elemental yield are expected to be especially significant for describing reprocessing operations in industrial scale rotary furnaces. There is insufficient data at the present time to determine the functional relationship, but after the recycling operation is constructed and operated for a significant period of time, enough data should be available to inform a relationship for material recovery as a function of the dross characteristics and reprocessing parameters. An improved understanding of the value of combinations of aluminum dross and post-consumed scrap can also inform binning decisions.

The significant cost to store aluminum dross resulting from environmental and quality concerns motivates combining different aluminum dross materials into the same storage area or bin. However, binning aluminum dross materials limits the compositional flexibility of the operators to create recycled products by mixing the dross compositions. This tension creates a balance between minimizing storage constraints and providing sufficient raw material feedstocks to produce the optimal recycled product compositions. Quantifying the cost savings resulting from binning dross materials is not presently included in the current model formulation. Binning introduces model complexity because of requirement to bin the aluminum dross materials in a way to avoid dynamic bin compositions or compositions that fluctuate depending on the aluminum dross shipment schedule. Incorporating a constraint or term in the objective function to model the cost benefits resulting from binning recycled materials is an area of further work.

Identifying opportunities to bin aluminum dross materials without sacrificing performance would further quantify the compositional limitations of the proposed recycling operation and identify opportunities to improve performance from sorting a selection of recycled materials based on composition.

Compositionally sorting secondary materials is a promising upgrading technology to improve raw material value. The potential to increase value is expected to be particularly large in the proposed recycling operation because of the anticipated large degree of compositional variation within the secondary materials. For example, chapter four determined that the high silicon concentration in the aluminum dross and post-consumed scrap limited the ability to increase recycled material content in the downstream remelter production. Dissolving silicon alloying additions during aluminum production can be difficult and as a result silicon aggregates can rise to the dross layer at the surface aided by the density difference between solid silicon and liquid aluminum. Such effects can be mitigated by using additional equipment and care during production, but without proper precaution, silicon aggregates remaining in the dross would be sent to the recycling center for reprocessing. Removing the silicon aggregates from the dross by compositional based sorting methods could reduce the overall silicon composition in the dross and promote incorporation into downstream remelter production. The tendency of impurities in the melt to accumulate in the dross layer during aluminum remelter may offer additional opportunities to increase the value of the dross materials using compositional based sorting techniques. Calculating the shadow prices corresponding to the compositional constraints of the finished alloy products can be performed to identify the secondary materials and corresponding elements to sort upon to maximize profitability. Additional modeling work to identify which secondary materials to sort and the compositional specifications to categorize the sorted groups is necessary. A sorting operation is expected to offer advantages because of the availability limits of several of the aluminum dross and post-consumed secondary materials. Studying the two stage recycling operation in the absence of secondary material availability limits may reveal several opportunities for improvement including: purchasing strategy, upper limits on performance based on the set of presently available secondary materials, and the value of installing a sorting operation relative to pursuing an alternative purchasing strategy.

8.2 Expanded dynamic simulation including time intervals longer than one day

The dynamic simulation performed in this work includes optimization models to calculate the optimal recycling center operation plan based on the downstream remelter order schedule for that particular day. One of the motivations for a daily timeframe was the limited ability of the downstream remelters to predict customer orders over a long time horizon. Additionally, the perishability of the recycled products and the energy required to maintain liquid state necessitates accounting for their incorporation into downstream remelter production within a 24 hour period. To expand the time horizon beyond one day, integer variables to represent the units of heated liquid recycled products and monitor production scheduling must be included to ensure that the recycled products produced on a particular day are consumed or cast as sows on the same day. The introduction of integer variables increases the computational complexity of the model. Formulating operational optimization models with a time scale beyond one day is expected to provide significant performance improvements because of the ability of long term planning to further mitigate the negative effects of stock depletion. The extent the planning horizon can be expanded must be discussed with the downstream remelters based on the availability of their future customer orders. A set of optimization models that describe a longer production period can also help quantify the value of altering the downstream production schedule and alloy production order to increase recycled content. Further discussions with the downstream aluminum producers regarding the feasibility of altering the production schedule are required because of their own extensive internal constraints and concerns. Extending the operational optimization model's time horizon may cause one of the more flexible model formulations to outperform the fixed recipe with flexible production model formulation, which would advocate for providing additional flexibility to the recycling center during daily operations. Although extending the time horizon of the operational optimization models is an effective strategy to mitigate stock depletion, inherent uncertainty in the customer order schedule may limit the extension. Another strategy to mitigate stock depletion is improving the fixed production plan algorithm implemented in the operational optimization models.

The current fixed production operational optimization models calculate the recycling center production plan using an algorithm that converts the allocation of recycled products across the finished alloys calculated by the long term production model to a daily recycled product production plan. Presently the algorithm calculates the daily recycling center production plan using a hierarchical method that selects recycled products based on the calculated weight that can be included in downstream production. An improved algorithm could decide which recycled product to produce on a particular day based on information about potential substitutions between recycled products, combinations of downstream products that are especially able to consume compositionally challenging recycled products, and individual alloy products that are produced infrequently but necessitate a low volume customized recycled product.

8.3 Alternative clustering methods and recourse model formulation

The presented simulation optimization method calculates the recycled product compositional specifications by performing a k-means clustering analysis on the results of the simulation tool. The performance of using compositional specifications determined by the 40th percentile, median, 60th percentile, and upper quartile of each compositional cluster were compared. Performance improvements are expected to result from determining the compositional specifications using alternative techniques, such as excluding non-binding elements from the clustering analysis and selecting the elemental specifications from different regions within the cluster. Such a sensitivity analysis was excluded from the present work to maintain simplicity, but performing the analysis may significantly improve performance. Further increasing the flexibility in determining the compositional specifications by developing a stochastic pooling problem with recourse may also improve performance.

The simulation optimization method provides a method to incorporate demand uncertainty into recycling center design decision making but is an approximation method proposed because of the large size of the two stage recycling operation. A more accurate method to calculate the recycled product compositional specifications in the context of demand uncertainty would be to formulate the long term production model as a stochastic pooling problem with recourse according to the formulation developed by (Li, Armagan et al. 2011). This formulation was not pursued in the present work because the size of the recycling operation problem was much larger than the formulation developed by (Li, Armagan et al. 2011). However, applying the decomposition method developed by (Li, Armagan et al. 2011) to a simplified version of the proposed recycling center may reveal insights about the impact of stochastic demand on the optimal recycling center parameters. Additionally, incorporating stochastic compositions of the aluminum dross and post-consumed secondary materials in addition to stochastic demand may provide recycling designs that improve performance in the presence of downstream demand and compositional uncertainty.

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