Economic and Environmental Evaluation of End-of-Life Aerospace Aluminum Options Using Optimization Methods

by

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Evaluation of the Economics of Aerospace Scrap Sortation Using a Chance-constrained Mathematical Model

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Abstract

The benefits of recycling have long been understood and the conspicuous energy savings of secondary aluminum production have caused aluminum recycling to increase. Obsolete aircraft are a valuable source of aluminum scrap and recent efforts to fortify the aerospace aluminum recycling infrastructure have drawn attention to the potential of sophisticated sorting methods to maximize the economic gain of using aerospace scrap in secondary production. The aim of this research was to use linear optimization to assess the economic viability of sorting technologies for enabling wrought products in general and aerospace alloys in particular to be recycled back to high value applications. A chance-constrained model was used to select the alloys that consumed the largest quantity of aerospace alloys in their production, thereby establishing a strategic portfolio of finished goods. Ten of the fifteen alloys in the portfolio were of the 2xxx and 7xxx alloy series that are standard in the production of aerospace components. An aerospace end-of-life case study was performed in which cases varied by their input scrap streams, each having a compositional uncertainty associated with the different degrees of sorting that methods currently in use and technologies in development can achieve. The chance-constrained model calculated the production cost for each case and determined that when aerospace components were identified to the precision of individual alloys, the production cost was 20.87% lower than the cost for primary production. Using automatically sorted scrap input yielded a production cost that was 5.34% lower than the cost of primary production. Before concluding that the development of sorting technology should only be pursued with a budget of \$0.0743/kT, a break-even point calculated by the model, it is necessary to take into account the fact that dismantled scrap is more expensive than sorted. In addition to performing sensitivity analysis on the scrap prices, future work should test the production of different portfolios of finished goods and take varying demand for each alloy into consideration.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 Introduction

1.1 Aluminum Recycling

Recycling is an obvious way to conserve valuable natural resources, reducing our dependence on finite reserves of metals in the Earth's crust. By making products from recycled materials instead of virgin materials, we conserve land and non-renewable resources, and reduce our energy needs. Recycling metals minimizes the need for mining new minerals and decreases damage to wilderness. The use of scrap in secondary production also conserves landfill space, and recovery of strategic metals inside the United States could significantly decrease dependence on imports.

Another key reason to recycle is that doing so may save energy, consequently reducing acid rain, global warming and air pollution. In many cases, less energy is used in producing secondary materials than in primary production or mining non-ferrous metals from the ground. It takes almost four times more energy per unit mass to produce primary aluminum compared with iron, but for secondary metal production from scrap, thermodynamically it takes 14% less energy to produce secondary aluminum than primary iron [1]. Of all the materials included in Figure 1, aluminum is saves the most energy in secondary production, using 95% less than the amount required for primary production.

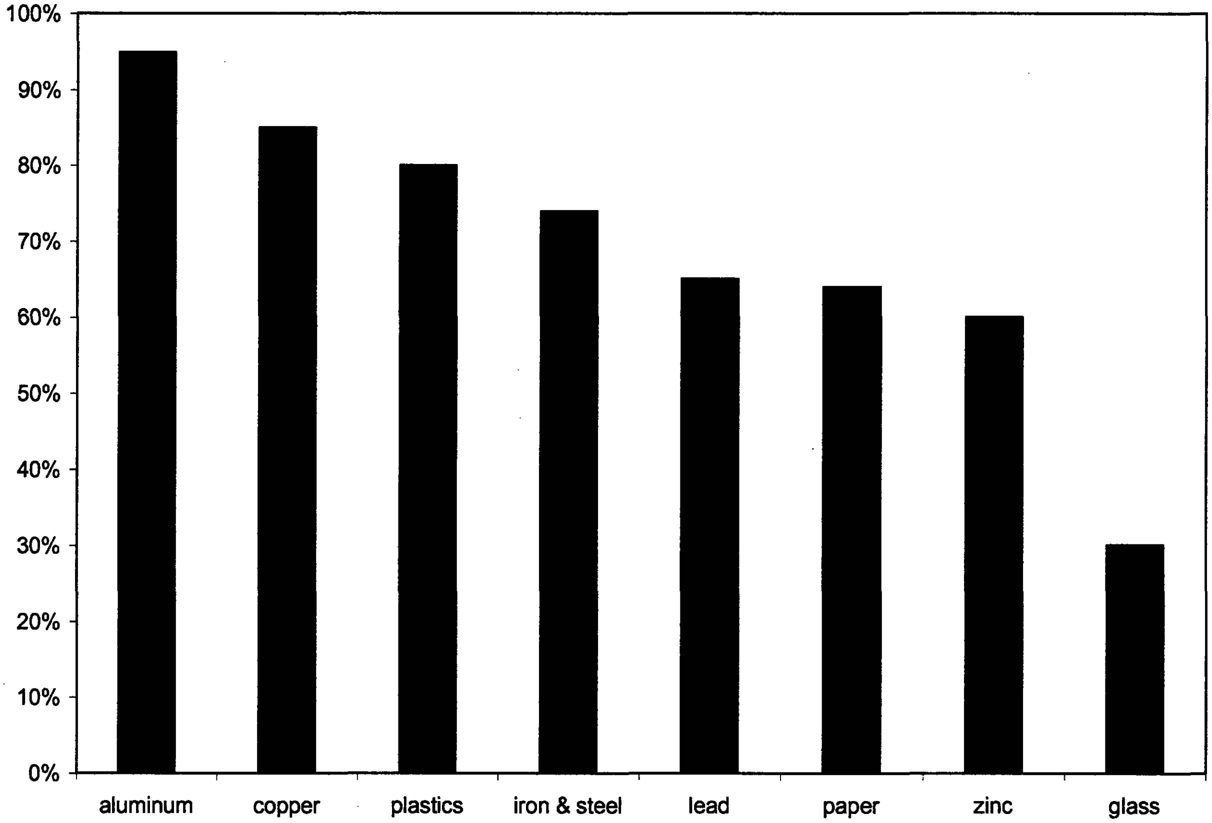

Figure 1. Energy Saved Compared to Primary Production [2].

Often, secondary production can be less polluting than primary production. For instance, producing paper from recycled paper rather than wood results in 35% less water pollution and 74% less air pollution [3]. Producing steel from recycled steel results in 86% less air pollution; scrap-based aluminum production emits significantly less CO_2 as well [3]. More and more today, companies with high energy consumption and high CO_2 emissions are not looked upon favorably by either the general public or the financial community.

According to the Bureau of Mines, aluminum is one of 22 metals that meet three criteria: (1) limited U.S. reserves; (2) extensive industrial use; and (3) strategic importance [4]. Although the cost of primary aluminum has been volatile in the last fifty years, the general trend shown in Figure 2 is that it is increasing [18]. Examining the most recent prices of primary aluminum,

Figure 3 shows that the price has increased by 68.3% in the last ten years and by 84.9% from 2002 to 2006 [18].

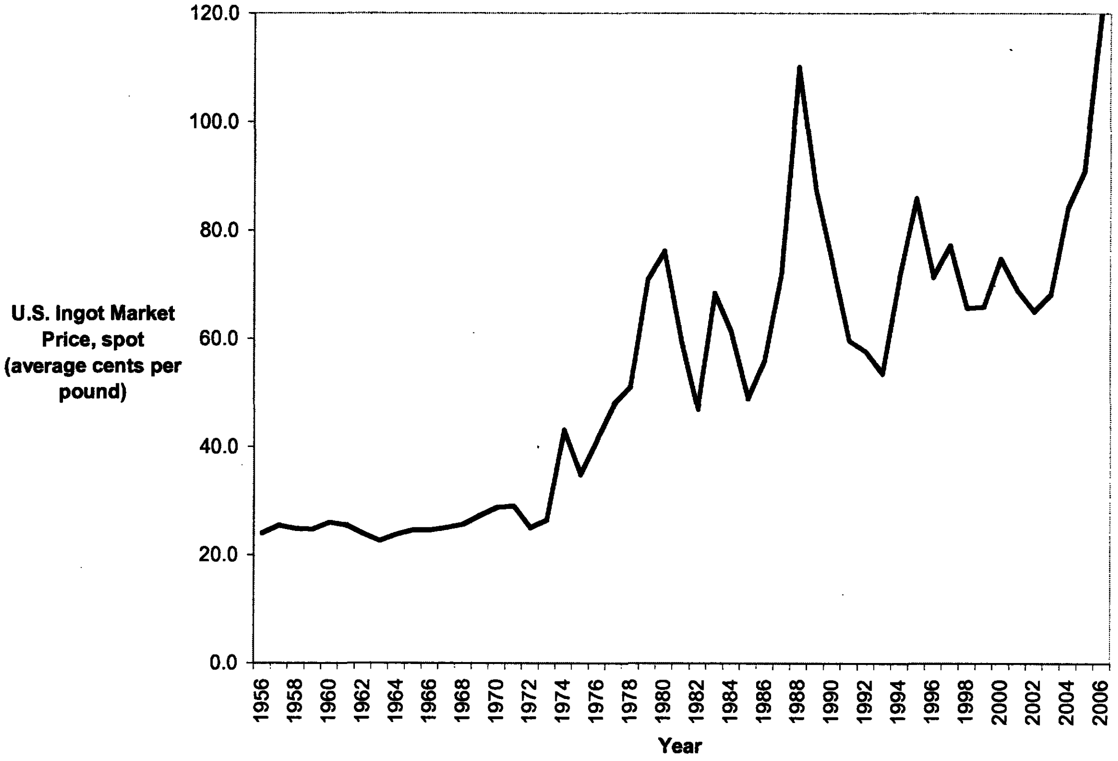

Figure 2. Price of primary aluminum over the last 50 years [18].

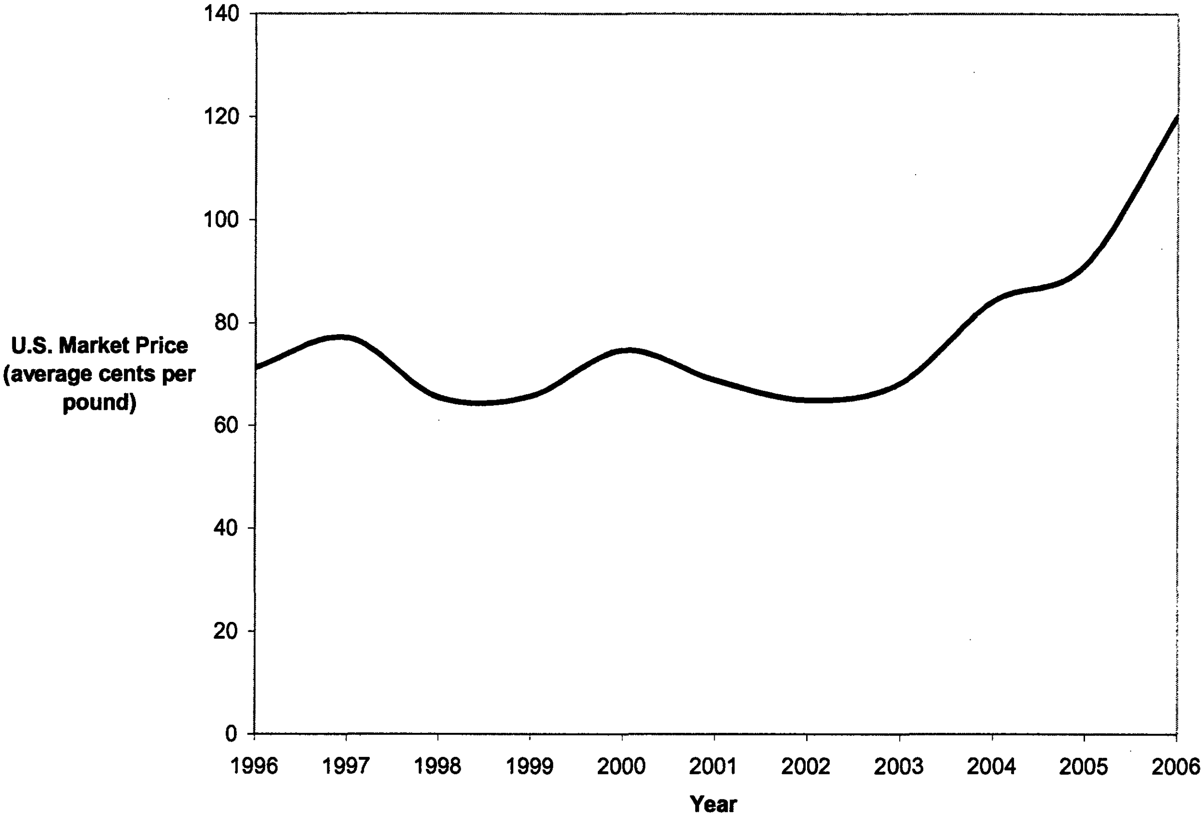

Figure 3. Price of primary aluminum over the past ten years [18].

Old scrap becomes available to the secondary industry when durable and nondurable consumer products are discarded. The secondary production of aluminum has been on the rise since World War II and surged again in recent years, as can be seen in Figure 4 [18].

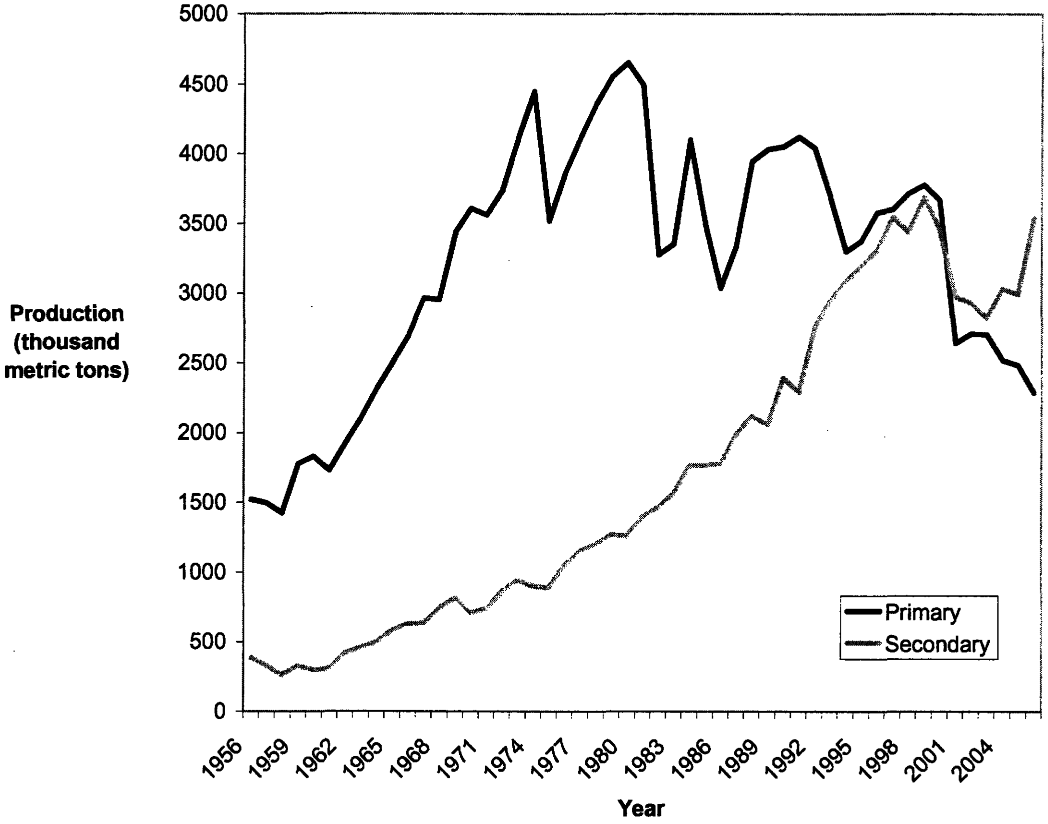

Figure 4. Primary and secondary production of aluminum over the past 50 years [18].

Although increased costs for energy and growing concerns over waste management motivate increased recycling rates, it is the economics of recycling that has sustained the growth of the market for recycled aluminum. To achieve a given output of ingot, recycled aluminum requires only about 10 percent of the capital equipment compared with primary aluminum [1]. The use of scrap offers the opportunity to produce high quality products more economically, provided there are economical and technically feasible recovery technologies available. The economics of recycled aluminum are even more attractive in light of the fact that a large part of the raw materials currently used for virgin aluminum production in the United States are imported. Because the value of recycling is universally recognized, the market for recycled aluminum is robust [17].

Currently, high value wrought products, particularly those from aerospace, are down-cycled into castings and not recycled back into high value forms. Recycling of aerospace alloys empirically has not been significant enough, so aerospace scrap streams often are not sorted [11]. Industry forecasts project that wrought products will represent a growing fraction of future production. According to data from 2005, U.S. net shipments of aluminum wrought products grew 8.8% while shipments of cast products fell 5% over the last three years [21]. These observations pose the following questions that this research attempts to address: Can technological solutions be identified that would allow wrought products in general and aerospace alloys in particular to be recycled back to high value applications? Are sorting or upgrading technologies economically viable to enable this?

2.0 Background

2.1 Aluminum Alloys- The Basics

Aluminum alloys are produced in wrought or cast form. The designation "wrought" indicates alloys that are available in the form of worked products such as sheet, foil, plate, extrusions, tube, forgings, rod, bar, and wire. Under the guidance of the Aluminum Association (AA), the major aluminum producers in the United States have agreed on a four-digit numerical system for designating wrought aluminum alloys. The first digit defines the major alloying class of the series starting with that number and the last two digits designate the specific alloy within the series. Table I lists the wrought alloy series and their major components. The second of the four digits defines variations in the original alloys; it is a zero for the original composition, a one for the first variation, a two for the second variation, and so forth. Variations are typically defined by differences in one or more alloying elements of 0.15 to 0.50% or more, depending on the level of the added element. Alloys with a composition that is still considered experimental have the letter X preceding their designation [5].

Table I. Aluminum alloy series designations.

Wrought	Cast	Major Alloying Element
1xxx	1xx	Al 99% or higher
2xxx	2xx	Copper
3xxx		Manganese
4xxx	4xx	Silicon
5xxx	5xx	Magnesium
6xxx		Magnesium + Silicon
7xxx	7xx	Zinc
8xxx	9xx	Other
	8xx	Tin
	3xx	Silicon with Cu, Mg
9xxx	6xx	Unused Series

The large quantities of aluminum alloy castings produced with high-pressure die, permanent mold, and sand are registered by the AA with the form xxx.x. The first digit has the same significance as the first digit of a wrought alloy designation. The cast alloy series designations can also be found in Table I. The next two digits designate specific casting alloys within the compositional series in the same manner as the last two digits of a wrought alloy designation. In a cast alloy designation, the digit following the decimal indicates the product form. xxx.0 indicates castings, xxx.1 indicates ingot with similar compositional limits as the casting form, and xxx.2 indicates ingot with narrower limits on certain impurities to achieve specific properties in the finished product [5]. A letter in front of the numerical designation denotes a modification to the original casting alloy.

Under the guidance of the AA, a temper system has been developed that identifies the type and sequence of mechanical and thermal operations used to produce the temper. Each temper for any given alloy-product-size combination has specific mechanical property limits, and some have other designated characteristics as well [6].

2.2 Aluminum Alloys in Aerospace

Aluminum's relatively high strength, low density, and excellent corrosion resistance have led to its broad use across the transportation sector. Aluminum has approximately one third the weight of steel and one third the modulus [7]. In a flat sheet, bending stiffness increases as the cube of the thickness. Thus, an aluminum sheet of equal weight per square foot is nine times as stiff as its steel counterpart [7]. Reducing the structural weight of transportation equipment by developing materials that combine relatively low mass with the requisite strength and flexibility reduces fuel consumption and improves performance. Less weight, consistent with other performance and safety requirements, means more useful work can be extracted from a unit of fuel or other energy source. As seen in Figure 5, the transportation sector accounted for 36% of the end-use shipments of aluminum products in the United States and Canada, in 2005 [21].

The aircraft industry was the first to introduce such lightweight materials as aluminum alloys on a widespread scale in the 1920s. The total global consumption of lightweight materials used in transportation equipment was 42.8 million tons/$80.5 billion in 2006 and will increase to 68.5 million tons/$106.4 billion by 2011, at a compound annual growth rate (CAGR) of 9.9% in tonnage terms and 5.7% in value terms between 2006 and 2011 [8]. High strength steel accounts for the largest percentage of total tons of lightweight materials consumed, followed by aluminum and plastics. Motor vehicles, particularly passenger cars and light trucks, are by far the largest end-user segment, while the aircraft industry ranks second in the value of the lightweight materials consumed [8].

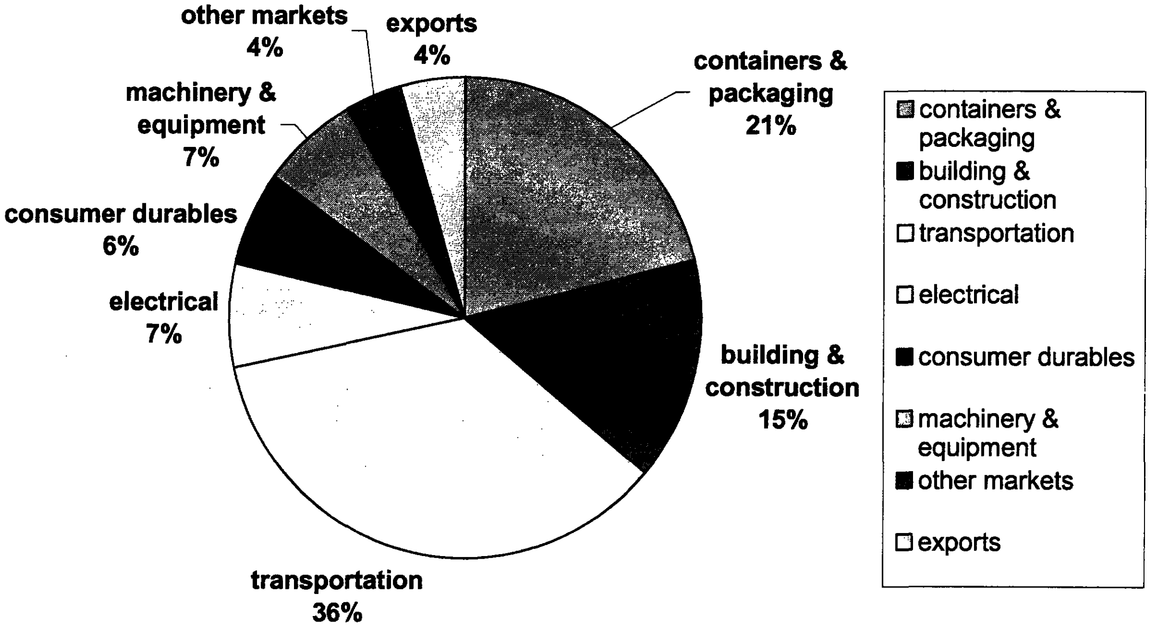

Figure 5. 2005 distribution of end-use shipments of aluminum products in the United States and Canada, by industry [21].

The cylinder block of the engine that powered the Wright brothers' plane at Kitty Hawk in 1903 was cast in an aluminum alloy containing 8% copper. Aluminum parts were used in control mechanisms in 1908; aluminum propeller blades appeared as early as 1907; and aluminum covers, seats, cowlings, cast brackets, and similar parts were common by the beginning of the first World War. In 1916, L. Brequet designed a reconnaissance bomber that marked the initial use of aluminum in the working structure of an airplane. By the end of WWI, the Allies and Germany employed aluminum alloys for the structural framework of fuselage and wing assemblies [7].

Aluminum alloy sheet first appeared as fuselage and wing skin in 1919 on the Junkers F-13. Early development activities, many involving only prototype projects, led to the all-aluminum structure of the CO-1 observation airplane, designed in 1921 by the Engineering Division at McCook Field (now Wright-Patterson Air Force Base). A year later, the United States Navy issued a production order to the Glenn L. Martin Company for the MO-1, the Navy's first essentially all-aluminum land-based monoplane [7].

A method of cladding alloy 2017 with commercial-purity aluminum to improve corrosion resistance was developed during the mid 1920's. Alclad 2017-T4 sheet 0.0095 in. thick was used for the skin of the ZMC-2, the first all-metal airship. Concurrently, the famous Ford Trimotor airplane also employed the new clad alloy. By the early 1930's, aluminum alloys were firmly established as the major airframe material [7].

World War II had an enormous impact on the American aluminum industry. In April 1939, Congress authorized the Army to acquire 6000 airplanes in the next two years and the Navy to procure 3000 planes in the next five years. Because aluminum alloys constituted a high percentage of the weight of a typical airplane and the war was to develop into a struggle largely dominated by aircraft, most wartime production of aluminum had to be utilized for this purpose alone. When government authorities foresaw the scope of the war in the air in 1941, they approved the first government aluminum program. Private industry subsequently expanded as rapidly as possible. Alcoa was already under way with a $300,000 program, and Reynolds

Metals Company entered the business or producing aluminum, assisted by a loan from the Reconstruction Finance Corporation [7]. In addition, the Defense Plant Corporation let contracts for the construction of aluminum plants utilize expensive excess power in large industrial centers. Alcoa had the responsibility of designing, constructing and operating 40 government plants in 25 different locations [7].

At the peak of the war, 1,250,000 tons of aluminum was available annually, including metal purchased from Canada. Total American production in 1939 had been 163,500 tons. The growth in six years was an amazing sevenfold increase [7]. A grand total of 304,000 military airplanes was produced in the United States in 5 ½ years, requiring 1,750,000 tons of aluminum. It was estimated that 85% of the war output went into the aircraft program [7].

Aluminum now is used extensively for airframes, landing gear and wheels, reciprocating and turbine engine components, propellers, systems elements, and interior trim. The Federal Aviation Agency must approve aluminum alloys and their design mechanical properties for use in civil aircraft registered in the United States. In military aircraft, similar approval is the responsibility of the procuring agency. To guide aircraft designers and achieve standardization, a joint effort by the Federal Aviation Agency and the Department of Defense is maintained to approve materials and adopt design mechanical properties [22]. The most important characteristics to consider when choosing an alloy for a specific application are static and fatigue strengths, corrosion, fracture toughness, and ease of fabrication [7].

Of the 1xxx-9xxx groups, Cu-rich 2xxx alloys and Zn-rich 7xxx alloys are the most commonly found in aircraft components. Both series contain heat-treatable alloys. 2024 is one of the most widely used alloys of the aluminum-copper-magnesium class. It was introduced in the 1930's as a higher strength, naturally aging alloy to replace 2017 in the aircraft field [6].

Alloys 2124, 2224, and 2324 are higher-purity variations of alloy 2024. Although the original alloy has been and continues to be useful for transportation applications, controlling impurity elements such as iron and silicon enhanced the toughness needed for critical aerospace applications.

The 7xxx alloys provide the highest strengths of all aluminum alloys [5]. Despite their attractive tensile properties and good fabricating characteristics, these alloys were initially not commercial due to their unsatisfactory resistance to stress-corrosion cracking. The chromium in 7075, introduced in 1943, imparted good resistance to the stress-corrosion cracking of sheet. The higher strength modification 7178 appeared in 1951 and the highest strength aluminum alloy ever commercially available, 7001, was introduced in 1960. More recently, 7x49 and 7x50 alloys, as well as higher purity modifications of 7075, have garnered commercial prominence for their high strength, transverse ductility, and lower quench sensitivity in heavy sections [6].

For applications requiring maximum mechanical properties, alloys 2014, 2024, 7075, 7079, and X7080 are the most frequently used. Alloy 2014 and 2024 forgings are extensively used for airframe components, truck wheel hubs, and ordnance and missile parts. Alloys 7075, 7079 and X7080 are used primarily for airframe applications requiring the highest mechanical properties. Alloy X7080 is particularly useful for heavy-section airframe and landing gear parts involving sections over 3 in. thick and requiring low residual stress, because of its ability to be quenched in boiling water and still retain high mechanical properties [7].

Alloys 2024, 2218, 2219, 2618 and 4032 have good mechanical properties at elevated temperatures. With proper heat treatment they provide maximum dimensional stability, and are employed for aircraft engine pistons, cylinder heads, and other elevated-temperature applications [7].

Aluminum alloy castings traditionally have been used in nonstructural airplane hardware, such as pulley brackets, quadrants, doublers, clips, ducts, and wave guides. They also have been employed extensively in complex valve bodies of hydraulic control systems. The philosophy of some aircraft manufacturers still is to specify castings only in places where failure of the part cannot cause loss of the airplane. Redundancy in cable and hydraulic control systems "permits" the use of castings [7].

Casting technology has made great advances in the last decade. Time-honored alloys such as 355 and 356 have been modified to produce higher levels of strength and ductility. New alloys such as 354, A356, A357, 359 and Tens 50 were developed for premium-strength castings. Alloys A357 and Tens 50 contain small but useful amounts of beryllium. Attainment of premium strength with these alloys requires application of advanced casting technology. The high strength is accompanied by enhanced structural integrity and performance reliability [7].

Table II lists some of the specific applications for aluminum alloys in aerospace [7].

Table II. Aerospace pplications of aluminum alloys [7].

alloy	Aerospace component
142	Cylinder heads of in-line engines of light personal and military aircraft; cast cylinder heads on large radial engines
354	Canopy supports and frames, fuselage members, and heavily loaded pylons that support external loads (high performance aircraft)
355	Crankcase and cylinder blocks for the Allison and Rolls Royce Merlin in-line, liquid-cooled engines; cylinder heads, manifolds, covers, and various fittings for aircraft engines; crankcases for in-line engines of light military and personal aircraft; crankcases, cylinder blocks, and cylinder heads for recent liquid-cooled engines of light personal and military aircraft; the front frame of some turbojet engines
C355	Fuel and oxidizer pump body for the RL-10 liquid rocket engine; wings and fins of smaller liquid-fuel missiles; electronic housings, gyro gimbals, and intricate waveguide assemblies in the electronic and guidance portions of missiles and space boosters
356	Wheels, brackets, bellcranks, pulleys, and various fittings for light planes; valve bodies and fittings in hydraulic and pneumatic systems in aircraft; jet aircraft landing mats
A356	Wheels, brackets, bellcranks, pulleys, and various fittings for light planes; wings and fins of smaller liquid-fuel missiles; electronic housings, gyro gimbals, and intricate waveguide assemblies in the electronic and guidance portions of missiles and space

	boosters
A357	Canopy supports and frames, fuselage members, and heavily loaded pylons that support external loads (high-performance aircraft); wings and fins of smaller liquid-fuel rockets
380	Housings for multiple-point electrical connectors in aircraft systems
A380	Wheels for light aircraft
2014	Landing gear and hydraulic cylinders; wing tension members, shear webs, ribs, and fuselages for light aircraft; skin sheet in the engine areas; the main cylinders of landing gear for older heavy airplanes; heavy-duty forged wheels; skin sheet in heat-affected areas of supersonic aircraft; main spar member of helicopter rotor blades; compressor, diffuser, and impeller parts of early turbojet engines; housings for multiple-point electrical connectors in aircraft systems; valve bodies and cylinders in hydraulic and pneumatic aircraft systems; Hound Dog air-to-ground missile fuselage; wings and fins of smaller liquid-fuel missiles; liquid fuel and oxidizer tanks for smaller liquid-fuel missiles; basic satellite structure of the NASA orbiting astronomical observatory (OAO)
2024	Skin sheet on light airplanes of recent design; external skin sheets in larger light aircraft; fuselage, fuselage longerons, leading edge wing skins, and rivets for sheet assembly in light aircraft; thin skins for trim tabs, servo tabs, control surfaces, flaps, and non-load-carrying access door; skin sheet in supersonic aircraft; main spar member for helicopter rotor blades; helicopter blade skins; helicopter cabin and fuselage sheet bulkheads, stringers, and skins; helicopter landing skids; helicopter synchronizing and drive shafts; aluminum screws, bolts, and nuts made to military specifications; electronic cabinets used in ground support equipment (large console unit); aircraft systems conduit (employed extensively in the wing area); hydraulic and pneumatic systems in aircraft (systems for dispersion of anti-icing fluids, and for actuation of brakes, flaps, control servos, and landing gear); hydraulic fittings meeting military standards and approved by the Federal Aviation Agency; engine fairing for the Jupiter missile; antislosh baffles and fin of Saturn V launch vehicle
2017	Rivets for sheet assembly of light aircraft
2117	General structures,especially automatic riveting; rivets for sheet assembly of light aircraft
2018	Forged pistons for large radial air-cooled engines
2218	Forged cylinder heads for large radial air-cooled engines; forged pistons for large radial air-cooled engines
2618	Skin sheet for heat-affected areas of supersonic aircraft; compressor, diffuser, and impeller parts for more recent turbojet engines; the stator and rotor blades in the compressor stage of turbojet engines; wings and fins of smaller liquid-fuel missiles
2025	Aircraft propellers of smaller sizes
2219	Rivets; skin sheet in the engine areas; sheet, rivets, and forgings in the engine pods of supersonic aircraft; fuel tank of the Bomarc antiaircraft missile; tank sidewalls and ends for the Saturn V launch vehicle
3003	Space chamber cryopanels (panels maintained at a cryogenic temperature to simulate the heat absorption characteristics of space); electronic cabinets used in ground support equipment (small black box size); low-stressed structure in light aircraft; lubricating oil and hydraulic oil tanks in light aircraft; piping, instrument tubing, brazed heat exchangers, and hydraulic accessories of light aircraft; helicopter blade honeycomb core; radiators and oil coolers for aircraft engines; aircraft systems conduit (employed extensively in the wing areas); air-conditioning ducts

4032	Aircraft engine pistons; forged pistons for large radial radial air-cooled engines
5052	Low-stressed structure in light aircraft; fuel, lubricating oil, and hydraulic oil tanks in light aircraft; piping and instrument tubing for light aircraft; wing panels of supersonic bombers; helicopter blade honeycomb core; fuel and oil lines; internal fuel and oil tanks; hydraulic and pneumatic systems in aircraft (systems for dispersion of anti-icing fluids, and for actuation of brakes, flaps, control servos, and landing gear); storage bottles for liquid oxygen; low-pressure lines in oxygen systems; backup panels for padded and fabric-covered installations in aircraft interior trim; fuel and oxidizer tankage for Redstone, an early liquid-fueled ballistic missile; jet aircraft landing mats
5056	Rivets
5456	Construction of space chambers (enclosures evacuated to sufficiently low pressures to simulate outer space)
5083	See 5456
5086	Fuel and oxidizer tankage for the Jupiter ballistic missile
5454	See 5456
6061	Low stressed structure in light aircraft; fuel, lubricating oil, and hydraulic oil tanks in light aircraft; piping, instrument tubing, skin, miscellaneous fittings, brazed heat exchangers, and hydraulic accessories for light aircraft; thin skins for trim tabs, servo tabs, control surfaces, flaps, and non-load-carrying access door; main spar member for rotor blade of helicopter; helicopter blade skins; radiators and oil coolers for aircraft engines; the front frame of some turbojet engines; housings for multiple-point electrical connectors in aircraft systems; aircraft systems conduit (employed extensively in the wing areas); fuel and oil lines; tip and external fuel and oil tanks; hydraulic and pneumatic systems in aircraft (for dispersion of anti-icing fluids, and for actuation of brakes, flaps, control servos, and landing gear); valve bodies, reservoirs, fittings, and accumulators in hydraulic and pneumatic systems in aircraft; air-conditioning ducts; backup panels for padded and fabric-covered installations in aircraft interior trim; jet aircraft landing mats; missile and engine containers; antennas for radar and radio ground support equipment
6063	See 5456
6151	Forged crankcases for large radial air-cooled engines; valve bodies in hydraulic or pneumatic systems in aircraft
6951	Brazed heat exchangers and hydraulic accessories for light aircraft; radiators and oil coolers for aircraft engines
7075	Integrally stiffened aircraft wing panel; high-shear-strength fasteners; rivets; external skin sheets in larger light aircraft; upper skins and spar caps of wings for light planes; fuselage and fuselage longerons for light aircraft; keel members for the fuselage on larger aircraft; thin skins for trim tabs, servo tabs, control surfaces, flaps, and non-load-carrying access door; machining stock for spar caps in high-performance aircraft; wing skins of high-performance aircraft; wing panels for supersonic bombers; helicopter cabin and fuselage sheet bulkheads, stringers, and skins; helicopter landing skids; cylinders in hydraulic and pneumatic aircraft systems; forward skirt structure, intertank structure, center engine support, thrust column, upper thrust ring, lower thrust ring, engine fairing, and fin of Saturn V launch vehicle; cylindrical intertank structure to transmit thrust loads between fuel and oxidizer tanks; liquid rocket engine components; skirt area and heads of solid-fuel rocket motor cases; hydraulic system components in space boosters; electronic

	cabinets used in ground support equipment (large console unit)
7076	The largest blades of propellers for light planes
7079	Fuselage for light aircraft; the main cylinders of landing gear for more recent heavy airplanes; machining stock for spar caps in high-performance aircraft; wing ribs and bulkheads of high-performance aircraft; cylinders in hydraulic and pneumatic systems in aircraft; skirt area and heads of solid-fuel rocket motor cases
7080	Thick parts
7178	Structural members where performance is crucial under compressive loading; high-shear-strength fasteners; upper skins and spar caps of wings for light planes; keel members for the fuselage on larger aircraft; antislosh baffles of Saturn V launch vehicle; jet aircraft landing mats

Aluminum, which is the primary aircraft material, comprises about 80 percent of an aircraft's unladen weight [19]. The standard Boeing 747 jumbo jet contains approximately 75,000 kg of aluminum [19]. Of the thousands of aircraft models in existence, the manufacturer's empty weight (MEW) was calculated for a few in each of the following categories: small commercial aircraft, large commercial aircraft, and military aircraft. The MEW is defined as the weight of the structure, powerplant, furnishings, systems, and other items of equipment that are considered an integral part of a particular airplane configuration [9].

Table III. Manufacturer's empty weight of various aircraft [9].

Category	Model	Weight (lbs)
Small commercial aircraft	CITATION-500	6,379
	MDAT-30	20,465
	MDAT-50	26,685
	F-28	33,505
	MDAT-70	34,140
	DC-9-10	48,075
	BAC-111	51,762
	DC-9-30	55,930
	737-200	57,452
	727-100	84,850
Large commercial aircraft	727-200	95,695
	707-320	125,176
	DC-8-55	133,471
	DC-8-62	136,065
	DC-10-10	226,750
	L-1011	229,014
	DC-10-40	249,735
	747	333,567
	SCAT-15*	301,224
Military aircraft	C-130A	60,499
	C-130E	68,687
	KC-135A	92,678
	C-133B	120,425
	C-141A	128,640
	C-5A	322,657
	AST(M)*	112,670

As indicated in Table III, weights of small commercial aircraft range from 6,300-85,000lb [9]. The average weight of the models listed for that category is approximately 42,000lb [9]. Weights of large commercial aircraft range from 95,000-334,000lb [9]. The average weight of the models listed is approximately 203,400lb [9]. Planes in the third category, military aircraft, can weigh between 60,000-323,000lb [9]. The average weight of the military aircraft models listed in Table III is approximately 129,500lb [9].

2.3 Aerospace at End-of-Life

Aircraft face a number of fates at their end-of-life. About 300 aircraft worldwide are retired each year [10]. Aircraft dismantling and recycling companies currently handle between 100 and 120 aircraft a year [10]. Of the remaining retired aircraft, some are parked in the desert, waiting to return to service. Newer aircraft whose parts are currently in demand, such as A320s, are sold piece by piece. The engines, landing gear, avionics, rotational parts and components are removed because they are reusable and hence the most profitable. Older aircraft with less demand for their parts often just corrode because they have been abandoned. Such desertion of aircraft usually takes place in parts of Africa and some countries in the Soviet Union where recycling infrastructure is lacking.

2.3.1 Dismantling

Obsolete aircraft can be dismantled into component groups composed of alloys of the same series, so that landing gears, engine nacelles, tail sections, and flaps are presorted and wings are separated from fuselages [11]. For a more thorough breakdown of aerospace vehicle and equipment by alloy composition, see Table II in section 1.2. Figure 6 is a schematic explaining the available aerospace end-of-life options.

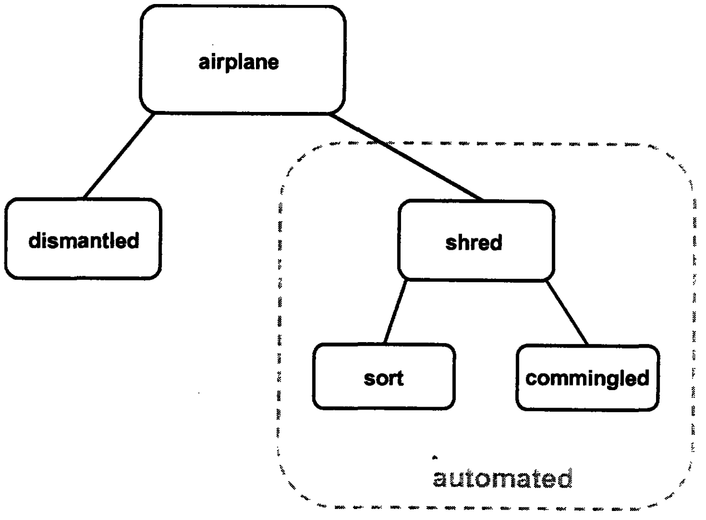

Figure 6. End-of-life options for obsolete aircraft scrap.

Aircraft manufacturers and industry stakeholders have only recently undertaken the effort to investigate methods of recycling retired aircraft. The Aircraft Fleet Recycling Association (AFRA), formed by Boeing in June 2006 to recycle aircraft, now has 21 members. Along the same lines, a €2.4 million project called PAMELA (Process for Advanced Management of End-of-Life Aircraft) was started by European aircraft maker Airbus to enable the testing of processes for dismantling materials in end-of-life aircraft and to demonstrate that by 2015, 85% of an aircraft's parts and materials can be safely recycled or reused [12]. Even after reusable parts are removed, recycling the remaining metal may be beneficial. "The raw materials are going to become more and more expensive and if we manage to extract them very finely, it will be possible to get the full price for the...aluminum," said Jean-Luc Taupiac of Airbus [13]. An Airbus A300 plane flown to a French aircraft recycling plant for PAMELA's implementation in February 2006 had a life span of 30 years before it was dismantled. Regardless of how life spans of newer planes compare to those of the older ones, the number of planes to be recycled in the future far surpasses past inventory, emphasizing the need for a more organized approach to the recycling of aviation scrap. At an approximate rate of 300 per year, more than 6000 civil aircraft are forecast to arrive at end-of-life in the next 20 years, forging an incredible market [12]. Taupiac said, "The growth curve is exponential. Just compare the hundred planes made each year in the 1970s with the 700 aircraft made in 2005 [13]." Taubiac is in charge of the aircraft recycling plant in Tarbes, France that treated the Airbus A300 flown there in February 2006; that new facility reflects the boom in aircraft recycling created by the explosion in the number of old planes seeking to be dismantled an increasing number of companies interested in performing the dismantling.

The industrial phase of 2006's PAMELA test project was initiated on June 22, 2007 when the TARMAC (Tarbes Advanced Recycling & Maintenance Aircraft Company) AEROSAVE project bred the first industrial firm for the dismantling of end-of-life aircraft. Jean Macheret, Vice President Strategy and Development at Snecma Services (the engine MRO specialist in the SAFRAN Group), identified TARMAC as an additional supply source for aluminum alloys that could be reused in the SAFRAN Group's manufacturing processes and asserted that "we intend to duplicate this type of project around the world [14]."

2.3.2 Sorting

Not only are efforts to dismantle obsolete aircraft proliferating, but AFRA members such as Milled Carbon, Huron Valley Fritz West (HVFW) and Aircraft End-of-Life Solutions (AELS) network through AFRA on new technologies to separate alloys in melted aviation scrap. AFRA member HVFW is developing laser technology that is on the forefront of such sortation techniques. Their technology sorts aluminum alloy series from military and commercial aircraft and can separate 40 to 50 percent of the aluminum of an aircraft [10].

Of the sortation methods in use now, many are not sophisticated enough to differentiate between specific aluminum alloys or even wrought alloys in different series. Spark testing, chemical analysis, and heavy media separation are some of these crude sortation methods. In spark testing, the operator touches the sample to a grinding wheel and identifies the metal type by examining the spark generated. Titanium can be sorted from aluminum but it would not be possible for the operator to even determine the aluminum alloy series. With chemical analysis, an operator can guess the type of alloy under consideration, apply drops of chemicals onto the sample surface, and confirm the identity of the alloy by comparing the change in coloration to a table of results. Equally time consuming is the heavy media separation method in which various metals having a range of densities are placed into a liquid bath containing a fine suspension of water and magnetite. The quantity of magnetite in suspension is adjusted so that the apparent density of the fluid is in between the specific density of the alloys that are to be sorted. Since aluminum has a specific density of 2.7 and most of the other heavy nonferrous metals have specific densities on the order of 6.0–7.0 or above, the aluminum floats to the top of this fluid suspension while the heavier nonferrous metals will sink. Heavy media separation effectively sorts mixed aluminum from other heavier nonferrous metals but cannot sort 2000 series aluminum from 3000 series or 5000 series [15].

Alternately, hand-held spectrographic analyzers such as the Spectramet technology developed by Spectro or similar devices manufactured by Vericheck Technical Services, Thermo Electron, Niton, and Innovex can sort a wide range of metals into various alloy types. The Spectramet technology uses an optical emission spectrograph (OES). An arc or spark is applied to the sample and sensitive light detectors read the light spectrum emitted from the spark. The spectrum is characteristic of the alloy and can be used to identify the composition of the alloy. Other handheld analyzers generate x-ray florescence (XRF) from the unknown sample. In the case of both XRF and OES analyzers, it is necessary to push the analyzer against the sample surface. The time required to develop a valid spectrum can vary from a few seconds to one-half minute or more. In many cases the output can be a quantitative analysis showing the percentage of each element present. In other cases, the output includes an estimate of the particular alloy that was examined. Optical emission spectrograph analyzers work well on aluminum samples. However, XRF analyzers do not work well on aluminum samples because the XRF emissions from aluminum have such low characteristic energy levels that the XRF is quickly absorbed in small amounts of air. Thus, the signal output is typically so low that the detectors cannot read it [15].

The highest degree of scrap metal sortation currently possible is achieved using the laser-induced breakdown spectroscopy (LIBS) method developed by Huron Valley Steel Corp. (HVSC). LIBS is a sorting technology that utilizes a laser beam to produce the same type of light emission plasma as is produced using the OES methods. Whether LIBS is discriminating enough to differentiate between the impurity levels of higher toughness alloys 2124, 7175, and 7475 as opposed to alloys 2024 and 7075 is a question to address to HVSC scientists and other manufacturers.

Given the room for growth of these sortation technologies, a case study examining the behavior of secondary production cost and scrap use in response to different degrees of scrap sortation could yield the break-even points that determine whether or not certain sortation technologies are worth developing.

3.0 Methods

3.1 Linear Optimization

To identify ways of maximizing usage of scrap from discarded aircraft, a mathematical optimization model is needed to represent the primary and scrap inputs and to output the most economical allocation of these resources in secondary production. The linear programming procedure used must be able to account for the compositional uncertainty of the scrap streams. Deterministic approaches use mean expected conditions and therefore cannot consider uncertainty in the decision-making. Other shortcomings include that the mean-based method assumes that deviation from a compositional value has symmetric consequences, which is not the case. Exceeding a maximum compositional limit increases production cost more than failing to meet a compositional minimum, since dilution with primary metal is often more expensive than addition of alloying element. Another common practice, the window narrowing method, sets production targets well inside the window of compositional specification required for performance reasons. This paper utlizes a third option, a chance-constrained optimization method which embeds the mean and variance of available raw materials into one of model's parameters, the coefficient of variance (COV):

$$\mathrm{COV} = \sigma / \mu \tag{1}$$

The COV can be used in conjunction with a confidence parameter so that the user can find optimal solutions at specified levels of confidence for meeting the compositional specifications.

To determine which modeling method to use, the author consulted Gaustad et al's [16] case study that compared the mean-based, chance-constrained, and 30% window narrowing methods where scrap compositions ranged two standard deviations from the mean and a 70% window was used for the third case. The chance-constrained stochastic programming method provides both increased scrap consumption and associated economic benefits over the mean-based and window-narrowing modeling methods. Although the optimal solution generated by the mean-based method used more scrap and costs less than the other two methods, the mean-based case yielded the highest error rate when tested by the Monte Carlo simulations; its error rate of 98.6% discounted it from further study.

The most striking difference between the chance-constrained and window narrowing result is the dramatic increase in the number and types of scraps used by the output of the chance-constrained model. Gaustad et al's results showed that the window-narrowing optimal solution can only approach or exceed the scrap usage of the chance-constrained solution by increasing its error rate. The chance-constrained method also showed the lowest error rate and production cost in response to increasing uncertainty in scrap composition (For more detail, refer to Gaustad et al. [16]. Since benefits of the chance-constrained method grow with increase in compositional uncertainty and are driven by scrap portfolio diversification, it is a model well-suited for assessing resource allocation in cases of varying degrees of scrap sortation that would also correspond to a wide spectrum of compositional uncertainty.

3.2 Chance-constrained Model

To formulate the scrap charge optimization problem as a chance constrained linear programming problem, the goal of combining the raw materials so that the composition of finished goods falls within desired maximum and minimum targets has to be captured in the constraints. The aim of this study is to minimize the production cost. The variables to be reported in the optimal solution are the amount of scrap purchased, the amount of primary material purchased, and the amount of each scrap used to make each finished good. Unlike the variables, the parameters of the model are constants. They include the demand for each finished good, the number and type of each finished good, the number and type of primary materials, the number and type of scrap, the prices of the primary materials, the number of compositions, scrap availability, and COV.

The mathematical formulation for the chance-constrained model is as follows [16]:

$$\text{Min: } \sum_s C_s P_s + \sum_p C_p P_p \tag{6}$$

$$\text{Subject to: } P_s \le A_s \tag{7}$$

$$P_p \le A_p \tag{8}$$

$$\sum_s P_{sf} + \sum_p P_{pf} = B_f \ge M_f \tag{9}$$

For each alloying element *c*, the composition of each alloy produced must meet production specifications:

$$\sum_s P_{sf} U_{sc} + \sum_p P_{pf} U_{pc} + X(\alpha)\Big(\sum_s \sum_t \rho_{st}\sigma_s\sigma_t x_s x_t\Big)^{1/2} \le B_f U_{fc}\alpha \tag{10}$$

$$\sum_s P_{sf} L_{sc} + \sum_p P_{pf} L_{pc} + X(1-\beta)\Big(\sum_s \sum_t \rho_{st}\sigma_s\sigma_t x_s x_t\Big)^{1/2} \ge B_{fz} L_{fc}\beta \tag{11}$$

All other variables are defined below:
C_s = unit cost (\$/T) of scrap material *s*
C_p = unit cost of primary material *p*
P_s = amount (kt) of purchased scrap material *s*
P_p = amount (kt) of purchased primary material *p*
A_s = amount of scrap material *s* available for purchasing
A_p = amount of primary material *p* available for purchasing
P_{pf} = amount of scrap material *s* used in making finished good *f*
B_f = amount of finished good *f* produced
M_f = amount of finished good *f* demanded
U_{sc} = max. amount (wt. %) of element *c* in scrap material *s*
L_{sc} = min. amount of element *c* in scrap material *s*
U_{pc} = max. amount of element *c* in primary material *p*
L_{pc} = min. amount of element *c* in primary material *p*
U_{fc} = max. amount of element *c* in finished good *f*
L_{fc} = min. amount of element *c* in finished good *f*

4.0 Case Study

The dismantling and sortation options discussed in 1.3 generate an array of scrap sets that vary in the precision of alloys identified. The highest level of sortation possible would be able to differentiate between individual alloys, this would be a dismantled case. It can be conjectured that dismanlting will separate the components into the seven listed alloys that are widely found in aircraft. 2024 has historically been the most prevalent 2xxx alloy in the older aircraft more likely to be found in graveyards and 7075 the most widely used of the 7xxx series. The more high-purity alloys 2124, 2324, 7050, 7175, and 7475 are found in newer aircraft.

In the sorted case, a technology such as LIBS can only identify alloy series, therefore the compositions of recycled aircraft components might resemble a series average 2xxx alloys have high Cu, Mg, Mn and Si content while 7xxx alloys have high Zn, Cu, and Mg content. Table VI indicates that the composition of the 2xxx scrap type in the sorted case most closely resembles that of alloy 2024, and the composition of the 7xxx scrap type most closely resembles that of 7075. Hence, the properties of the two scrap types in the sorted case are likely to take after those of 2024 and 7075 [11].

If 2xxx and 7xxx alloys cannot be separated before melting, the composition of the resulting scrap can be taken to be an average equally weighted between the seven alloys (commingledA). Alternatively, this unsorted scrap set could be characterized by an average of the compositions of the two series-specific scrap types in Case2 (commingledB). The composition of either unsorted scrap set does not match any existing registered alloy. Table VI specifies the cases to be tested.

In order to test the cases, we needed to define a portfolio of finished goods that may be able to utilize the aerospace-derived scrap sets specified previously. To identify the fifteen aluminum alloys that have the ability to utilize the most scrap in their production, the model was run testing all the scrap types in Table VI with an arbitrarily chosen COV of 15%, seven primary materials as available raw materials, and a comprehensive list of cast and wrought alloy outputs as shown in Appendix A and B. The fifteen top scrap consumers each utilized more than 50kT of scrap input, so they were selected for further study.

Demand for each finished good was assumed to be 100 kton. The finished goods are produced from 7 primary materials and various scrap streams at an availability of 10,000kton each. All raw materials were not limited in their availability. Due to the lack of pricing information, it was assumed that all scraps cost $1000 per metric ton. The prices of the primary materials in Table IV were obtained from the London Metal Exchange (LME) and their compositions in Table V were specified by the average of the minimum and maximum weight fraction concentration limits for the following elements: Si, Mg, Fe, Cu, Mn, Zn [23].

Table IV. Prices of primary input materials [23].

Primary Material	Price
P1020	1.36
Silicon	1.88
Manganese	2.02
Iron	0.32
Copper	2.66
Zinc	0.98
Mg_Raufoss	2.27

Table V. Average weight fraction compositions of primary materials [23].

Averages	Si	Mg	Fe	Cu	Mn	Zn
P1020	0.0005	0	0	0	0	0
Silicon	0.985	0	0	0	0	0
Manganese	0	0	0	0	0.999	0
Iron	0	0	0.999	0	0	0
Copper	0	0	0	0.999	0	0
Zinc	0	0	0	0	0	0.999
Mg_Raufoss	0.0005	0.999	0	0	0	0

Table VI. Scrap types and their weight fraction compositions, by case [11].

Case	Scrap type	Si	Mg	Fe	Cu	Mn	Zn
Dismantled	2014	0.0085	0.005	0.0035	0.0445	0.008	0.00125
	2024	0.0025	0.015	0.0025	0.0435	0.006	0.00125
	2324	0.0005	0.015	0.0006	0.041	0.006	0.00125
	7050	0.0006	0.0225	0.00075	0.023	0.0005	0.062
	7075	0.002	0.025	0.0025	0.016	0.0015	0.056
	7475	0.0005	0.0225	0.0006	0.0155	0.0003	0.057
	7178	0.0025	0.0275	0.0035	0.02	0.0015	0.068
Sorted	R2xxx	0.005	0.01	0.005	0.044	0.007	0.001
	R7xxx	0.002	0.025	0.004	0.02	0.002	0.06
CommingledA	avg(dismantled)	0.002443	0.018929	0.001993	0.029071	0.0034	0.03525
CommingledB	avg(sorted)	0.0035	0.0175	0.0045	0.032	0.0045	0.0305

After developing a finished good portfolio as described previously, each of the four cases were tested in the model with the selected portfolio of fifteen finished goods at an arbitrarily chosen, constant COV of 15% to see how production cost and scrap use would change according to each of the end-of-life scenarios. After performing this base case, it was acknowledged that the scrap compositions across the sorting cases must be associated with different values of COV. Lacking a method of determining the discrete COV for the scrap compositions of each case, each case was tested in the model with a spectrum of COV values. This not only provided the freedom to estimate the COV associated with a given level of sortation, but allowed observation of the behavior of the objective function with respect to changes in COV.

5.0 Results & Discussion

5.1 Analysis of Possible Finished Goods Portfolio

The total scrap usages of all the alloys in the finished goods portfolio are compared in Figure 7. Not surprisingly, three of these alloys are among the scrap types of the input for the dismantled case: 7178, 7075, 2024. It is also not surprising that the alloy 2124 should be among the fifteen that consume the most scrap available, since both 2024 and 2324 are in the dismantled scrap stream. It is interesting to see not only that a third of the portfolio are cast alloys of the 3xx series, but that these finished goods are among the top two-thirds of the scrap consumers in the portfolio. Otherwise, the remainder of the portfolio, consisting of 2xxx and 7xxx wrought alloys, is expected because the alloys most suitable for making aerospace components are the ones likely to consume the most aerospace scrap.

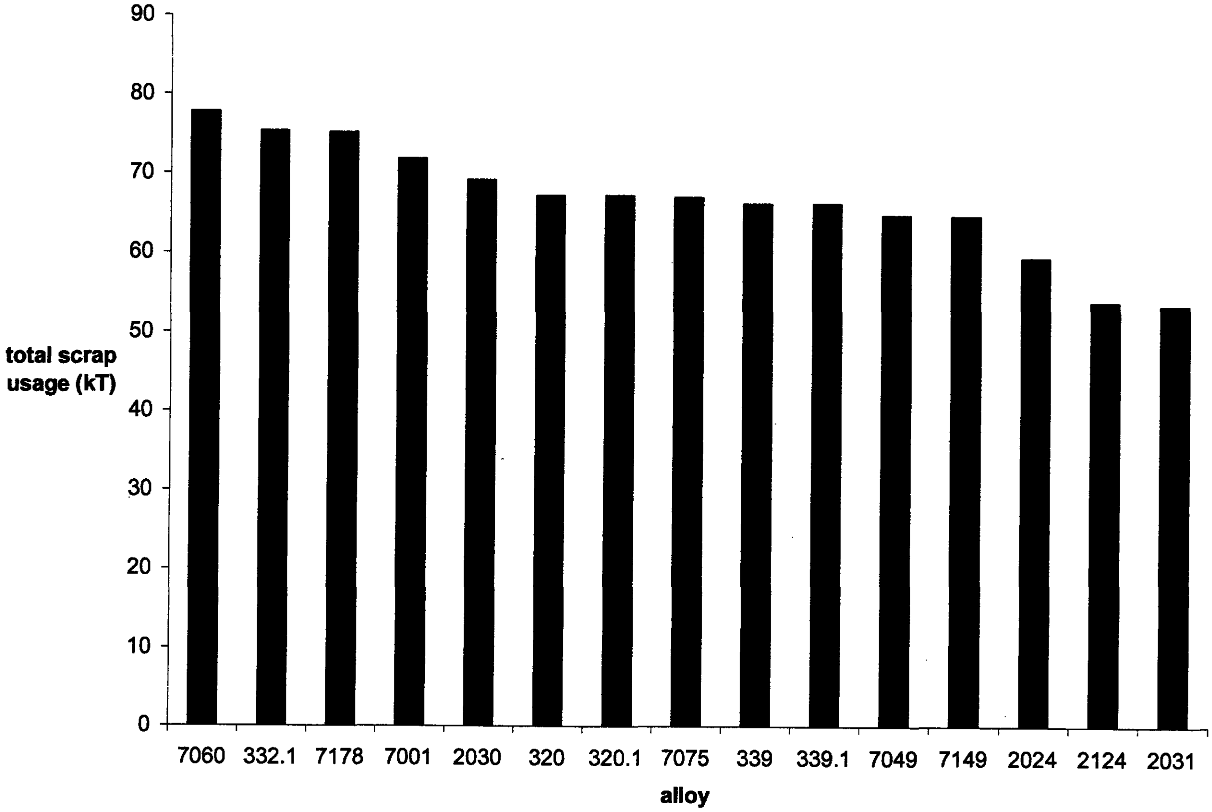

Figure 7. Total scrap usage of all 15 alloys in the finished goods portfolio.

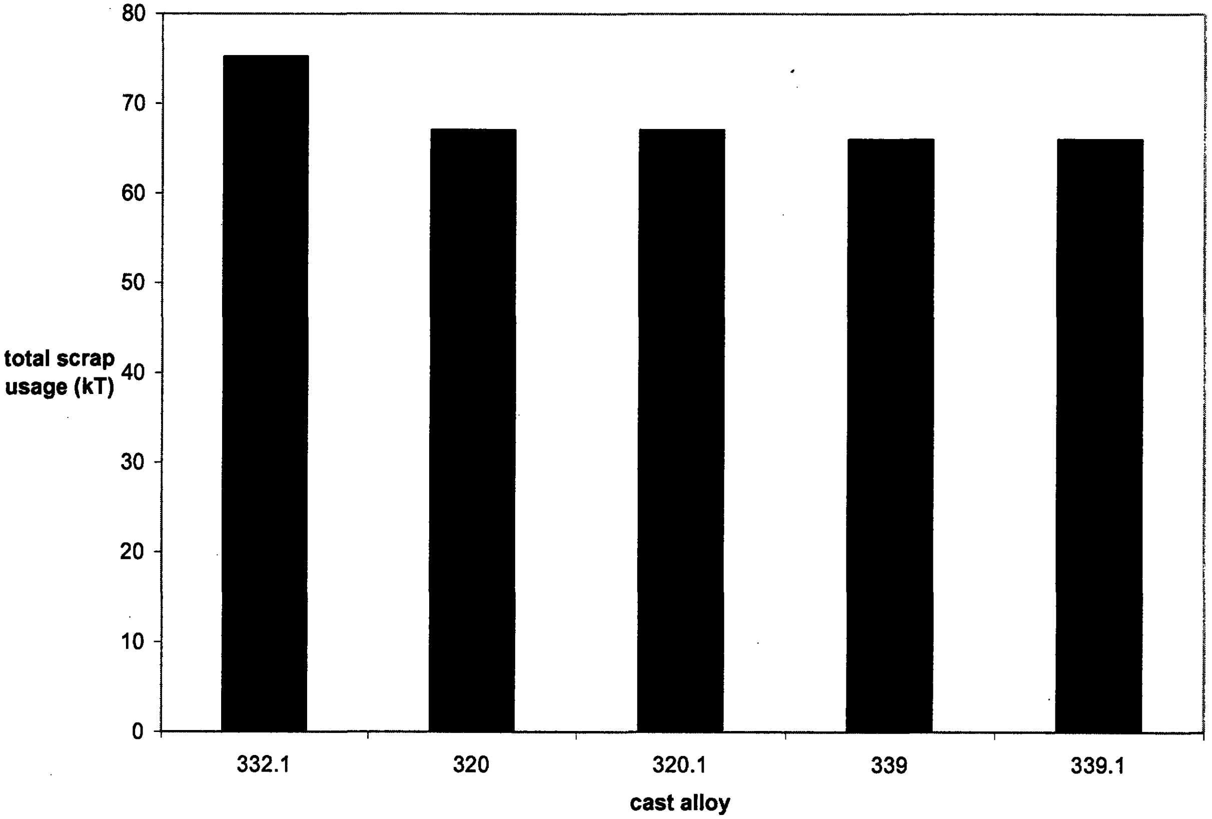

Figure 8. Total scrap usage of alloys in finished good portfolio, cast alloys only.

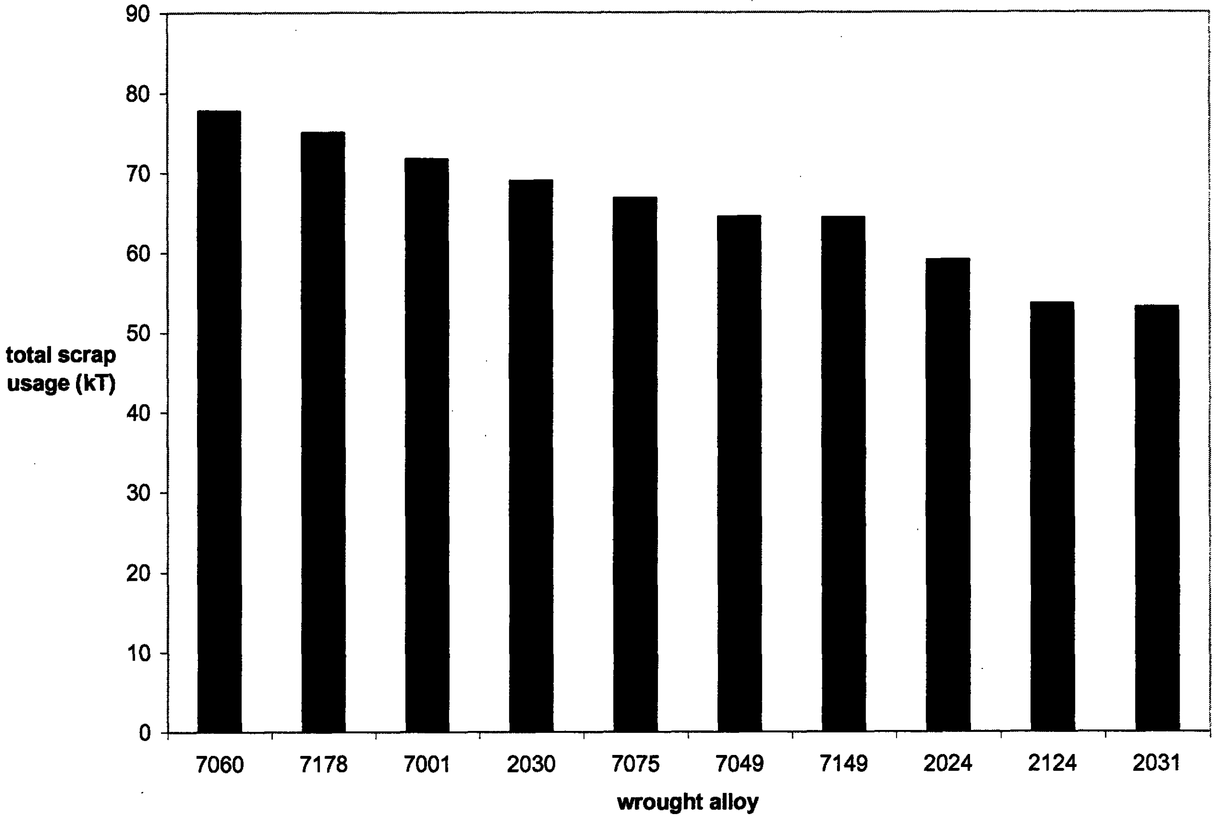

Figure 9. Total scrap usage of alloys in finished goods portfolio, wrought alloys only.

When scrutinizing the compositions in Table VII, it can be noted that the average weight fraction of silicon in the 3xx cast alloys exceeds that of all the scrap types by at least a factor of ten, signifying a far higher silicon content in the cast alloys that consumed scrap. However, their average weight fraction of copper is always intermediate between that of the 2xxx and 7xxx scrap inputs. The average weight fraction of zinc for the 7xxx alloys in the portfolio are either the same as that for the scrap input 7178, or higher. The average weight fraction of copper for the first and fourth highest scrap consumers, 7060 and 7001, resembles the averages for scrap inputs 7050 and 7178. The 7xxx alloys that consume on the lower end of the portfolio, 7049 and 7149, have an average weight fraction of copper that closely resembles to the input scrap 7475.

Table VII. Weight fraction compositions of each alloy in the finished goods portfolio.

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
7060	0.0015	0	0.021	0.013	0.002	0	0.026	0.018	0.002	0	0.075	0.061
7178	0.004	0	0.031	0.024	0.005	0	0.024	0.016	0.003	0	0.073	0.063
7001	0.0035	0	0.034	0.026	0.004	0	0.026	0.016	0.002	0	0.08	0.068
7075	0.004	0	0.029	0.021	0.005	0	0.02	0.012	0.003	0	0.061	0.051
7049	0.0025	0	0.029	0.02	0.0035	0	0.019	0.012	0.002	0	0.082	0.072
7149	0.0015	0	0.029	0.02	0.002	0	0.019	0.012	0.002	0	0.082	0.072
332.1	0.105	0.085	0.015	0.006	0.009	0	0.04	0.02	0.005	0	0.01	0
320	0.08	0.05	0.006	0.0005	0.012	0	0.04	0.02	0.008	0	0.03	0
320.1	0.08	0.05	0.006	0.001	0.009	0	0.04	0.02	0.008	0	0.03	0
339	0.13	0.11	0.015	0.005	0.012	0	0.03	0.015	0.005	0	0.01	0
339.1	0.13	0.11	0.015	0.006	0.009	0	0.03	0.015	0.005	0	0.01	0
2030	0.008	0	0.013	0.005	0.007	0	0.045	0.033	0.01	0.002	0.005	0
2024	0.005	0	0.018	0.012	0.005	0	0.049	0.038	0.009	0.003	0.0025	0
2124	0.002	0	0.018	0.012	0.0025	0	0.049	0.038	0.009	0	0.002	0
2031	0.013	0.005	0.012	0.006	0.012	0.006	0.028	0.018	0.005	0	0.002	0

For applications requiring maximum mechanical properties, alloys 2024 and 7075 are the most frequently used. Alloy 2024 forgings are extensively used for airframe components, truck wheel hubs, and ordnance and missile parts. Alloy 2024 has good mechanical properties at elevated temperatures. With proper heat treatment, it provides maximum dimensional stability and is employed for aircraft engine pistons, cylinder heads, and other elevated-temperature applications. Alloy 7075 is used primarily for airframe applications requiring the highest mechanical properties. Familiar aircraft alloys 7075, 7178 and the newer alloy 7001, in the T6-type temper are the highest-strength aluminum alloys. Heat-treatable 7xxx series plate, extrusions, and forgings are used extensively in weldable aluminum armor. 7xxx alloys are also used in pipelines to wells completed on the ocean floor (Schedule 10 7xxx anchor-anode pipe). 2024, 7001, 7075, 7178 are some of the principal alloys commercially produced in wire, rod and bar, including wire for electrical power transmission and distribution, welding electrode for tungsten, brazing rod, armor rods for electrical overhead conductors, and tie wire [7]. Detailed applications of the alloys in the portfolio of finished goods are listed in Table VIII [7].

Table VIII. Applications of alloys in finished goods portfolio, across all industries.

Finished Good	Applications
7178	Flooded structure on ocean floor for supporting detecting devices; badminton racket frames; high quality skis; ski and vaulting poles
7001	Motor closure for rocket
7075	Structural brackets and ground stakes for missile transporter; retardation attachments for conventional bombs; gun receiver; automatic rifle butt-plate assembly; grenade launcher barrel; deep-sea housings for instruments and photographic equipment; jig material for low-production manufacturing; computer memory disks; skis; aluminum drill pipe
332.1	Automotive pistons
339	production of pistons for automotive internal combustion engines
2030	Precision machining
2024	missile launcher; wheels for tanks, missile transporters, and lightweight tracked vehicles; ammunition cartridges; retardation attachments for conventional bombs; antiaircraft rocket launcher barrel; manufacturing of plywood, chip board, veneers, and high-pressure overlays; clock frames and gears; needle bars for warp knitting machines; hosiery boarding forms; arrow stock; luggage bodies; beam-type aluminum guardrail for roadside or medial strip protection; travel trailer walls; railroad passenger cars

5.2 Aerospace End-of-Life Case Study

The fifteen alloys found in the analysis above were modeled in four cases, each using a different scrap stream as the input according to the various end-of-life aerospace options described in Section 1.3. The production cost and breakdown of primary and secondary input materials needed to produce the portfolio are listed for each case in Table IX. In each of these trials the COV was constant at 15%.

Table IX. Total scrap use and production cost of all four cases, COV = 15%.

Case	Production Cost	Total Scrap Purchased (kT)	Total Primary Used (kT)
Dismantled	1732.6	903.3	596.7
Sorted	1876.5	551.5	948.5
commingledA (avg dismantled)	1975.6	301.5	1198.5
commingledB (avg sorted)	1978.7	292.7	1207.3

As expected, the portfolio utilized the dismantled scrap stream in highest volume. Presumably this is due to the higher purity of this scrap stream as well as the fact that it contains the most alloy options; and higher differentiation between the input scrap types makes it easier for the model to delegate scrap types to the production of specific finished goods. The sorted scrap stream, containing two scrap types, is consumed in the next highest volume because while it is more co-mingled than the dismantled case, it still offers series specification segregation As expected, the case with the least amount of segration is also the lowest performing in terms of utilization. Although both the commingled A and commingled B scrap streams consist of only one scrap type, and neither of these inputs seems more likely than the other to resemble any aluminum alloy currently used in the production of aircraft components, the commingled A stream is slightly more utilized than its counterpart case.

Because primary material is more expensive than scrap, the production cost decreases as more scrap input is used in production. Accordingly, the production cost decreases with increasing level of scrap sortation. The largest cost differential is observed between the dismantled and sorted cases, the cases with the largest disparity in scrap input used (cf. Table IX).

5.3 Sensitivity Analysis: Compositional Uncertainty

For the sensitivity analysis, each case in the model was run with a spectrum of COV settings in order to test the impact of compositional uncertainty on the results. The commingled A case was omitted from this analysis because the two commingled cases yielded similar results in the base case of constant COV; commingled B case was determined to be a better approximation to the composition of a commingled scrap stream since it is unlikely that each of the alloys identified in the dismantled case would contribute equally to the composition of a commingled scrap stream. Figures 10 and 11 chart the production cost and total scrap usage as the COV is changed.

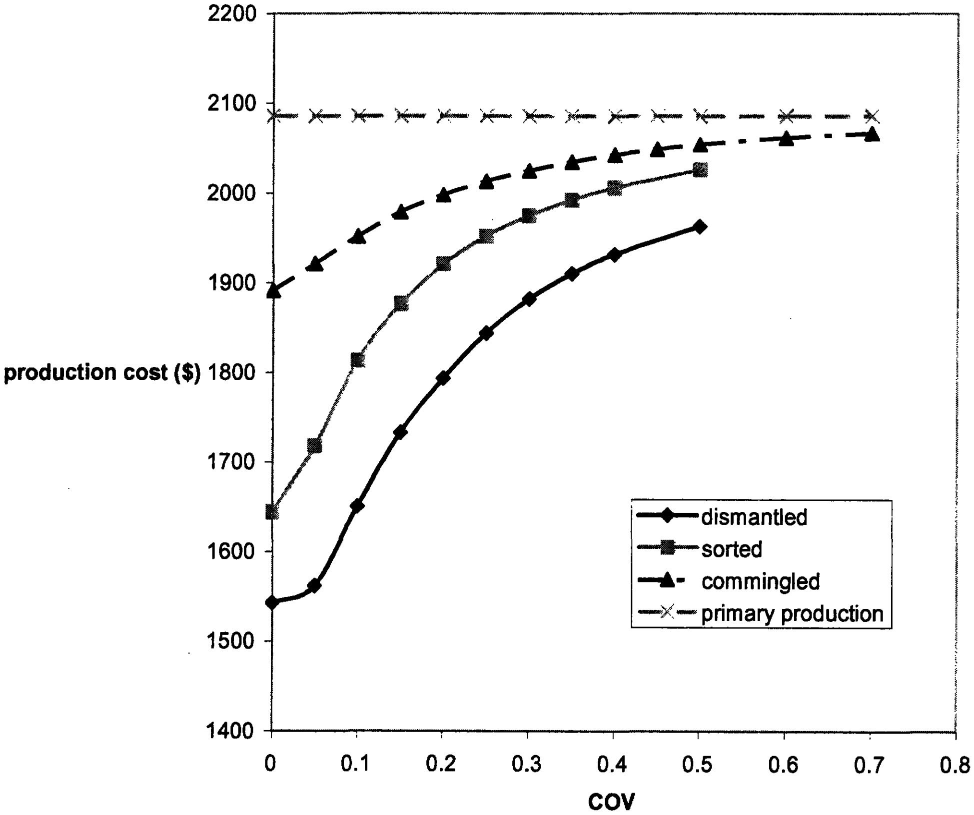

Figure 10. Production cost of dismantled, sorted, and commingled cases when COV is varied.

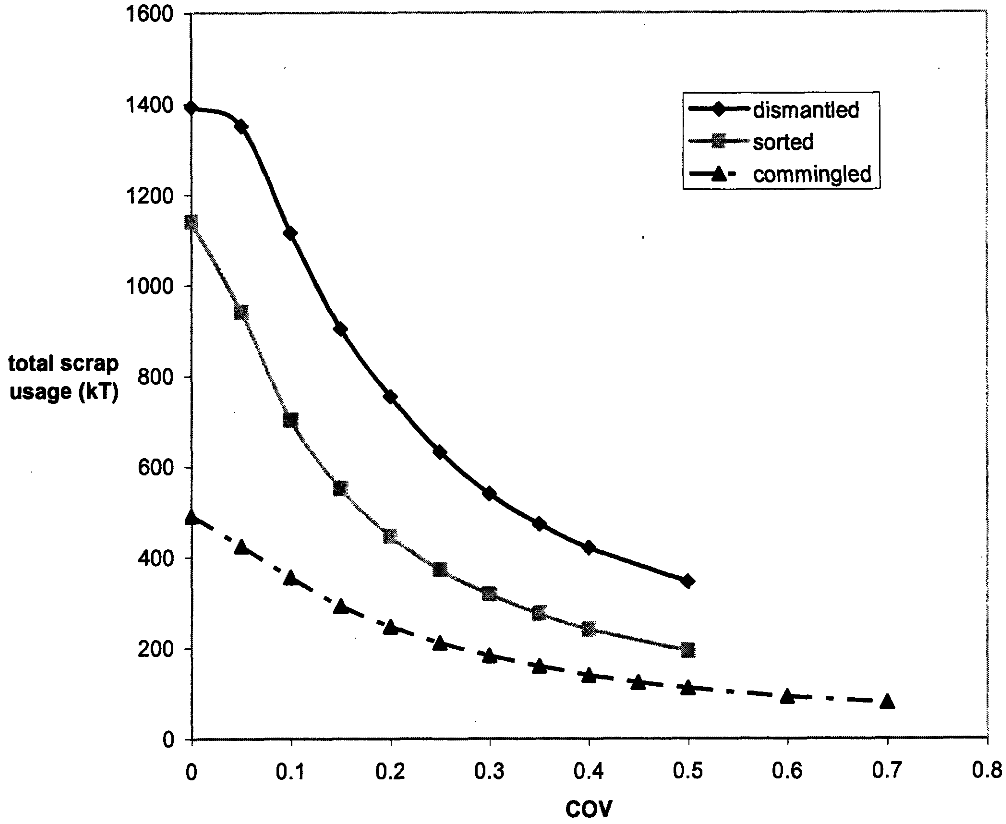

Figure 11. Total scrap usage of dismantled, sorted, and commingled cases when COV is varied.

The lowest possible production cost is achieved if aircraft components are separated with such refinement that the alloys in the dismantled stream can be identified without any uncertainty. The production cost reported by the model with the dismantled scrap input when COV = 0 is \$1542.77 (\$1.03/kT). The cost of primary production of the portfolio, determined when all scrap availability for the model is set to zero, is \$2086.03 (\$1.39/kT). Thus the highest precision of dismantling yields cost savings of \$543.27 (\$0.362/kT) in this case study; this would be the associated highest allowable cost for the technology. In the next case, scrap sorting technology advanced enough to separate scrap into its respective alloy series that have the exact compositions specified in Table VI would correlate to zero compositional uncertainty and result in a production cost \$442.99 (\$0.295/kT) lower than the cost of primary production. Finally, if the composition of the unsorted scrap input in the commingled case matched our model parameters with 100% accuracy, production would still be \$194.65 (\$0.130/kT) cheaper than if we were to use no scrap at all.

Realistically, however, there is variation in the composition of the scrap materials that result in smaller differences from the cost of primary production. Figure 10 is interpreted with one's own discretion, but under all readings the compositional uncertainty is lowest for the dismantled case and highest for the commingled case. If we estimate the COV of the dismantled scrap compositions to be 10%, the labor cost of dismantling for secondary production should not exceed \$435.44 (\$0.290/kT). The COV of the sorted scrap compositions was estimated to be 30%, in which case sorting technology should only be pursued under a cost of \$111.48 (0.0743/kT). If the commingled scrap composition had a COV of 45%, secondary production would still be \$39.95 (\$0.0266/kT) cheaper than primary production.

Even at a COV of 45%, 124.4kT of the commingled scrap is used production. The combined effects of the sorted stream's lower compositional uncertainty and greater scrap type variety result in 317.7kT of it being consumed. The dismantled stream has the least amount of co-mingling and hence is consumed in the greatest quantity: 1115.1kT.

The amount of scrap used in production in each of the three cases converges with increasing compositional uncertainty. Only 80.0kT of commingled scrap is used when the COV is 70%. It is highly unlikely that COV would near 70% in the sorted and dismantled cases, but it is interesting nonetheless to note that total scrap usage approaches zero as COV approaches 100%. Accordingly, the production cost in each scenario converge to the cost of primary production as COV approaches 100% and less scrap is used.

6.0 Conclusion

The results of this analysis indicate it is possible to reuse end-of-life aerospace scrap. As Figures 10 and 11 demonstrate, the amount of scrap that can be consumed and the cost of producing with such scrap are very dependent on the variability in the scrap streams, hinging on the effectiveness of sorting. For reasonable assumptions, it seems that dismantling would be attractive for costs at or below $0.362/kT and alloy series sorting would be attractive at or below $0.295/kT.

7.0 Future Work

Although the portfolio of fifteen finished goods produced here consumed the largest quantity of the end-of-life aerospace scrap streams chosen for our case studies, many of them could be specialty alloys produced in lesser amounts than other aluminum alloys not addressed in the study. Some of the alloys that consume less aerospace scrap are used in a wider range of industries and could be in higher demand than the alloys produced by our model. Table X [7] lists some aluminum alloys that are used extensively in the aerospace industry, as well as in the construction, chemical processing, military, automotive, electronic and marine sectors. These alloys could also be produced from the scrap derived from recycled aerospace components, so other industries could stand to benefit from ongoing development of sortation technology.

Table X. Applications of alloys potentially produced in higher volume than those in finished goods portfolio.

Alloy	Applications
356	Street lighting; organic compound production; cylinder blocks for gasoline engines; front engine covers; cylinder blocks and cylinder heads for diesel engines; widespread auto applications
360	Widespread auto applications
380	Widespread auto applications; pump components; die cast compressor parts; computer die cast plug board frame; pressure devices and recorders
262, 323, 231, 232, 396, 397, 398, 399	Aluminum conductors used in insulated cable
1100	Building construction; ammonium nitrate storage tanks; aluminum foil for packaging; cryogenic applications
2014	Drill pipe; mobile crane booms and jibs; cryogenic applications; wide range of military vehicles and equipment; wide range of aviation and aerospace applications
2017	Wide range of aviation and aerospace applications
2219	Cryogenic applications; wide range of aviation and aerospace applications
3003	Building construction; street name signs; ammonium nitrate storage tanks; aluminum foil for packaging; steel reactor lining for organic compound production, alcohol processing, water-white alkyd resin, nylon, acrylic and rayon production; explosive and rocket-propellant production; cryogenic applications
3004	Nitrogen fertilizer bulk storage tank; ammonium nitrate storage tank
3105	Building construction; street name sign
5005	Building construction; refrigerator and freezer shelf; stranded aluminum conductors

	for transmission and distribution lines
5050	Building construction; air instrument lines around storage tanks; ammonium nitrate storage tank; flashlight case; swimming pool
5052	Building construction; street name signs; nitrogen fertilizer bulk storage tank; widespread auto applications; car tanks; sliding doors for boxcars; missile fuel and oxidizer tankage; antenna reflector surface; track armored vehicles; addressing machine plates; pressure-containing components of highly portable, dry-chemical fire-fighting machines for airport use; piping systems; hull of small boat; cabins of aluminum personnel boats; fishing vessels; ammonium nitrate storage tank
5056	Building construction
5083	Bridges; Rocky Reach Dam construction; cryogenic applications; freight cars; sides of house cars; aviation, aerospace and military applications
5086	Car tanks; marine, aviation, aerospace and military applications
5454	Nitrogen fertilizer bulk storage tank; ammonium nitrate storage tank; cryogenic applications; freight cars; car tanks; space chambers
5456	Mobile crane buckets; Suriname River gates; aluminum personnel boats; naval vessels; aircraft carrier; hydrofoils; cryogenic applications
6061	Building construction; bridge drainage systems; bridge rails and posts; highway sign blanks; street name signs; ammonium nitrate storage tank; cryogenic applications; freight cars; sides of house cars; hull of small boat; cabins of aluminum personnel boats; fishing vessels
6063	Building construction; bridge drainage systems; bridge rails and posts; street name signs; ammonium nitrate storage tank
6201	Stranded aluminum conductors for transmission and distribution lines
7005	Cryogenic applications; railroad passenger cars
7079	Cryogenic applications; atomic energy weapon hardware; "Aluminaut" research vehicle
5257, 5657, 5457, 5252, X5053	Auto trim

Hence, a metric should be developed to assess which other finished goods portfolios would be worth studying, such as a ratio of overall demand to aerospace scrap usage. Since demand varies for finished goods, it would be useful to perform case studies with the demand adjusted accordingly for each alloy. A final suggestion for future work would be sensitivity analysis for scrap prices, since in reality dismantled scrap costs more than sorted scrap, and sorted scrap is more expensive than commingled scrap. In this case study, all scrap prices were equal, but the price used by the model should reflect the grade of scrap being used as input.

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Appendix A: Finished Good Compositions for Cast Alloys [20]

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
A201.0	0.0005	0	0.0035	0.0015	0.001	0	0.05	0.04	0.004	0.002	0	0
A201.1	0.0005	0	0.0035	0.002	0.0007	0	0.05	0.045	0.004	0.002	0	0
A206.0	0.0005	0	0.0035	0.0015	0.001	0	0.05	0.042	0.005	0.002	0.001	0
A206.2	0.0005	0	0.0035	0.002	0.0007	0	0.05	0.042	0.005	0.002	0.0005	0
A242.0	0.006	0	0.017	0.012	0.008	0	0.045	0.037	0.001	0	0.001	0
A242.1	0.006	0	0.017	0.013	0.006	0	0.045	0.037	0.001	0	0.001	0
A242.2	0.0035	0	0.017	0.013	0.006	0	0.045	0.037	0.001	0	0.001	0
A305.0	0.055	0.045	0.001	0	0.002	0	0.015	0.01	0.001	0	0.001	0
A305.1	0.055	0.045	0.001	0	0.0015	0	0.015	0.01	0.001	0	0.001	0
A305.2	0.055	0.045	0	0	0.0013	0	0.015	0.01	0.0005	0	0.0005	0
A319.0	0.065	0.055	0.001	0	0.01	0	0.04	0.03	0.005	0	0.03	0
A319.1	0.065	0.055	0.001	0	0.008	0	0.04	0.03	0.005	0	0.03	0
A333	0.1	0.08	0.005	0.0005	0.01	0	0.04	0.03	0.005	0	0.03	0
A333.1	0.1	0.08	0.005	0.001	0.008	0	0.04	0.03	0.005	0	0.03	0
A355.0	0.055	0.045	0.006	0.0045	0.0009	0	0.015	0.01	0.0005	0	0.0005	0
A355.2	0.055	0.045	0.006	0.005	0.0006	0	0.015	0.01	0.0003	0	0.0003	0
A356.0	0.075	0.065	0.0045	0.0025	0.002	0	0.002	0	0.001	0	0.001	0
A356.1	0.075	0.065	0.0045	0.003	0.0015	0	0.002	0	0.001	0	0.001	0
A356.2	0.075	0.065	0.0045	0.003	0.0012	0	0.001	0	0.0005	0	0.0005	0
A357.0	0.075	0.065	0.007	0.004	0.002	0	0.002	0	0.001	0	0.001	0
A357.2	0.075	0.065	0.007	0.0045	0.0012	0	0.001	0	0.0005	0	0.0005	0
A360.0	0.1	0.09	0.006	0.004	0.013	0	0.006	0	0.0035	0	0.005	0
A360.1	0.1	0.09	0.006	0.0045	0.01	0	0.006	0	0.0035	0	0.004	0
A360.2	0.1	0.09	0.006	0.0045	0.006	0	0.001	0	0.0005	0	0.0005	0
A380.0	0.095	0.075	0.001	0	0.013	0	0.04	0.03	0.005	0	0.03	0
A380.1	0.095	0.075	0.001	0	0.01	0	0.04	0.03	0.005	0	0.029	0
A380.2	0.095	0.075	0.001	0	0.006	0	0.04	0.03	0.001	0	0.001	0
A384.0	0.12	0.105	0.001	0	0.013	0	0.045	0.03	0.005	0	0.01	0
A384.1	0.12	0.105	0.001	0	0.01	0	0.045	0.03	0.005	0	0.009	0
A390.0	0.18	0.16	0.0065	0.0045	0.005	0	0.05	0.04	0.001	0	0.001	0
A390.1	0.18	0.16	0.0065	0.005	0.004	0	0.05	0.04	0.001	0	0.001	0
A413.0	0.13	0.11	0.001	0	0.013	0	0.01	0	0.0035	0	0.005	0
A413.1	0.13	0.11	0.001	0	0.01	0	0.01	0	0.0035	0	0.004	0
A413.2	0.13	0.11	0.0005	0	0.006	0	0.001	0	0.0005	0	0.0005	0
A443.0	0.06	0.045	0.0005	0	0.008	0	0.003	0	0.005	0	0.005	0
A443.1	0.06	0.045	0.0005	0	0.006	0	0.003	0	0.005	0	0.005	0
A444.0	0.075	0.065	0.0005	0	0.002	0	0.001	0	0.001	0	0.001	0
A444.1	0.075	0.065	0.0005	0	0.0015	0	0.001	0	0.001	0	0.001	0
A444.2	0.075	0.065	0.0005	0	0.0012	0	0.0005	0	0.0005	0	0.0005	0
A535.0	0.002	0	0.075	0.065	0.002	0	0.001	0	0.0025	0.001	0	0
A535.1	0.002	0	0.075	0.066	0.0015	0	0.001	0	0.0025	0.001	0	0
B201.0	0.0005	0	0.0035	0.0025	0.0005	0	0.05	0.045	0.005	0.002	0	0
B319.0	0.065	0.055	0.005	0.001	0.012	0	0.04	0.03	0.008	0	0.01	0
B319.1	0.065	0.055	0.005	0.001	0.009	0	0.04	0.03	0.008	0	0.01	0
B356.0	0.075	0.065	0.0045	0.0025	0.0009	0	0.0005	0	0.0005	0	0.0005	0
B356.2	0.075	0.065	0.0045	0.003	0.0006	0	0.0003	0	0.0003	0	0.0003	0
B357.0	0.075	0.065	0.006	0.004	0.0009	0	0.0005	0	0.0005	0	0.0005	0
B357.2	0.075	0.065	0.006	0.0045	0.0006	0	0.0003	0	0.0003	0	0.0003	0
B380.0	0.095	0.075	0.001	0	0.013	0	0.04	0.03	0.005	0	0.01	0
B380.1	0.095	0.075	0.001	0	0.01	0	0.04	0.03	0.005	0	0.009	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
B390.0	0.18	0.16	0.0065	0.0045	0.013	0	0.05	0.04	0.005	0	0.015	0
B390.1	0.18	0.16	0.0065	0.005	0.01	0	0.05	0.04	0.005	0	0.014	0
B413.0	0.13	0.11	0.0005	0	0.005	0	0.001	0	0.0035	0	0.001	0
B413.1	0.13	0.11	0.0005	0	0.004	0	0.001	0	0.0035	0	0.001	0
B443.0	0.06	0.045	0.0005	0	0.008	0	0.0015	0	0.0035	0	0.0035	0
B443.1	0.06	0.045	0.0005	0	0.006	0	0.0015	0	0.0035	0	0.0035	0
B535.0	0.0015	0	0.075	0.065	0.0015	0	0.001	0	0.0005	0	0	0
B535.2	0.001	0	0.075	0.066	0.0012	0	0.0005	0	0.0005	0	0	0
C355	0.055	0.045	0.006	0.004	0.002	0	0.015	0.01	0.001	0	0.001	0
C355.1	0.055	0.045	0.006	0.0045	0.0015	0	0.015	0.01	0.001	0	0.001	0
C355.2	0.055	0.045	0.006	0.005	0.0013	0	0.015	0.01	0.0005	0	0.0005	0
C356.0	0.075	0.065	0.0045	0.0025	0.0007	0	0.0005	0	0.0005	0	0.0005	0
C356.2	0.075	0.065	0.0045	0.003	0.0004	0	0.0003	0	0.0003	0	0.0003	0
C357.0	0.075	0.065	0.007	0.0045	0.0009	0	0.0005	0	0.0005	0	0.0005	0
C357.2	0.075	0.065	0.007	0.005	0.0006	0	0.0003	0	0.0003	0	0.0003	0
C443.0	0.06	0.045	0.001	0	0.02	0	0.006	0	0.0035	0	0.005	0
C443.1	0.06	0.045	0.001	0	0.011	0	0.006	0	0.0035	0	0.004	0
C443.2	0.06	0.045	0.0005	0	0.011	0.007	0.001	0	0.001	0	0.001	0
D357.0	0.075	0.065	0.006	0.0055	0.002	0	0	0	0.001	0	0	0
F356.0	0.075	0.065	0.0025	0.0017	0.002	0	0.002	0	0.001	0	0.001	0
F356.2	0.075	0.065	0.0025	0.0017	0.0012	0	0.001	0	0.0005	0	0.0005	0
201	0.001	0	0.0055	0.0015	0.0015	0	0.052	0.04	0.005	0.002	0	0
201.2	0.001	0	0.0055	0.002	0.001	0	0.052	0.04	0.005	0.002	0	0
203	0.003	0	0.001	0	0.005	0	0.055	0.045	0.003	0.002	0.001	0
203.2	0.002	0	0.001	0	0.0035	0	0.052	0.048	0.003	0.002	0.001	0
204	0.002	0	0.0035	0.0015	0.0035	0	0.05	0.042	0.001	0	0.001	0
204.2	0.0015	0	0.0035	0.002	0.002	0.001	0.049	0.042	0.0005	0	0.0005	0
206	0.001	0	0.0035	0.0015	0.0015	0	0.05	0.042	0.005	0.002	0.001	0
206.2	0.001	0	0.0035	0.002	0.001	0	0.05	0.042	0.005	0.002	0.0005	0
208	0.035	0.025	0.001	0	0.012	0	0.045	0.035	0.005	0	0.01	0
208.1	0.035	0.025	0.001	0	0.009	0	0.045	0.035	0.005	0	0.01	0
208.2	0.035	0.025	0.0003	0	0.008	0	0.045	0.035	0.003	0	0.002	0
213	0.03	0.01	0.001	0	0.012	0	0.08	0.06	0.006	0	0.025	0
213.1	0.03	0.01	0.001	0	0.009	0	0.08	0.06	0.006	0	0.025	0
222	0.02	0	0.0035	0.0015	0.015	0	0.107	0.092	0.005	0	0.008	0
222.1	0.02	0	0.0035	0.002	0.012	0	0.107	0.092	0.005	0	0.008	0
224	0.0006	0	0	0	0.001	0	0.055	0.045	0.005	0.002	0	0
224.2	0.0002	0	0	0	0.0004	0	0.055	0.045	0.005	0.002	0	0
240	0.005	0	0.065	0.055	0.005	0	0.09	0.07	0.007	0.003	0.001	0
240.1	0.005	0	0.065	0.056	0.004	0	0.09	0.07	0.007	0.003	0.001	0
242	0.007	0	0.018	0.012	0.01	0	0.045	0.035	0.0035	0	0.0035	0
242.1	0.007	0	0.018	0.013	0.008	0	0.045	0.035	0.0035	0	0.0035	0
242.2	0.006	0	0.018	0.013	0.006	0	0.045	0.035	0.001	0	0.001	0
243	0.0035	0	0.023	0.018	0.004	0	0.045	0.035	0.0045	0.0015	0.0005	0
243.1	0.0035	0	0.023	0.019	0.003	0	0.045	0.035	0.0045	0.0015	0.0005	0
295	0.015	0.007	0.0003	0	0.01	0	0.05	0.04	0.0035	0	0.0035	0
295.1	0.015	0.007	0.0003	0	0.008	0	0.05	0.04	0.0035	0	0.0035	0
295.2	0.012	0.007	0.0003	0	0.008	0	0.05	0.04	0.003	0	0.003	0
296	0.03	0.02	0.0005	0	0.012	0	0.05	0.04	0.0035	0	0.005	0
296.1	0.03	0.02	0.0005	0	0.009	0	0.05	0.04	0.0035	0	0.005	0
296.2	0.03	0.02	0.0035	0	0.008	0	0.05	0.04	0.003	0	0.003	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
305	0.055	0.045	0.001	0	0.006	0	0.015	0.01	0.005	0	0.0035	0
305.2	0.055	0.045	0	0	0.0025	0.0014	0.015	0.01	0.0005	0	0.0005	0
308	0.06	0.05	0.001	0	0.01	0	0.05	0.04	0.005	0	0.01	0
308.1	0.06	0.05	0.001	0	0.008	0	0.05	0.04	0.005	0	0.01	0
308.2	0.06	0.05	0.001	0	0.008	0	0.05	0.04	0.003	0	0.005	0
319	0.065	0.055	0.001	0	0.01	0	0.04	0.03	0.005	0	0.01	0
319.1	0.065	0.055	0.001	0	0.008	0	0.04	0.03	0.005	0	0.01	0
319.2	0.065	0.055	0.001	0	0.006	0	0.04	0.03	0.001	0	0.001	0
320	0.08	0.05	0.006	0.0005	0.012	0	0.04	0.02	0.008	0	0.03	0
320.1	0.08	0.05	0.006	0.001	0.009	0	0.04	0.02	0.008	0	0.03	0
324	0.08	0.07	0.007	0.004	0.012	0	0.006	0.004	0.005	0	0.01	0
324.1	0.08	0.07	0.007	0.0045	0.009	0	0.006	0.004	0.005	0	0.01	0
324.2	0.08	0.07	0.007	0.0045	0.006	0	0.006	0.004	0.001	0	0.001	0
328	0.085	0.075	0.006	0.002	0.01	0	0.02	0.01	0.006	0.002	0.015	0
328.1	0.085	0.075	0.006	0.002	0.008	0	0.02	0.01	0.006	0.002	0.015	0
332	0.085	0.075	0.006	0.002	0.008	0	0.02	0.01	0.006	0.002	0.015	0
332.1	0.105	0.085	0.015	0.006	0.009	0	0.04	0.02	0.005	0	0.01	0
332.2	0.1	0.085	0.013	0.009	0.006	0	0.04	0.02	0.001	0	0.001	0
333	0.1	0.08	0.005	0.0005	0.01	0	0.04	0.03	0.005	0	0.01	0
333.1	0.1	0.08	0.005	0.001	0.008	0	0.04	0.03	0.005	0	0.01	0
336	0.13	0.11	0.013	0.007	0.012	0	0.015	0.005	0.0035	0	0.0035	0
336.1	0.13	0.11	0.013	0.008	0.009	0	0.015	0.005	0.0035	0	0.0035	0
336.2	0.13	0.11	0.013	0.009	0.009	0	0.015	0.005	0.001	0	0.001	0
339	0.13	0.11	0.015	0.005	0.012	0	0.03	0.015	0.005	0	0.01	0
339.1	0.13	0.11	0.015	0.006	0.009	0	0.03	0.015	0.005	0	0.01	0
343	0.077	0.067	0.001	0	0.012	0	0.009	0.005	0.005	0	0.02	0.012
343.1	0.077	0.067	0.001	0	0.009	0	0.009	0.005	0.005	0	0.019	0.012
354	0.094	0.086	0.006	0.004	0.002	0	0.02	0.016	0.001	0	0.001	0
354.1	0.094	0.086	0.006	0.0045	0.0015	0	0.02	0.016	0.001	0	0.001	0
355.2	0.055	0.045	0.006	0.005	0.0025	0.0014	0.015	0.01	0.0005	0	0.0005	0
356.2	0.075	0.065	0.0045	0.003	0.0025	0.0013	0.001	0	0.0005	0	0.0005	0
357	0.075	0.065	0.006	0.0045	0.0015	0	0.0005	0	0.0003	0	0.0005	0
357.1	0.075	0.065	0.006	0.0045	0.0012	0	0.0005	0	0.0003	0	0.0005	0
358	0.086	0.076	0.006	0.004	0.003	0	0.002	0	0.002	0	0.002	0
358.2	0.086	0.076	0.006	0.0045	0.002	0	0.001	0	0.001	0	0.001	0
359	0.095	0.085	0.007	0.005	0.002	0	0.002	0	0.001	0	0.001	0
359.2	0.095	0.085	0.007	0.0055	0.0012	0	0.001	0	0.001	0	0.001	0
360	0.1	0.09	0.006	0.004	0.02	0	0.006	0	0.0035	0	0.005	0
360.2	0.1	0.09	0.006	0.0045	0.011	0.007	0.001	0	0.001	0	0.001	0
361	0.105	0.095	0.006	0.004	0.011	0	0.005	0	0.0025	0	0.005	0
361.1	0.105	0.095	0.006	0.0045	0.008	0	0.005	0	0.0025	0	0.004	0
364	0.095	0.075	0.004	0.002	0.015	0	0.002	0	0.001	0	0.0015	0
364.2	0.095	0.075	0.004	0.0025	0.011	0.007	0.002	0	0.001	0	0.0015	0
369	0.12	0.11	0.0045	0.0025	0.013	0	0.005	0	0.0035	0	0.01	0
369.1	0.12	0.11	0.0045	0.003	0.01	0	0.005	0	0.0035	0	0.009	0
380	0.095	0.075	0.001	0	0.02	0	0.04	0.03	0.005	0	0.03	0
380.2	0.095	0.075	0.001	0	0.011	0.007	0.04	0.03	0.001	0	0.001	0
383	0.115	0.095	0.001	0	0.013	0	0.03	0.02	0.005	0	0.03	0
383.1	0.115	0.095	0.001	0	0.01	0	0.03	0.02	0.005	0	0.029	0
383.2	0.115	0.095	0.001	0	0.01	0.006	0.03	0.02	0.001	0	0.001	0
384	0.12	0.105	0.001	0	0.013	0	0.045	0.03	0.005	0	0.03	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
384.1	0.12	0.105	0.001	0	0.01	0	0.045	0.03	0.005	0	0.029	0
384.2	0.12	0.105	0.001	0	0.01	0.006	0.045	0.03	0.001	0	0.001	0
385	0.13	0.11	0.003	0	0.02	0	0.04	0.02	0.005	0	0.03	0
385.1	0.13	0.11	0.003	0	0.011	0	0.04	0.02	0.005	0	0.029	0
390	0.18	0.16	0.0065	0.0045	0.013	0	0.05	0.04	0.001	0	0.001	0
390.2	0.18	0.16	0.0065	0.005	0.01	0.006	0.05	0.04	0.001	0	0.001	0
392	0.2	0.18	0.012	0.008	0.015	0	0.008	0.004	0.006	0.002	0.005	0
392.1	0.2	0.18	0.012	0.009	0.011	0	0.008	0.004	0.006	0.002	0.004	0
393	0.23	0.21	0.013	0.007	0.013	0	0.011	0.007	0.001	0	0.001	0
393.1	0.23	0.21	0.013	0.008	0.01	0	0.011	0.007	0.001	0	0.001	0
393.2	0.23	0.21	0.013	0.008	0.008	0	0.011	0.007	0.001	0	0.001	0
408.2	0.095	0.085	0	0	0.013	0.006	0.001	0	0.001	0	0.001	0
409.2	0.1	0.09	0	0	0.013	0.006	0.001	0	0.001	0	0.001	0
411.2	0.12	0.1	0	0	0.013	0.006	0.002	0	0.001	0	0.001	0
413	0.13	0.11	0.001	0	0.02	0	0.01	0	0.0035	0	0.005	0
413.2	0.13	0.11	0.0007	0	0.011	0.007	0.001	0	0.001	0	0.001	0
435.2	0.039	0.033	0.0005	0	0.004	0	0.0005	0	0.0005	0	0.001	0
443	0.06	0.045	0.0005	0	0.008	0	0.006	0	0.005	0	0.005	0
443.1	0.06	0.045	0.0005	0	0.006	0	0.006	0	0.005	0	0.005	0
443.2	0.06	0.045	0.0005	0	0.006	0	0.001	0	0.001	0	0.001	0
444	0.075	0.065	0.001	0	0.006	0	0.0025	0	0.0035	0	0.0035	0
444.2	0.075	0.065	0.0005	0	0.0025	0.0013	0.001	0	0.0005	0	0.0005	0
445.2	0.075	0.065	0	0	0.013	0.006	0.001	0	0.001	0	0.001	0
511	0.007	0.003	0.045	0.035	0.005	0	0.0015	0	0.0035	0	0.0015	0
511.1	0.007	0.003	0.045	0.036	0.004	0	0.0015	0	0.0035	0	0.0015	0
511.2	0.007	0.003	0.045	0.036	0.003	0	0.001	0	0.001	0	0.001	0
512	0.022	0.014	0.045	0.035	0.006	0	0.0035	0	0.008	0	0.0035	0
512.2	0.022	0.014	0.045	0.036	0.003	0	0.001	0	0.001	0	0.001	0
513	0.003	0	0.045	0.035	0.004	0	0.001	0	0.003	0	0.022	0.014
513.2	0.003	0	0.045	0.036	0.003	0	0.001	0	0.001	0	0.022	0.014
514	0.0035	0	0.045	0.035	0.005	0	0.0015	0	0.0035	0	0.0015	0
514.2	0.003	0	0.045	0.036	0.003	0	0.001	0	0.001	0	0.001	0
515	0.01	0.005	0.04	0.025	0.013	0	0.002	0	0.006	0.004	0.001	0
515.2	0.01	0.005	0.04	0.027	0.01	0.006	0.001	0	0.006	0.004	0.0005	0
516	0.015	0.003	0.045	0.025	0.01	0.0035	0.003	0	0.004	0.0015	0.002	0
516.1	0.015	0.003	0.045	0.026	0.007	0.0035	0.003	0	0.004	0.0015	0.002	0
518	0.0035	0	0.085	0.075	0.018	0	0.0025	0	0.0035	0	0.0015	0
518.1	0.0035	0	0.085	0.076	0.011	0	0.0025	0	0.0035	0	0.0015	0
518.2	0.0025	0	0.085	0.076	0.007	0	0.001	0	0.001	0	0	0
520	0.0025	0	0.106	0.095	0.003	0	0.0025	0	0.0015	0	0.0015	0
520.2	0.0015	0	0.106	0.096	0.002	0	0.002	0	0.001	0	0.001	0
535	0.0015	0	0.075	0.062	0.0015	0	0.0005	0	0.0025	0.001	0	0
535.2	0.001	0	0.075	0.066	0.001	0	0.0005	0	0.0025	0.001	0	0
705	0.002	0	0.018	0.014	0.008	0	0.002	0	0.006	0.004	0.033	0.027
705.1	0.002	0	0.018	0.015	0.006	0	0.002	0	0.006	0.004	0.033	0.027
707	0.002	0	0.024	0.018	0.008	0	0.002	0	0.006	0.004	0.045	0.04
710	0.0015	0	0.008	0.006	0.005	0	0.0065	0.0035	0.0005	0	0.07	0.06
710.1	0.0015	0	0.008	0.0065	0.004	0	0.0065	0.0035	0.0005	0	0.07	0.06
711	0.003	0	0.0045	0.0025	0.014	0.007	0.0065	0.0035	0.0005	0	0.07	0.06
711.1	0.003	0	0.0045	0.003	0.011	0.007	0.0065	0.0035	0.0005	0	0.07	0.06
712	0.003	0	0.0065	0.005	0.005	0	0.0025	0	0.001	0	0.065	0.05

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
712.2	0.0015	0	0.0065	0.005	0.004	0	0.0025	0	0.001	0	0.065	0.05
713	0.0025	0	0.005	0.002	0.011	0	0.01	0.004	0.006	0	0.08	0.07
713.1	0.0025	0	0.005	0.0025	0.008	0	0.01	0.004	0.006	0	0.08	0.07
771	0.0015	0	0.01	0.008	0.0015	0	0.001	0	0.001	0	0.075	0.065
771.2	0.001	0	0.01	0.0085	0.001	0	0.001	0	0.001	0	0.075	0.065
772	0.0015	0	0.008	0.006	0.0015	0	0.001	0	0.001	0	0.07	0.06
772.2	0.001	0	0.008	0.0065	0.001	0	0.001	0	0.001	0	0.07	0.06
850	0.007	0	0.001	0	0.007	0	0.013	0.007	0.001	0	0	0
850.1	0.007	0	0.001	0	0.005	0	0.013	0.007	0.001	0	0	0
851	0.03	0.02	0.001	0	0.007	0	0.013	0.007	0.001	0	0	0
851.1	0.03	0.02	0.001	0	0.005	0	0.013	0.007	0.001	0	0	0
852	0.004	0	0.009	0.006	0.007	0	0.023	0.017	0.001	0	0	0
852.1	0.004	0	0.009	0.007	0.005	0	0.023	0.017	0.001	0	0	0
853	0.065	0.055	0	0	0.007	0	0.04	0.03	0.005	0	0	0
853.2	0.065	0.055	0	0	0.005	0	0.04	0.03	0.001	0	0	0

Appendix B: Finished Good Compositions for Wrought Alloys [20]

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
1035	0.0035	0	0.0005	0	0.006	0	0.001	0	0.0005	0	0.001	0
1040	0.003	0	0.0005	0	0.005	0	0.001	0	0.0005	0	0.001	0
1045	0.003	0	0.0005	0	0.0045	0	0.001	0	0.0005	0	0.0005	0
1050	0.0025	0	0.0005	0	0.004	0	0.0005	0	0.0005	0	0.0005	0
1060	0.0025	0	0.0003	0	0.0035	0	0.0005	0	0.0003	0	0.0005	0
1065	0.0025	0	0.0003	0	0.003	0	0.0005	0	0.0003	0	0.0005	0
1070	0.002	0	0.0003	0	0.0025	0	0.0004	0	0.0003	0	0.0004	0
1080	0.0015	0	0.0002	0	0.0015	0	0.0003	0	0.0002	0	0.0003	0
1085	0.001	0	0.0002	0	0.0012	0	0.0003	0	0.0002	0	0.0003	0
1090	0.007	0	0.0001	0	0.0007	0	0.0002	0	0.0001	0	0.0003	0
1098	0.0001	0	0	0	0.00006	0	0.00003	0	0	0	0.00015	0
1110	0.003	0	0.0025	0	0.008	0	0.0004	0	0.0001	0	0	0
1120	0.001	0	0.002	0	0.004	0	0.0035	0.0005	0.0001	0	0.0005	0
1180	0.0009	0	0.0002	0	0.0009	0	0.0001	0	0.0002	0	0.0003	0
1188	0.0006	0	0.0001	0	0.0006	0	0.00005	0	0.0001	0	0.0003	0
1190	0.0005	0	0.0001	0	0.0007	0	0.0001	0	0.0001	0	0.0002	0
1193	0.0004	0	0.0001	0	0.0004	0	0.00006	0	0.0001	0	0.0003	0
1199	0.00006	0	0.00006	0	0.00006	0	0.00006	0.00006	0.00002	0	0.00006	0
1275	0.0008	0	0.0002	0	0.0012	0	0.001	0.0005	0.0002	0	0.0003	0
1345	0.003	0	0.0005	0	0.004	0	0.001	0	0.0005	0	0.0005	0
1350	0.001	0	0	0	0.004	0	0.0005	0	0.0001	0	0.0005	0
1370	0.001	0	0.0002	0	0.0025	0	0.0002	0	0.0001	0	0.0004	0
1385	0.0005	0	0.0002	0	0.0012	0	0.0002	0	0.0001	0	0.0003	0
1435	0.0015	0	0.0005	0	0.005	0.003	0.0002	0	0.0005	0	0.001	0
2001	0.002	0	0.0045	0.002	0.002	0	0.06	0.052	0.005	0.0015	0.001	0
2002	0.008	0.0035	0.01	0.005	0.003	0	0.025	0.015	0.002	0	0.002	0
2003	0.003	0	0.0002	0	0.003	0	0.05	0.04	0.008	0.003	0.001	0
2004	0.002	0	0.005	0	0.002	0	0.065	0.055	0.001	0	0.001	0
2005	0.008	0	0.01	0.002	0.007	0	0.05	0.035	0.01	0	0.005	0
2006	0.013	0.008	0.014	0.005	0.007	0	0.02	0.01	0.01	0.006	0.002	0
2007	0.008	0	0.018	0.004	0.008	0	0.046	0.033	0.01	0.005	0.008	0
2008	0.008	0.005	0.005	0.0025	0.004	0	0.011	0.007	0.003	0	0.0025	0
2011	0.004	0	0	0	0.007	0	0.06	0.05	0	0	0.003	0
2014	0.012	0.005	0.008	0.002	0.007	0	0.05	0.039	0.012	0.004	0.0025	0
2017	0.008	0.002	0.008	0.004	0.007	0	0.045	0.035	0.01	0.004	0.0025	0
2018	0.009	0	0.009	0.0045	0.01	0	0.045	0.035	0.002	0	0.0025	0
2020	0.004	0	0.0003	0	0.004	0	0.05	0.04	0.008	0.003	0.0025	0
2021	0.002	0	0.0002	0	0.003	0	0.068	0.058	0.004	0.002	0.001	0
2024	0.005	0	0.018	0.012	0.005	0	0.049	0.038	0.009	0.003	0.0025	0
2025	0.012	0.005	0.0005	0	0.01	0	0.05	0.039	0.012	0.004	0.0025	0
2030	0.008	0	0.013	0.005	0.007	0	0.045	0.033	0.01	0.002	0.005	0
2031	0.013	0.005	0.012	0.006	0.012	0.006	0.028	0.018	0.005	0	0.002	0
2034	0.001	0	0.019	0.013	0.0012	0	0.048	0.042	0.013	0.008	0.002	0
2036	0.005	0	0.006	0.003	0.005	0	0.03	0.022	0.004	0.001	0.0025	0
2037	0.005	0	0.008	0.003	0.005	0	0.022	0.014	0.004	0.001	0.0025	0
2038	0.013	0.005	0.01	0.004	0.006	0	0.018	0.008	0.004	0.001	0.005	0
2048	0.0015	0	0.018	0.012	0.002	0	0.038	0.028	0.006	0.002	0.0025	0
2090	0.001	0	0.0025	0	0.0012	0	0.03	0.024	0.0005	0	0.001	0
2091	0.002	0	0.019	0.011	0.003	0	0.025	0.018	0.001	0	0.0025	0
2098	0.0012	0	0.008	0.0025	0.0015	0	0.038	0.032	0.0035	0	0.0035	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
2117	0.008	0.002	0.01	0.004	0.007	0	0.045	0.035	0.01	0.004	0.0025	0
2124	0.002	0	0.018	0.012	0.0025	0	0.049	0.038	0.009	0	0.002	0
2195	0.0012	0	0.008	0.0025	0.0015	0	0.043	0.037	0.0025	0	0.0025	0
2214	0.012	0.005	0.008	0.002	0.003	0	0.05	0.039	0.012	0.004	0.0025	0
2218	0.009	0	0.018	0.012	0.01	0	0.045	0.035	0.002	0	0.0025	0
2219	0.002	0	0.0002	0	0.0003	0	0.068	0.058	0.004	0.002	0.001	0
2224	0.0012	0	0.018	0.012	0.0015	0	0.044	0.038	0.009	0.003	0.0025	0
2297	0.001	0	0.0025	0	0.001	0	0.031	0.025	0.005	0.001	0.0005	0
2319	0.002	0	0.0002	0	0.003	0	0.068	0.058	0.004	0.002	0.001	0
2324	0.001	0	0.018	0.012	0.0012	0	0.044	0.038	0.009	0.003	0.0025	0
2419	0.0015	0	0.0002	0	0.0018	0	0.068	0.058	0.004	0.002	0.001	0
2618	0.0025	0	0.018	0.013	0.013	0.009	0.027	0.019	0	0	0	0
3002	0.0008	0	0.002	0.0005	0.001	0	0.0015	0	0.0025	0.0005	0.0005	0
3003	0.006	0	0	0	0.007	0	0.002	0.0005	0.015	0.01	0.001	0
3004	0.003	0	0.013	0.008	0.007	0	0.0025	0	0.015	0.01	0.0025	0
3005	0.006	0	0.006	0.002	0.007	0	0.003	0	0.015	0.01	0.0025	0
3006	0.005	0	0.006	0.003	0.007	0	0.003	0.001	0.008	0.005	0.004	0.0015
3007	0.005	0	0.006	0	0.007	0	0.003	0.0005	0.008	0.003	0.004	0
3008	0.004	0	0.0001	0	0.007	0	0.001	0	0.018	0.012	0.0005	0
3009	0.018	0.01	0.001	0	0.007	0	0.001	0	0.018	0.012	0.0005	0
3010	0.001	0	0	0	0.002	0	0.0003	0	0.009	0.002	0.0005	0
3011	0.004	0	0	0	0.007	0	0.002	0.0005	0.012	0.008	0.001	0
3012	0.006	0	0.001	0	0.007	0	0.001	0	0.011	0.005	0.001	0
3013	0.006	0	0.006	0.002	0.01	0	0.005	0	0.014	0.009	0.01	0.005
3014	0.006	0	0.001	0	0.01	0	0.005	0	0.015	0.01	0.01	0.005
3015	0.006	0	0.007	0.002	0.008	0	0.003	0	0.009	0.005	0.0025	0
3016	0.006	0	0.008	0.005	0.008	0	0.003	0	0.009	0.005	0.0025	0
3102	0.004	0	0	0	0.007	0	0.001	0	0.004	0.0005	0.003	0
3103	0.005	0.003	0	0	0.007	0	0.001	0	0.015	0.009	0.002	0
3104	0.006	0	0.013	0.008	0.008	0	0.0025	0.0005	0.014	0.008	0.0025	0
3105	0.006	0	0.008	0.002	0.007	0	0.003	0	0.008	0.003	0.004	0
3107	0.006	0	0	0	0.007	0	0.0015	0.0005	0.009	0.004	0.002	0
3203	0.006	0	0	0	0.007	0	0.0005	0	0.015	0.01	0.001	0
3207	0.003	0	0.001	0	0.0045	0	0.001	0	0.008	0.004	0.001	0
3303	0.006	0	0	0	0.007	0	0.002	0.0005	0.015	0.01	0.003	0
3307	0.006	0	0.003	0	0.008	0	0.003	0	0.009	0.005	0.0025	0
4004	0.105	0.09	0.02	0.01	0.008	0	0.0025	0	0.001	0	0.002	0
4006	0.012	0.008	0.0001	0	0.008	0.005	0.0005	0	0.0003	0	0.0005	0
4007	0.017	0.01	0.002	0	0.01	0.004	0.002	0	0.015	0.008	0.001	0
4008	0.075	0.065	0.045	0.003	0.0009	0	0.0005	0	0.0005	0	0.0005	0
4009	0.055	0.045	0.006	0.0045	0.002	0	0.015	0.01	0.001	0	0.001	0
4010	0.075	0.065	0.0045	0.003	0.002	0	0.002	0	0.001	0	0.001	0
4011	0.075	0.065	0.007	0.0045	0.002	0	0.002	0	0.001	0	0.001	0
4013	0.045	0.035	0.002	0.0005	0.0035	0	0.002	0.0005	0.0003	0	0.0005	0
4032	0.135	0.11	0.013	0.008	0.01	0	0.013	0.005	0	0	0.0025	0
4043	0.06	0.045	0.0005	0	0.008	0	0.003	0	0.0005	0	0.001	0
4044	0.092	0.078	0	0	0.008	0	0.0025	0	0.001	0	0.002	0
4045	0.11	0.09	0.0005	0	0.008	0	0.003	0	0.0005	0	0.001	0
4047	0.13	0.11	0.001	0	0.008	0	0.003	0	0.0015	0	0.002	0
4104	0.105	0.09	0.02	0.01	0.008	0	0.0025	0	0.001	0	0.002	0
4145	0.107	0.093	0.0015	0	0.008	0	0.047	0.033	0.0015	0	0.002	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
4343	0.082	0.068	0	0	0.008	0	0.0025	0	0.001	0	0.002	0
4543	0.07	0.05	0.004	0.001	0.005	0	0.001	0	0.0005	0	0.001	0
4643	0.046	0.036	0.003	0.001	0.008	0	0.001	0	0.0005	0	0.001	0
5005	0.003	0	0.011	0.005	0.007	0	0.002	0	0.002	0	0.0025	0
5006	0.004	0	0.013	0.008	0.008	0	0.001	0	0.008	0.004	0.0025	0
5010	0.004	0	0.006	0.002	0.007	0	0.0025	0	0.003	0.001	0.003	0
5013	0.002	0	0.038	0.032	0.0025	0	0.0003	0	0.005	0.003	0.001	0
5014	0.004	0	0.055	0.04	0.004	0	0.002	0	0.009	0.002	0.015	0.007
5016	0.0025	0	0.019	0.014	0.006	0	0.002	0	0.007	0.004	0.0015	0
5017	0.004	0	0.022	0.019	0.007	0	0.0028	0.0018	0.008	0.006	0	0
5040	0.003	0	0.015	0.01	0.007	0	0.0025	0	0.014	0.009	0.0025	0
5042	0.002	0	0.04	0.03	0.0035	0	0.0015	0	0.005	0.002	0.0025	0
5043	0.004	0	0.013	0.007	0.007	0	0.0035	0.0005	0.012	0.007	0.0025	0
5049	0.004	0	0.025	0.016	0.005	0	0.001	0	0.011	0.005	0.002	0
5050	0.004	0	0.018	0.011	0.007	0	0.002	0	0.001	0	0.0025	0
5051	0.004	0	0.022	0.017	0.007	0	0.0025	0	0.002	0	0.0025	0
5052	0.0045	0	0.028	0.022	0.0045	0	0.001	0	0.001	0	0.002	0
5056	0.003	0	0.056	0.045	0.004	0	0.001	0	0.002	0.0005	0.001	0
5082	0.002	0	0.05	0.04	0.0035	0	0.0015	0	0.0015	0	0.0025	0
5083	0.007	0.004	0.049	0.04	0.004	0	0.001	0	0.001	0.0004	0.0025	0
5086	0.004	0	0.045	0.035	0.005	0	0.001	0	0.007	0.002	0.0025	0
5150	0.0008	0	0.017	0.013	0.001	0	0.001	0	0.0003	0	0.001	0
5151	0.002	0	0.021	0.015	0.0035	0	0.0015	0	0.001	0	0.0015	0
5154	0.0025	0	0.039	0.031	0.004	0	0.001	0	0.001	0	0.002	0
5182	0.002	0	0.05	0.04	0.0035	0	0.0015	0	0.005	0.002	0.0025	0
5205	0.0015	0	0.01	0.006	0.007	0	0.001	0.0003	0.001	0	0.0005	0
5250	0.0008	0	0.018	0.013	0.001	0	0.001	0	0.0015	0.0005	0.0005	0
5251	0.004	0	0.024	0.017	0.005	0	0.0015	0	0.005	0.001	0.0015	0
5252	0.0008	0	0.028	0.022	0.001	0	0.001	0	0.001	0	0.0005	0
5283	0.003	0	0.051	0.045	0.003	0	0.0003	0	0.01	0.005	0.001	0
5351	0.0008	0	0.022	0.016	0.001	0	0.001	0	0.001	0	0.0005	0
5356	0.0025	0	0.055	0.045	0.004	0	0.001	0	0.002	0.0005	0.001	0
5357	0.0012	0	0.012	0.008	0.0017	0	0.002	0	0.0045	0.0015	0.0005	0
5451	0.0025	0	0.024	0.018	0.004	0	0.001	0	0.001	0	0.001	0
5454	0.0025	0	0.03	0.024	0.004	0	0.001	0	0.005	0.001	0.0025	0
5456	0.0025	0	0.055	0.047	0.004	0	0.001	0	0.01	0.005	0.0025	0
5552	0.0004	0	0.028	0.022	0.0005	0	0.001	0	0.001	0	0.0005	0
5554	0.0025	0	0.03	0.024	0.004	0	0.001	0	0.005	0.001	0.0025	0
5556	0.0025	0	0.055	0.047	0.004	0	0.001	0	0.01	0.005	0.0025	0
5557	0.001	0	0.008	0.004	0.0012	0	0.0015	0	0.004	0.001	0	0
5657	0.0008	0	0.01	0.006	0.001	0	0.001	0	0.0003	0	0.0005	0
5754	0.004	0	0.036	0.026	0.004	0	0.001	0	0.005	0	0.002	0
6002	0.009	0.006	0.007	0.0045	0.0025	0	0.0025	0.001	0.002	0.001	0	0
6003	0.01	0.0035	0.015	0.008	0.006	0	0.001	0	0.008	0	0.002	0
6004	0.006	0.003	0.007	0.004	0.003	0.001	0.001	0	0.006	0.002	0.0005	0
6005	0.009	0.006	0.006	0.004	0.0035	0	0.001	0	0.001	0	0.001	0
6006	0.006	0.002	0.009	0.0045	0.0035	0	0.003	0.0015	0.002	0.0015	0.001	0
6007	0.014	0.009	0.009	0.006	0.007	0	0.002	0	0.0025	0.0005	0.0025	0
6008	0.009	0.005	0.007	0.004	0.0035	0	0.003	0	0.003	0	0.002	0
6009	0.01	0.006	0.008	0.004	0.005	0	0.006	0.0015	0.008	0.002	0.0025	0
6010	0.012	0.008	0.01	0.006	0.005	0	0.006	0.0015	0.008	0.002	0.0025	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
6011	0.012	0.006	0.012	0.006	0.01	0	0.009	0.004	0.008	0	0.015	0
6012	0.014	0.006	0.012	0.006	0.005	0	0.001	0	0.01	0.004	0.003	0
6013	0.01	0.006	0.01	0.008	0.005	0	0.011	0.006	0.008	0.002	0.0025	0
6014	0.006	0.003	0.008	0.004	0.0035	0	0.0025	0	0.002	0.0005	0.001	0
6015	0.004	0.002	0.011	0.008	0.003	0.001	0.0025	0.001	0.001	0	0.001	0
6016	0.015	0.01	0.006	0.0025	0.005	0	0.002	0	0.002	0	0.002	0
6017	0.007	0.0055	0.006	0.0045	0.003	0.0015	0.002	0.0005	0.001	0	0.0005	0
6060	0.006	0.003	0.006	0.0035	0.003	0.001	0.001	0	0.001	0	0.0015	0
6061	0.008	0.004	0.012	0.008	0	0	0.004	0.0015	0.0015	0	0.0025	0
6063	0.006	0.002	0.009	0.0045	0.0035	0	0.001	0	0.001	0	0.001	0
6066	0.018	0.009	0.014	0.008	0.005	0	0.012	0.007	0.011	0.006	0.0025	0
6069	0.012	0.006	0.016	0.012	0.004	0	0.01	0.0055	0.0005	0	0.0005	0
6070	0.017	0.01	0.012	0.005	0.005	0	0.004	0.0015	0.01	0.004	0.0025	0
6081	0.011	0.007	0.01	0.006	0.005	0	0.001	0	0.0045	0.001	0.002	0
6082	0.013	0.007	0.012	0.006	0.005	0	0.001	0	0.01	0.004	0.002	0
6101	0.007	0.003	0.008	0.0035	0.005	0	0.001	0	0.0003	0	0.001	0
6103	0.01	0.0035	0.015	0.008	0.006	0	0.003	0.002	0.008	0	0.002	0
6105	0.01	0.006	0.008	0.0045	0.0035	0	0.001	0	0.001	0	0.001	0
6106	0.006	0.003	0.008	0.004	0.0035	0	0.0025	0	0.002	0.0005	0.001	0
6110	0.015	0.007	0.011	0.005	0.008	0	0.007	0.002	0.007	0.002	0.003	0
6111	0.011	0.007	0.01	0.005	0.004	0	0.009	0.005	0.0045	0.0015	0.0015	0
6151	0.012	0.006	0.008	0.0045	0.01	0	0.0035	0	0.002	0	0.0025	0
6162	0.008	0.004	0.011	0.007	0.005	0	0.002	0	0.001	0	0.0025	0
6181	0.012	0.008	0.01	0.006	0.0045	0	0.001	0	0.0015	0	0.002	0
6201	0.009	0.005	0.009	0.006	0.005	0	0.001	0	0.0003	0	0.001	0
6205	0.009	0.006	0.006	0.004	0.007	0	0.002	0	0.0015	0.0005	0.0025	0
6261	0.007	0.004	0.01	0.007	0.004	0	0.004	0.0015	0.0035	0.002	0.002	0
6262	0.008	0.004	0.012	0.008	0.007	0	0.004	0.0015	0.0015	0	0.0025	0
6301	0.009	0.005	0.009	0.006	0.007	0	0.001	0	0.0015	0	0.0025	0
6351	0.013	0.007	0.008	0.004	0.005	0	0.001	0	0.008	0.004	0.002	0
6463	0.006	0.002	0.009	0.0045	0.0015	0	0.002	0	0.0005	0	0.0005	0
6763	0.006	0.002	0.009	0.0045	0.0008	0	0.0016	0.0004	0.0003	0	0.0003	0
6863	0.006	0.004	0.008	0.005	0.0015	0	0.002	0.0005	0.0005	0	0.001	0
6951	0.005	0.002	0.008	0.004	0.008	0	0.004	0.0015	0.001	0	0.002	0
7001	0.0035	0	0.034	0.026	0.004	0	0.026	0.016	0.002	0	0.08	0.068
7003	0.003	0	0.01	0.005	0.0035	0	0.002	0	0.003	0	0.065	0.05
7004	0.0025	0	0.02	0.01	0.0035	0	0.0005	0	0.007	0.002	0.046	0.038
7008	0.001	0	0.014	0.007	0.001	0	0.0005	0	0.0005	0	0.055	0.045
7009	0.002	0	0.029	0.021	0.002	0	0.013	0.006	0.001	0	0.056	0.055
7010	0.0012	0	0.026	0.021	0.0015	0	0.02	0.015	0.001	0	0.067	0.057
7011	0.0015	0	0.016	0.01	0.002	0	0.0005	0	0.003	0.001	0.055	0.04
7012	0.0015	0	0.022	0.018	0.0025	0	0.012	0.008	0.0015	0.0008	0.065	0.058
7013	0.006	0	0	0	0.007	0	0.001	0	0.015	0.01	0.02	0.015
7014	0.005	0	0.032	0.022	0.005	0	0.007	0.003	0.007	0.003	0.062	0.052
7015	0.002	0	0.021	0.013	0.003	0	0.0015	0.0006	0.001	0	0.052	0.046
7016	0.001	0	0.014	0.008	0.0012	0	0.01	0.0045	0.0003	0	0.05	0.04
7017	0.0035	0	0.03	0.02	0.0045	0	0.002	0	0.005	0.0005	0.052	0.04
7018	0.0035	0	0.015	0.007	0.0045	0	0.002	0	0.005	0.0015	0.055	0.045
7019	0.0035	0	0.025	0.015	0.0045	0	0.002	0	0.005	0.0015	0.045	0.035
7020	0.0035	0	0.014	0.01	0.004	0	0.002	0	0.005	0.0005	0.05	0.04
7021	0.0025	0	0.018	0.012	0.004	0	0.0025	0	0.001	0	0.06	0.05

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
7022	0.005	0	0.037	0.026	0.005	0	0.005	0.001	0.004	0.001	0.052	0.043
7023	0.005	0	0.03	0.02	0.005	0	0.01	0.005	0.006	0.001	0.06	0.04
7024	0.003	0	0.01	0.005	0.004	0	0.001	0	0.006	0.001	0.05	0.03
7025	0.003	0	0.015	0.008	0.004	0	0.001	0	0.006	0.001	0.05	0.03
7026	0.0008	0	0.019	0.015	0.0012	0	0.009	0.006	0.002	0.0005	0.052	0.046
7027	0.0025	0	0.011	0.007	0.004	0	0.003	0.001	0.004	0.001	0.045	0.035
7028	0.0035	0	0.023	0.015	0.005	0	0.003	0.001	0.006	0.0015	0.052	0.045
7029	0.001	0	0.02	0.013	0.0012	0	0.009	0.005	0.0003	0	0.052	0.042
7030	0.002	0	0.015	0.01	0.003	0	0.004	0.002	0.0005	0	0.059	0.048
7039	0.003	0	0.033	0.023	0.004	0	0.001	0	0.004	0.001	0.045	0.035
7046	0.002	0	0.016	0.01	0.004	0	0.0025	0	0.003	0	0.076	0.066
7049	0.0025	0	0.029	0.02	0.0035	0	0.019	0.012	0.002	0	0.082	0.072
7050	0.0012	0	0.026	0.019	0.0015	0	0.026	0.02	0.001	0	0.067	0.057
7051	0.0035	0	0.025	0.017	0.0045	0	0.0015	0	0.0045	0.001	0.04	0.03
7055	0.001	0	0.023	0.018	0.0015	0	0.026	0.02	0.0005	0	0.084	0.076
7060	0.0015	0	0.021	0.013	0.002	0	0.026	0.018	0.002	0	0.075	0.061
7075	0.004	0	0.029	0.021	0.005	0	0.02	0.012	0.003	0	0.061	0.051
7076	0.004	0	0.02	0.012	0.006	0	0.01	0.003	0.008	0.003	0.08	0.07
7079	0.003	0	0.037	0.029	0.004	0	0.008	0.004	0.003	0.001	0.048	0.038
7090	0.0012	0	0.03	0.02	0.0015	0	0.013	0.006	0	0	0.087	0.073
7091	0.0012	0	0.03	0.02	0.0015	0	0.018	0.011	0	0	0.071	0.058
7108	0.001	0	0.014	0.007	0.001	0	0.0005	0	0.0005	0	0.055	0.045
7109	0.001	0	0.027	0.022	0.0015	0	0.013	0.008	0.001	0	0.065	0.058
7116	0.0015	0	0.014	0.008	0.003	0	0.011	0.005	0.0005	0	0.052	0.042
7129	0.0015	0	0.02	0.013	0.003	0	0.009	0.005	0.001	0	0.052	0.042
7146	0.002	0	0.016	0.01	0.004	0	0	0	0	0	0.076	0.066
7149	0.0015	0	0.029	0.02	0.002	0	0.019	0.012	0.002	0	0.082	0.072
7150	0.0012	0	0.027	0.02	0.0015	0	0.025	0.019	0.001	0	0.069	0.059
7175	0.0015	0	0.029	0.021	0.002	0	0.02	0.012	0.001	0	0.061	0.051
7178	0.004	0	0.031	0.024	0.005	0	0.024	0.016	0.003	0	0.073	0.063
7179	0.0015	0	0.037	0.029	0.002	0	0.008	0.004	0.003	0.001	0.048	0.038
7229	0.0006	0	0.02	0.013	0.0008	0	0.009	0.005	0.0003	0	0.052	0.042
7277	0.005	0	0.023	0.017	0.007	0	0.017	0.008	0	0	0.043	0.037
7278	0.0015	0	0.032	0.025	0.002	0	0.022	0.016	0.0002	0	0.074	0.066
7472	0.0025	0	0.015	0.009	0.006	0	0.0005	0	0.0005	0	0.019	0.013
7475	0.001	0	0.026	0.019	0.0012	0	0.019	0.012	0.0006	0	0.062	0.052
8001	0.0017	0	0	0	0.007	0.0045	0.0015	0	0	0	0.0005	0
8004	0.0015	0	0.0002	0	0.0015	0	0.0003	0	0.0002	0	0.0003	0
8005	0.005	0.002	0.0005	0	0.008	0.004	0.0005	0	0	0	0.0005	0
8006	0.004	0	0.001	0	0.02	0.012	0.003	0	0.01	0.003	0.001	0
8007	0.004	0	0.001	0	0.02	0.012	0.001	0	0.01	0.003	0.018	0.008
8008	0.006	0	0	0	0.016	0.009	0.002	0	0.01	0.005	0.001	0
8010	0.004	0	0.005	0.001	0.007	0.0035	0.003	0.001	0.008	0.001	0.004	0
8011	0.009	0.005	0.0005	0	0.01	0.006	0.001	0	0.002	0	0.001	0
8014	0.003	0	0.001	0	0.016	0.012	0.002	0	0.006	0.002	0.001	0
8017	0.001	0	0.0005	0.0001	0.008	0.0055	0.002	0.001	0	0	0.0005	0
8020	0.001	0	0	0	0.001	0	0.00005	0	0.00005	0	0.00005	0
8030	0.001	0	0.0005	0	0.008	0.003	0.003	0.0015	0	0	0.0005	0
8076	0.001	0	0.0022	0.0008	0.009	0.006	0.0004	0	0	0	0.0005	0
8077	0.001	0	0.003	0.001	0.004	0.001	0.0005	0	0	0	0.0005	0
8079	0.003	0.0005	0	0	0.013	0.007	0.0005	0	0	0	0.001	0

Finished good	Si Max	Si Min	Mg Max	Mg Min	Fe Max	Fe Min	Cu Max	Cu Min	Mn Max	Mn Min	Zn Max	Zn Min
8081	0.007	0	0	0	0.007	0	0.013	0.007	0.001	0	0.0005	0
8090	0.002	0	0.013	0.006	0.003	0	0.016	0.01	0.001	0	0.0025	0
8091	0.003	0	0.012	0.005	0.005	0	0.022	0.016	0.001	0	0.0025	0
8111	0.011	0.003	0.0005	0	0.01	0.004	0.001	0	0.001	0	0.001	0
8112	0.01	0	0.007	0	0.01	0	0.004	0	0.006	0	0.01	0
8176	0.0015	0.0003	0	0	0.01	0.004	0	0	0	0	0.001	0
8177	0.001	0	0.0012	0.0004	0.0045	0.0025	0.0004	0	0	0	0.0005	0
8276	0.0025	0	0.0002	0	0.008	0.005	0.00035	0	0.0001	0	0.0005	0
8280	0.02	0.01	0	0	0.007	0	0.013	0.007	0.001	0	0.0005	0
X5090	0.005	0	0.08	0.06	0.005	0	0.0025	0	0.0035	0	0.002	0
X6206	0.007	0.0035	0.008	0.0045	0.0035	0	0.005	0.002	0.003	0.0013	0.002	0
X7005	0.0035	0	0.018	0.01	0.0035	0	0.001	0	0.007	0.002	0.05	0.042
X7064	0.0012	0	0.029	0.019	0.0015	0	0.024	0.018	0	0	0.08	0.068
X8092	0.001	0	0.014	0.009	0.0015	0	0.008	0.005	0.0005	0	0.001	0
X8192	0.001	0	0.014	0.009	0.0015	0	0.007	0.004	0.0005	0	0.001	0