ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

MÁSTER EN INGENIERÍA INDUSTRIAL

ANALYSIS AND PROPOSALS FOR THE BOTTOM ASH EXTRACTION AND TREATMENT IN AN ENERGY-FROM-WASTE FACILITY

Autor: Eduardo Quero Ruz
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Madrid
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ANALYSIS AND PROPOSALS FOR THE BOTTOM ASH EXTRACTION AND TREATMENT IN AN ENERGY-FROM-WASTE FACILITY

Eduardo Quero Ruz

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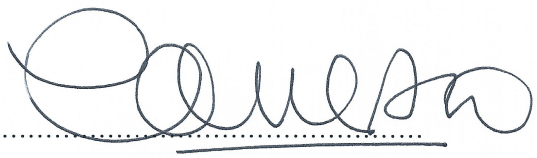

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Entidad Colaboradora/Collaborating entity: FCC Environment

RESUMEN DEL PROYECTO

Introducción

El objetivo de este proyecto es hacer un profundo análisis de las últimas tecnologías de extracción y tratamiento de las cenizas de fondo del incinerador (IBA) y encontrar la mejor opción para las condiciones del IBA producido en Greatmoor EfW que maximice los resultados económicos asociados.

Durante las últimas décadas, la tendencia en el tratamiento de residuos sólidos en Europa Occidental ha pasado de ser enviadas a vertederos a opciones más respetuosas con el medio ambiente como tratamientos térmicos y reciclado. El IBA es la ceniza resultado de la combustión del residuo sólido en el horno de la planta, y se ha probado que tiene un gran potencial en términos de material reciclable en plantas de energía desde residuos actuales. Tiene una notable cantidad de metales que pueden ser recogidos y el agregado residual tiene el potencial de ser usado en la industria de la construcción.

Las actividades de este proyecto tiene lugar en Greatmoor EfW en Buckinghamshire (Reino Unido), operada por FCC Environment. Se basa en un Ciclo Rankine para recuperar energía, usando residuos como combustible y con una capacidad de combustión de 300,000 toneladas de residuos al año que produce 75,000 toneladas de IBA al año. El objetivo del proyecto es plantear una serie de procesos para la recuperación de metales y comprobar su viabilidad técnica y económica para el IBA de Greatmoor EfW.

Metodología

El primer paso para cumplir con los objetivos es caracterizar el IBA producido por dos razones: comprobar si cumple con los requisitos marcados por la Agencia de Medio Ambiente del Reino Unido según las propiedades de peligro específicas y para obtener su composición elemental, que proporcionaría información sobre la cantidad de material que es potencialmente recuperable.

El condicionante principal de la eficacia de separación, junto con las características de los equipos, es el contenido de humedad del IBA. En Greatmoor EFW, IBA se extrae mediante un sistema de descarga húmedo y por lo tanto tiene un contenido de agua del 16% aprox. Los problemas debidos a este hecho surgen en el tratamiento de partículas de menos de 8 mm. Las partículas húmedas se concentran en la fracción fina y hacen que toda la fracción 0-8 mm esté pegajosa, lo que disminuye las posibilidades de separación.

Para hacer frente a este problema, se proponen 3 escenarios diferentes según el estado del IBA y tecnologías aplicadas para el tratamiento de la fracción fina.

- Escenario I – Extracción húmeda y separación convencional. Basado en el sistema de descarga húmeda de Greatmoor EfW sin tratamiento especial para la fracción fina.
- Escenario II – Extracción húmeda, separación convencional y separación de la fracción fina. Basado en el sistema de descarga húmeda de Greatmoor EfW con tratamiento específico para la fracción fina. Se proponen dos sistemas: mediante la adición de agua en diversos puntos del proceso para proceder a una separación húmeda de alta eficiencia y mediante la retirada de las partículas húmedas de menos de 2 mm para proceder a una separación seca.
- Escenario III – Extracción seca y separación convencional. Basado en un hipotético nuevo sistema de extracción seca que evitaría la necesidad de tratamiento especial debido a la humedad con recuperación de alta eficiencia.

Antes de la separación, el IBA en bruto se separará por fracciones de tamaño que se tratarán de forma distinta atendiendo a sus condiciones y contenido de humedad. En todos los escenario se usarán tres tipos de equipos de separación junto con equipos de clasificación, triturado y transporte. Estos tipos de equipos de separación son separación magnética para recuperar los metales ferrosos, separación de corrientes inducidas para los metales no ferrosos y separación por densidad para recuperar Al, Cu y Ag.

La viabilidad técnica se apoya en un estudio económico de los beneficios asociados a cada proceso en cada escenario. Se basa en un estudio del mercado de metales, incluyendo un modelo de predicción de precios para cada material, que afecta directamente los ingresos potenciales asociados a todos los escenarios, cálculo de los flujos de caja y análisis de sensibilidad. Para cada escenario, se propone una configuración diferente dependiendo de las características del proceso.

Resultados

La composición media de los materiales más valiosos para ser recuperados se muestra en la Tabla 1 como resultado de la etapa de caracterización.

***Tabla 1**: Cantidades de materiales valiosos contenidos en el IBA de Greatmoor EfW*

Hierro ligero	11.53%	8,647 ton/año
Aluminio	2.13%	1,597 ton/año
Cobre	0.24 %	177 ton/año
Plata	0.0001%	0.5 ton/año
Mezcla de no ferrosos	3.26%	2,445 ton/año

En todos los escenarios, una primera clasificación retiraría las partículas < 300 mm para triturarlas por debajo de 40 mm. Una segunda clasificación haría lo mismo con las

partículas < 40 mm. Ambas fracciones se introducirían otra vez en el sistema. Esto aumentaría la eficiencia de los procesos posteriores reduciendo las posibilidades de aglomeración.

El caso base para el Escenario I separaría el IBA en bruto en fracciones de tamaño 0-6, 6-20 y 20-40 mm, tratando cada una con separación magnética primero y posteriormente de corrientes inducidas. Debido a la baja eficiencia en la fracción 0-6 mm, se propone un caso alternativo en el que esta fracción no se trata.

En el Escenario II se presentan dos procesos distintos para lidiar con la fracción fina:

- Separación Seca Avanzada (ADR). Usando el concentrador ADR, basado en energía cinética, las partículas húmedas < 2 mm se retirarían de la fracción 0-12 mm, permitiendo una separación seca posterior. Se llevará a cabo una separación magnéticas y por corrientes inducidas antes de una separación por densidad para las fracciones 0-2 mm y 2-6 mm. Como una parte de los materiales valiosos sería retirada junto con las partículas húmedas en el concentrador ADR, se propone un caso alternativo en el que la fracción 0-2 mm no se separa por densidad.
- Separación húmeda. Mediante la adición de agua en diversos puntos y usando equipos de separación no convencionales se obtendría una separación de alta eficiencia pero requeriría tratamiento de aguas y lodos. El IBA se clasificaría en fracciones 0-2, 2-6, 6-20 y 20-40 mm. La fracción 0-2 mm se trataría con un hidrociclón y un concentrador "jig" para retirar el lodo y la fracción arenosa antes de separación magnética y por densidad. La fracción 2-6 mm se pasaría por un separador de gravedad cinética para retirar la materia orgánica y producir una corriente de Al/agregado y otra de Fe/metales pesados que se trataría con un separador de corrientes inducidas húmedo y un separador magnético húmedo. Ambas fracciones 6-20 mm y 20-40 mm se trataría con separación magnética y de corrientes inducidas convencionales.

El Escenario III se basa en un sistema de descarga seco, por lo que el IBA no tendría humedad y, por tanto, se obtendría una separación de alta eficiencia sin tratamientos especiales. El IBA en bruto se separaría en fracciones 0-6, 6-20 y 20-40 mm. La fracción 0-6 mm se pasaría por dos separadores magnéticos en serie y dos separadores de corrientes inducidas en serie, que mejoraría la eficiencia. Las fracciones 0-2 mm y 2-6 mm se tratarían con separación por densidad. Ambas fracciones 6-20 mm y 20-40 mm se trataría con separación magnética y de corrientes inducidas convencionales.

La eficiencia global de los procesos planteados se muestra en la Tabla 2. Desde el punto de vista técnico, la opción con mayor tasa de recuperación es la mejor, pero el resultado económico sería más indicativo.

Las tasaciones de equipos fueron facilitadas por los proveedores junto con sus requerimientos de agua y potencia. Los resultados de las predicciones para los precios de los metales con un intervalo de confianza del 95% se muestran en la Tabla 3. En el caso de los la mezcla de metales no-ferrosos, se asume un precio de 360 £/ton.

Partiendo de estos datos, se han calculado los flujos de caja con una tasa de impuestos del 20% y una tasa de descuento del 10.62%. Los resultados económicos para el caso óptimo de cada escenario se muestran en la Tabla 4. Con la excepción del Escenario I, en todos los casos la configuración óptima es aquella que maximice las tasas de recuperación.

Tabla 2: Eficiencia de recuperación de los escenarios

Material	Escenarios [% Recuperado]						
	I (B)	I (A)	II – ADR (B)	II – ADR (A)	II – Sep. húmeda	III (B)	III (A)
Fe	87.35	86.62	90.29	90.29	94.61	98.46	96.99
No-Fe	77.03	72.79	85.95	85.95	88.69	95.78	92.24
Al			9.90	5.74	15.53	21.27	18.06
Cu			17.28	11.70	13.35	32.17	27.31
Ag			37.83	32.32	13.19	54.95	46.65

Tabla 3: Resultados de la predicción de precios de metales

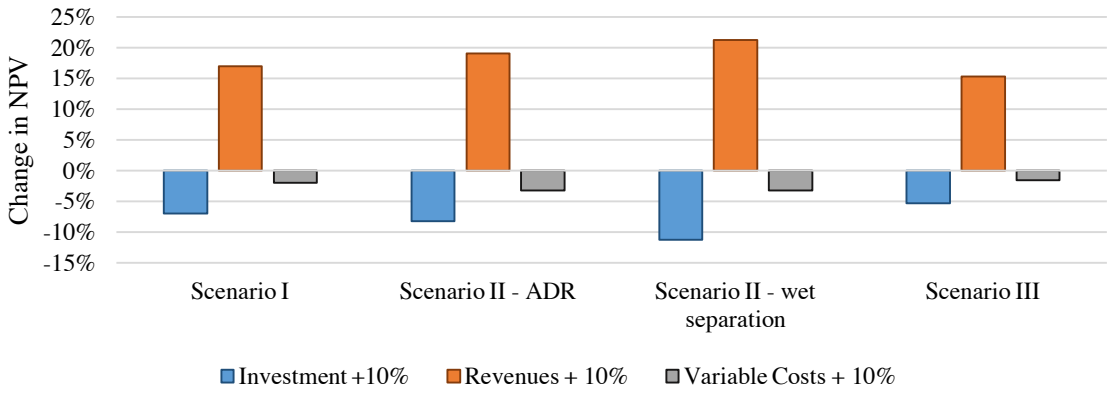
Año	Aluminio	Cobre	Planta	Hierro ligero
2017	1,420.84 ± 85.29 £/ton	3,457.43 ± 280.57 £/ton	312,639.47 ± 29,811.82 £/ton	51.24 ± 16.12 £/ton
2018	1,435.36 ± 85.29 £/ton	3,442.15 ± 280.57 £/ton	290,201.50 ± 29,811.82 £/ton	49.71 ± 16.12 £/ton
2019	1,449.88 ± 85.29 £/ton	3,426.87 ± 280.57 £/ton	267,763.54 ± 29,811.82 £/ton	48.18 ± 16.12 £/ton
2020	1,464.41 ± 85.29 £/ton	3,411.59 ± 280.57 £/ton	245,325.57 ± 29,811.82 £/ton	46.64 ± 16.12 £/ton
2021	1,478.93 ± 85.29 £/ton	3,396.31 ± 280.57 £/ton	222,887.60 ± 29,811.82 £/ton	45.11 ± 16.12 £/ton

El análisis de sensibilidad muestra que la variable que más afecta el resultado económico de todos los procesos es el valor de los ingresos asociados. La Figura 1 muestra el cambio en el VAN por un 10% de cambio en varios factores.

Tabla 4: Resumen de resultados económicos

Escenario	I	II - ADR	II – Sep. húm.	III
CAPEX	£1,924,344.84	£2,573,653.03	£3,319,911.16	£3,158,483.34
VAN	£3,447,747.16	£3,887,018.49	£3,664,051.89	£7,388,917.18
TIR	81%	71%	56%	100 %
PRC	1.12 años	1.24 años	1.48 años	0.94 años

Figura 1: Análisis de sensibilidad



Conclusiones

La instalación de una planta de recuperación de metales significaría un impacto significativamente positivo en Greatmoor EfW y en otras plantas de características similares. La rentabilidad de esta tecnología reside en la idoneidad del IBA producido, de la eficiencia del proceso y de la situación del mercado de metales.

- El IBA producido tiene una importante cantidad de metales que podrían ser recuperados con una planta de separación de metales.
- El Escenario III es el más rentable, siendo éste el que cuenta con mayores tasas de recuperación, lo que significa que para nuevas plantas EfW se debería plantear un sistema de descarga seca.
- Para las condiciones del IBA de Greatmoor EfW, el proceso ADR es el más rentable en un proyecto a 4 años.
- El nivel de ingresos es la variable más explicativa de todas las que afectan al VAN de cada proceso. Depende de la tasa de recuperación y de la situación del mercado.

En futuros estudios, debe hacerse un estudio de planificación considerando factores operativos que no se han tomado en cuenta en este proyecto. Además, deberían comprobarse las características del agregado para probar la idoneidad de éste para ser usado en la industria de la construcción.

SUMMARY

Introduction

The purpose of this thesis is to do a deep analysis of the last Incinerator Bottom Ash extraction and treatment technologies being developed and find the best option for the the conditions of Greatmoor Energy-from-Waste IBA that would maximize the economic benefits associated.

Over the last decades, there is a tendency in Western Europe in the treatment of solid waste from being landfill to more environmentally friendly options, like being thermally treated and recycled. IBA is the ash that is left over after the waste in burnt in the plant's boiler, and has been proven to have a great potential in terms of material to be recycled in state-of-art EfW facilities. It has a notable amount of metals that can be removed and the remaining aggregate has the potential to being used in the construction industry.

The activities carried out in this thesis take place at Greatmoor EfW in Buckinghamshire (UK), operated by FCC Environment. It is based on a conventional Rankine Cycle for energy recovery, using waste as combustible and has combustion capacity of 300,000 tons of waste per year which produces 75,000 tons of IBA per year. The drive of this thesis is to work out a series of layouts for a metal recovery process and check their technical and economic feasibility for Greatmoor EfW IBA.

Methodology

The first step to fulfil the objectives is to characterize the IBA produced for two reasons: check if it meets the requirements marked by the Environmental Agency of the UK according to specific hazard properties and to get its elemental composition, which would provide information about the amount of material that is potentially recoverable.

The main factor conditioning the efficiency of separation, together with the characteristics of the equipment, is the moisture content of IBA. At Greatmoor EfW, IBA is extracted by a wet discharge system and thus it has a water content of 16% approx. Problems due to this fact arise when treating particles smaller than 8 mm. Moist particles concentrate on the fine particle size fraction and make the entire 0-8 mm fraction sticky, which lowers the possibilities of separation. To deal with this problem, 3 different scenarios are proposed according to the status of the IBA and technologies applied for treating the fine fraction.

- Scenario I – Wet IBA extraction and conventional separation. Based on the wet extraction system installed at Greatmoor EfW, with no special treatment for the fine fraction.
- Scenario II – Wet IBA extraction, conventional separation and fine fraction separation. Based on the wet extraction system installed at Greatmoor EfW with specific treatments for the fine fraction. Two systems proposed: by adding water in several stages to perform a high efficient wet separation and by extracting the moist particles for dry separation.

- Scenario III – Dry IBA extraction and conventional separation. Based on a hypothetical new dry discharge system that would avoid special treatments due to moist content with high-rate metal recovery.

Before separation, the bulk IBA has to be screened into different size fractions that would be treated differently according to its conditions and moist content. In all scenarios, three different types of separation equipment are combined together with screening, crushing and conveying equipment. This separation equipment types are magnetic separation for ferrous metals removal, eddy current separation for non-ferrous metals removal and density separation for further non-ferrous metals separation of Al, Cu and Ag.

Technical feasibility is supported by an economic study of the benefits associated to each process in each scenario. It is based on a study of the metal market, including a metal price forecasting model for each material, that directly affects the potential revenues associated to all scenarios, project cash flow calculations and a sensibility analysis. For each scenario, an alternative layout is proposed according to the characteristics of the process.

Results

The average composition of the most valuable materials to be recovered is shown in Table 1 as a result of the characterization stage.

***Table 1**: Amounts of valuable materials contained in Greatmoor EfW IBA*

Light Iron scrap	11.53%	8,647 tons/year
Aluminum	2.13%	1,597 tons/year
Copper	0.24 %	177 tons/year
Silver	0.0001%	0.5 tons/year
Non-ferrous mix	3.26%	2,445 tons/year

In all scenarios, a first screen would remove the < 300 mm particles to being crushed down to > 40 mm. A second screen would separate the < 40 mm particles and would do the same. Both fractions would be reinserted in the system. This would increase the efficiency of the subsequent processes lowering the possibilities of agglomeration.

The base case for Scenario I would separate the bulk material into 0-6, 6-20 and 20-40 mm size fractions, treating all of them with magnetic separation first and then eddy current separation. Due to the low rate of recovery of the 0-6 mm fraction, an alternative case where that fraction is not treated is proposed.

In Scenario II, two different processes are proposed to deal with the fine fraction:

- Advanced Dry Recovery. Using the ADR concentrator, based on kinetic energy, the moist < 2 mm particles would be removed from the 0-12 mm fraction,

allowing a dry separation process after it. Magnetic and eddy current separation would be performed before density separation for the 0-2 mm and 2-6 mm fractions. Since most of the valuable materials contained in the 0-2 mm fraction would be extracted by the ADR concentrator together with the moist particles, an alternative case where this fraction would not be further treated is proposed.

- Wet separation. By adding water in several stages and using non conventional equipment, a high-rate recovery would be achieved but it would require water and sludge treatment. IBA would be screened into 0-2, 2-6, 6-20 and 20-40 mm fractions. The 0-2 mm fraction would be treated by a hydro-cyclone and a jig to remove the sludge and sand fraction before magnetic and density separators. The 2-6 mm fraction would be passed through a kinetic gravity separator to remove the organics and produce an Al/aggregate stream to be treated by a wet eddy current separator and a Fe/heavy metals stream to be treated by a wet magnetic separator. Both the 6-20 and the 20-40 mm fractions would be treated by magnetic and eddy current separators.

Scenario III is based on a dry discharge system, so the IBA would have no moisture content and thus high-rate separation would be achieved without special treatments. The bulk IBA would be screened into 0-6, 6-20 and 20-40 mm. The 0-6 mm fraction would be passed through two in-series magnetic separators and two in-series eddy current separators, which would increase the separation efficiency. The 0-2 and 2-6 mm fraction would be further treated by density separation. Both the 6-20 and the 20-40 mm fractions would be treated by single magnetic and eddy current separators. An alternative case with single magnetic and eddy current separators for the 0-6 mm fraction is proposed.

The overall efficiency rates for the proposed processes is shown in Table 2. From the technical point of view, the option with the higher rate of recovery is the most suitable, but the economic results would be more indicative in every case.

The equipment quotations were provided by several suppliers together with their power and water requirements. The results for the metal price forecasting with a confidence interval of 95% are shown in Table 3. In addition, the non-ferrous metals mix price assumed is 360 £/ton.

From this data, operating cash flows of each case in each scenario has been calculated using a corporate tax rate of 20% and a required return of 10.62%. The economic results for the optimal case of each scenario is shown in Table 4. With the exception of Scenario II, in all cases the optimal case from the economic point of view considering a 4-year project-life resulted to be the one with a higher rate of recovery.

The sensibility analysis shows that the variable affecting the most the economic result of all processes is the value of the revenues associated. Figure 1 shows the change in the NPV for a 10% change in the value several factors.

Table 2: Scenario recovery efficiencies

Material	Scenarios [% Recovered]						
	I (B)	I (A)	II – ADR (B)	II – ADR (A)	II – Wet sep.	III (B)	III (A)
Fe	87.35	86.62	90.29	90.29	94.61	98.46	96.99
Non-Fe	77.03	72.79	85.95	85.95	88.69	95.78	92.24
Al			9.90	5.74	15.53	21.27	18.06
Cu			17.28	11.70	13.35	32.17	27.31
Ag			37.83	32.32	13.19	54.95	46.65

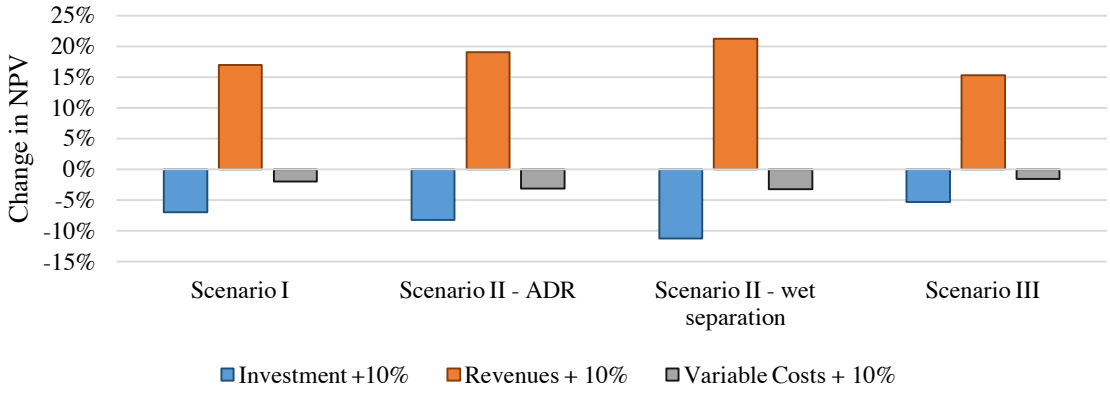
Table 3: Metal price forecasting results

Year	Aluminum	Copper	Silver	Light Iron
2017	1,420.84 ± 85.29 £/ton	3,457.43 ± 280.57 £/ton	312,639.47 ± 29,811.82 £/ton	51.24 ± 16.12 £/ton
2018	1,435.36 ± 85.29 £/ton	3,442.15 ± 280.57 £/ton	290,201.50 ± 29,811.82 £/ton	49.71 ± 16.12 £/ton
2019	1,449.88 ± 85.29 £/ton	3,426.87 ± 280.57 £/ton	267,763.54 ± 29,811.82 £/ton	48.18 ± 16.12 £/ton
2020	1,464.41 ± 85.29 £/ton	3,411.59 ± 280.57 £/ton	245,325.57 ± 29,811.82 £/ton	46.64 ± 16.12 £/ton
2021	1,478.93 ± 85.29 £/ton	3,396.31 ± 280.57 £/ton	222,887.60 ± 29,811.82 £/ton	45.11 ± 16.12 £/ton

Table 4: Economic results summary

Scenario	I	II - ADR	II - Wet sep	III
CAPEX	£1,924,344.84	£2,573,653.03	£3,319,911.16	£3,158,483.34
NPV	£3,447,747.16	£3,887,018.49	£3,664,051.89	£7,388,917.18
IRR	81%	71%	56%	100 %
PBP	1.12 years	1.24 years	1.48 years	0.94 years

Figure 1: Sensibility analysis



Conclusions

The installation of a metal recovery plant would have a significantly positive impact in Greatmoor EfW and in other plants of similar characteristics. The profitability of this technology resides in the suitability of the IBA produced, the efficiency of the process and the metal market situation.

- The IBA produced on site has an important amount of metals that could be recovered by a metal recovery plant.
- Scenario III is the most profitable process, being this the one with higher recovery rates, meaning that for new plants dry discharge is to be considered as an option for the IBA extraction system.
- For the conditions of Greatmoor EfW, the ADR process is the most profitable for a 4-year project life.
- The level of revenues is the most explicative variable of the those affecting the NPV of each process. It depends on the rate of recovery and the market situation.

In further studies, a full planning study should consider operating factors not taken into account in this thesis. In addition, the characteristics of the aggregate should be tested to prove its suitability to being used in the construction industry.

Contents

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Nomenclature

Acronyms and abbreviations

AEB Afval Energie Bedrijf

ACC Air Cooled Condenser

B Magnetic flux

c Centrifugal

CAPEX Capital Expenditures

CCS Cyclone Cut Size

comp Competing

Cov Covariance

d Hydrodynamic

DC Direct Cost

DES Double Exponential Smoothing

EA Environmental Agency

EBIT Earnings Before Interest and Taxes

ECS Eddy Current Separator

EfW Energy-from-Waste

ERF Energy Recovery Facility

ESA Environmental Service Association

EU European Union

F Force

FCC Fomento, Construcciones y Contratas

g Gravitational, gravity acceleration

H Magnetic field intensity

HZI Hitachi Zosen Inova

I Inducted current

i Discount Rate

IBA Incinerator Bottom Ash

IBAA Incinerator Bottom Ash Aggregate

IC Indirect Cost

INV Investment

IRR Internal Rate of Return

J Current density

KEZO Kehrichtverbrennung Zürcher Oberland

KGS Kinetic Gravity Separator

L Distance, working zone

LC Lifecycle Cost

LOI Loss On Ignition

M Magnetization of the particle

m Mass

MACRS Modified Accelerated Cost Recovery System

mag Magnetic

MC Maintenance Cost

MM Moving Means

MMLT Moving Means with Linear Tendency

MSE Minimum Squared Error

MSW Municipal Solid Waste

N Number

n Speed

NF Non-ferrous

NPV Net Present Value

NSC Non Site Cost

OCF Operating Cash Flow

p Particle, number of poles

PBP Payback Period

POP Persistent Organic Pollutant

r Repellent

s	Surface, shape factor
SC	Site Cost
SSC	Submerged Scraper Conveyor
t	Time
TOC	Total Organic Carbon
TR	Corporation Tax Rate
U	Potential energy
UK	United Kingdom
V	Volume, voltage
Var	Variance
WECS	Wet Eddy Current Separator
WTE	Waste to Energy
Z	Normal distribution values

Greek letters

$\boldsymbol{\alpha}$	Confidence level
$\boldsymbol{\eta}$	Dynamic viscosity
$\boldsymbol{\kappa}$	Volume magnetic susceptibility
$\boldsymbol{\mu}$	Magnetic permeability
$\boldsymbol{\rho}$	Density, conductivity
$\boldsymbol{\sigma}$	Standard deviation, conductivity
$\boldsymbol{\nabla}$	Gradient operator

Chapter 1

Introduction

1. Context

The purpose of this thesis is to do a deep analysis of the IBA[1] extraction and treatment technologies applied in state-of-art EfW[2] facilities and find the best option for the conditions of Greatmoor EfW IBA that would maximize the economic benefits associated. A comparison between the proposed processes will be based on their technical and economic feasibility.

All the human activities carry an associate production of waste. Progress and industrial development has helped to raise both the amount and variety in nature of residues, most of them hazardous for human life and nature, which has created an increasing concern about the impact of those residues in the last decades. The consumption habits of modern society are causing a worldwide waste problem in terms of storage. The existing elimination facilities are close to saturation, so alternatives are sought for waste handling. Approximately 34% of MSW[3] across the European Union is still landfilled, although landfilled gasses contribute significantly to global warming.

EfW facilities are an alternative way to recycling waste by generating electricity by combustion of residues that are unfit for conventional recycling. This way the volume of waste is greatly reduced and, thanks to its calorific power, energy can be recovered with no need to import organic fuels. This process needs to be carefully monitored and controlled in terms of emissions as the incinerated waste has hazardous components that have to be kept from emitting to the atmosphere.

The location of the activities carried out in this thesis is the Greatmoor EfW facility, located in the Buckinghamshire county (United Kingdom) which will be operated by FCC[4] Environment after it is ready for full operation. Once operational, Greatmoor EfW would thermally treat up to 300,000 tonnes of residual household and commercial waste per year and will generate approximately 24 MW of electricity to export to the national grid.

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[1] Incinerator Bottom Ash
[2] Energy-from-Waste
[3] Municipal Solid Waste
[4] Fomento de Construcciones y Contratas

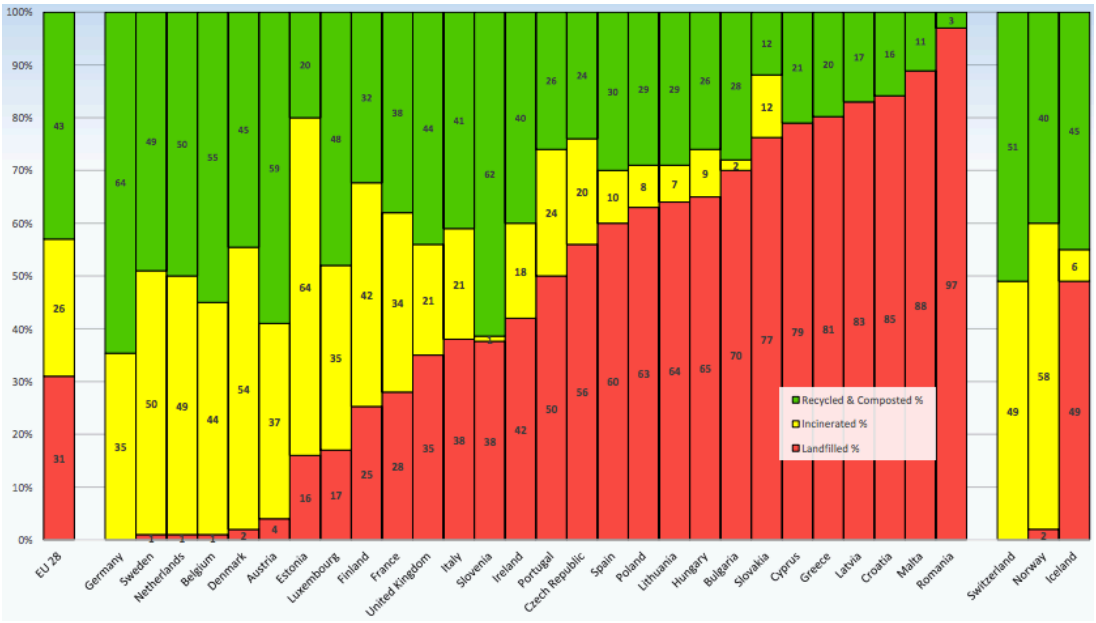

***Figure 1.1**: MSW treatment, Eurostat 2013*

The subject of study in this thesis is the IBA. This is the ash that is left over after the waste is burnt in the plant's boiler. As there is a wide range of waste used as fuel, this ash is not all powdery but may contain glass, brick, ceramics, metal, stone, concrete, etc. as well as combusted products such as ash and slag [ESA16]. IBA represents typically the 20-30% of the input residue.

***Figure 1.2**: Greatmoor EfW I*

***Figure 1.3**: Greatmoor EfW II*

Material recovery processes to be applied at Greatmoor EfW have been analysed technically and economically and compared in those terms maximise the associated benefit.

2. Greatmoor EfW operation

The Greatmoor EfW plant utilizes approximately 300,000 tons of municipal, commercial and industrial waste per year. The plant's operation is based on the combustion process, defined as the exothermic process of complete oxidation of matter at high temperature to convert it into gas and ash in addition to heat. The utilized oxidizer is air and the combustion technology is the grate incinerator, using a Rankine Cycle for heat recovery.

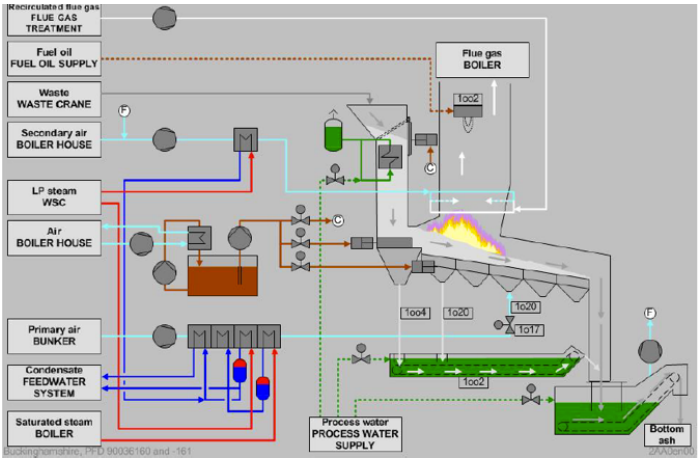

Figure 1.4: Grate process [HZI[5] learning modules]

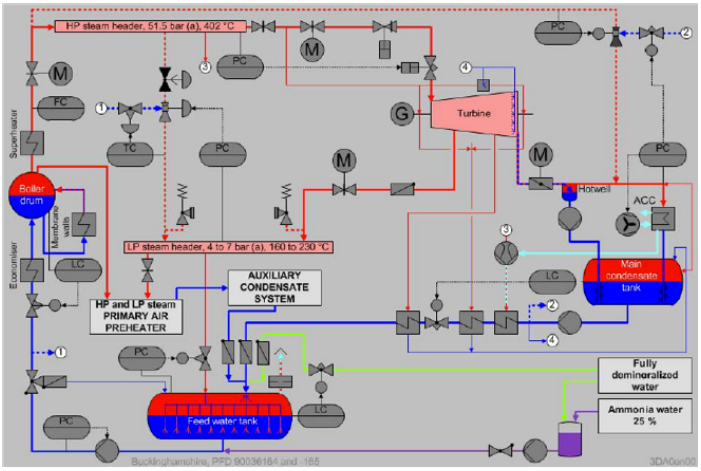

Figure 1.5: Steam water cycle [HZI learning modules]

Figure 1.4 shows the grate incinerator process, where the waste crane charges the feed hopper. The waste slides down the feed hopper chute and lands on the ram feeder, where it is pushed into the combustion chamber. The high temperature in the combustion chamber evaporates the moisture and ignites the waste, which burns on the grate producing thermal energy. The incombustible part (IBA) falls into the IBA extractor at the end of the grate where it is extinguished and discharged. The flue gas formed by the combustion flows through the boiler and is cooled as the heat emitted is used to generate steam.

Figure 1.5 shows the steam water cycle, where the superheated live steam flows from the boiler to the high pressure steam header. This high pressure steam reaches the turbine where it expands as it passes through the turbine stages. The exhaust steam is driven by underpressure into the ACC[6] where it is condensed. The condensate is pumped via three exchangers to increase its temperature and finally is led into the feed water tank. From the feed water tank, the water is pumped back to the boiler.

Figure 1.6 shows the flue gas treatment process. The flue gas after combustion is treated accordingly with several absorbers to clean it and lower pollutant levels to acceptable values

[5] Hitachi Zosen Inova AG, contractor
[6] Air Cooled Condenser

regulated by the UK[7] Environmental Agency via EU[8] legislation. The flue gas leaves the boiler and it passes through the reactor and fabric filter, where it is cooled down and additives absorb pollutants and improve the emission values. A partial flow of the clean gas is recirculated into the post-combustion chamber whereas the rest is drawn up through the stack and is discharged into the atmosphere.

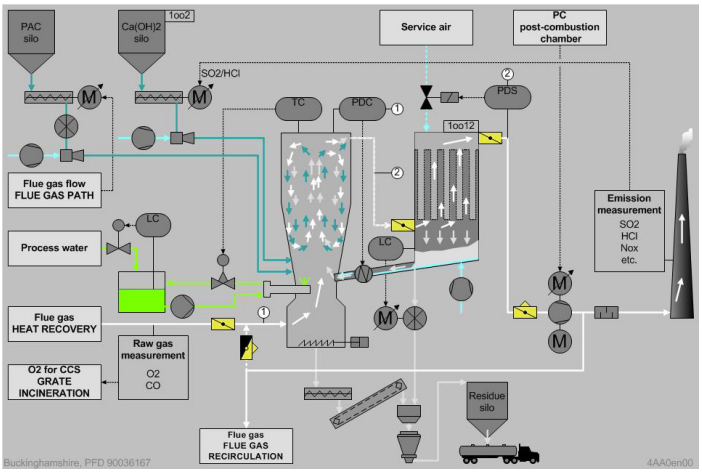

Figure 1.6: Flue gas treatment [HZI learning modules]

Figure 1.7 shows the IBA extraction process which is based on a wet removal using a SCC[9] system with water as cooling media.

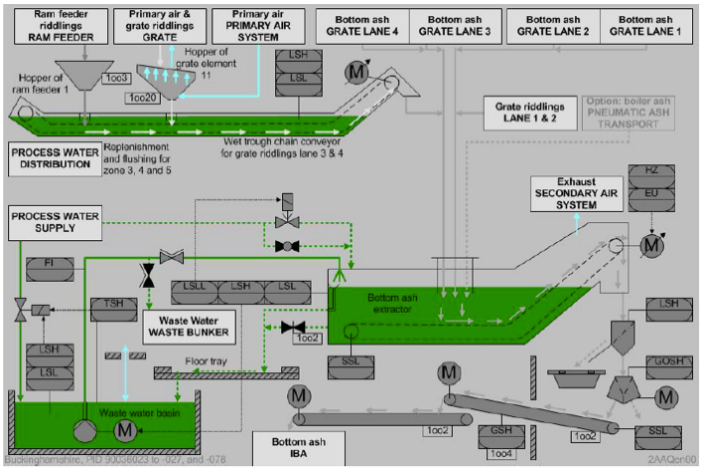

Figure 1.7: IBA extraction process [HZI learning modules]

The IBA falls from the last grate zone through the IBA chute into the IBA extractor chamber, flooded with water, where the IBA is quenched and cooled. A plated steel belt transports the IBA and dewaters it as it travels up the inclined section before it discharges it over an oversized separator where large pieces are driven to another container. The IBA is fed into a transfer conveyor, which transfers the IBA to storage.

[7] United Kingdom
[8] European Union
[9] Submerged Scraper Conveyor

Figure 1.8: IBA Extractor chamber

Figure 1.9: IBA Conveyor I

Figure 1.10: IBA Conveyor II

Figure 1.11: IBA storage

After the process, the IBA is placed in the IBA pad for later transportation to off site storage where it is held for further applications or to be landfilled.

Wet IBA handling systems are the industry standard and are the most commonly installed method in both coal-fired and EfW power industries. Nevertheless, the need of drying the IBA for further analysis, as well as efficient removal of ferrous and non-ferrous metals and other materials for recycling, are making necessary the search for environmentally suitable and more efficient alternatives by the companies of the sector.

If after analysis it is considered not hazardous, IBA is ideal for road paving, cement and construction blocks. The use of IBA in building blocks has been thoroughly tested and the results confirmed that it is safe to use in this applications. It has also been recognized that IBA has the potential of a valuable secondary aggregate [VEOL13].

EfW facilities are increasing in number every year: approximately 460 in the EU, being France the leader in number with 127 plants and Germany in amount of waste thermally treated with 21.9 million tons. The UK counts with 26 plants treating 6.1 million tons[10] [CEWE16].

[10] Data of 2013

3. Motivation

IBA consists of the non-combustible residual resulting from the combustion of the incoming waste. It is collected at the end of the grate and is made of a mix of materials such as sand, stone, glass, porcelain, metals (ferrous and non-ferrous) and ash from burnt materials.

EfW facilities around Europe process approximately 82 million tons of waste per year [CEWE16]. The main product of these facilities together with electricity is IBA, producing around 20 million tons per year. This raw IBA is subjected to a process where metals are separated and the remaining IBA is normally stored for ageing, drying and use as an aggregate.

Ferrous metals (steel and Iron) are normally separated magnetically and non-ferrous metals (Aluminum, Cooper, Zinc, etc.) by the eddy current technique (consisting on creating small currents in metal objects). The ferrous metal fraction makes up 8-12% of the total amount of IBA and can be sold to iron producers whereas the non-ferrous metals put into recycling. The remaining IBA can be used in road construction as a foundation material, in noise barriers and as an aggregate in asphalt and concrete.

To enable high-grade recycling, the material classification and separation has to be highly efficient. The problem comes with the adhering moisture due to the wet extraction methods of the IBA, such as the SCC installed at Greatmoor EfW. Moisture makes more difficult to separate metals with precision as it makes the ash to stick together as sludge, which leads to extra costs and time for drying it.

The motivation of this thesis is to find the best process that facilitates the separation of the different materials composing the IBA for a high-grade recycling. An economic and technical feasibility study of 3 different scenarios will be made, adjusting their implementation to the characteristics of Greatmoor EfW. Those scenarios are the following:

- The current IBA wet extraction system with conventional separation techniques.
- The current IBA wet extraction system with specific treatments for the moist fraction and innovative separation techniques.
- A completely new installation with a fully-dry ash extraction that would avoid specific treatments due to moisture content.

4. Objectives

For the particular needs and characteristics of Greatmoor EfW, the main objective of this thesis is to work out a series of systems for removing the valuable materials contained in the IBA. These alternatives would allow classification and separation of the different materials composing the IBA.

A technical feasibility study has been done, including the best technologies available for IBA treatment and technologies applied in other industries, such as mining, have been considered in this thesis. This study is based on proven material separation efficiencies of the different processes and the best layout has been proposed in each scenario.

An economic feasibility study of the alternatives proposed that include an analysis of investments, revenues arising from the implementation of the new technology and sensibility to fluctuations has been done. Metal prices have a great importance in this section and thus a time series analysis of the historical progression of their values has been done. This analysis also provides confidence intervals that has been used to analyze the sensibility of the project to price changes.

Sample taking and being familiarize with its procedure is essential for the purpose of this thesis, to get exact information about the Greatmoot EfW IBA specific composition.

Chapter 2

Incinerator Bottom Ash

1. Introduction

Over the last years, the tendency in Europe in the treatment of MSW has changed from being landfilled to other more environmentally friendly options like being pre-separated and thermally treated. In Figure 2.1 it can be seen the increases in separation and recycling and the decrease in the amount of waste being stored in landfills.

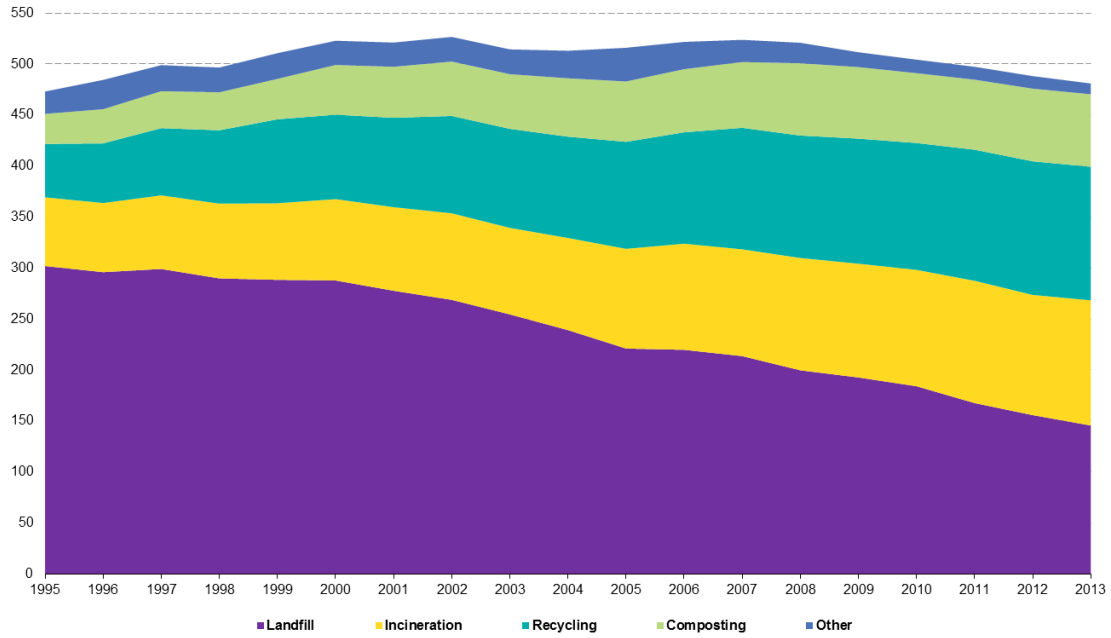

***Figure 2.1**: MSW treatment in EU-27 [kg per capita]1995 to 2013 - Eurostat 2013*

Thermal treatment represents an appropriate option for reducing the amount of waste to be landfilled as the combustion process reduces the volume of waste by about 90% and its mass by 70% [HJEL96], as well as providing recovery of energy from the waste to generate electricity. However, it generates solid residues, IBA and fly ash, and atmospheric emissions containing about 12% of CO_2 [SOCI99] IBA is the most significant by-product from the thermal treatment of MSW. Approximately 80% of combustion residue is IBA and represents between 20 and 30% in mass of the incoming waste.

The composition of MSW and therefore the composition of IBA changes depending on the geographical origin, being affected by the lifestyle and the recycling processes of the country. Table 2.1 shows the average composition of IBA in Western Europe. The major components of IBA are stone, glass and ceramics (aggregate) which can be reused as a building and road material as it has similar engineering properties to more common buildings materials such as gravel and sand. IBA also contains ferrous, non-ferrous and precious metals and some organic material.

***Table 2.1**: Average IBA composition in Western Europe*

Material	% by mass
Aggregate	~ 80
Ferrous metals	5-13
Non-ferrous metals	1.7-5
Precious metals	0.001
Organics	1-5

1.1. IBA valorization process

In order to make IBA components interesting from the commercial point of view to be reused in the industry, it is commonly followed the scheme showed in Figure 2.2.

***Figure 2.2**: IBA valuation process*

As mentioned previously, the composition of IBA varies depending on the MSW origin and also on the combustion and extraction method. Therefore, the characterization stage is critical for the election of the best treatment. How products are sold is also subject to change depending on the opportunities of the market and corresponding environmental permits are always to be met.

The following sections in this chapter discuss the characterization of the IBA produced in Greatmoor EfW, applicable permits and common treatments, potential utilization and products obtained.

2. Applicable legislation

Raw IBA (as it is extracted from the plant) is considered as Waste by the EU according to Directive 2001/118/EC and it is subject to analysis to ensure that no hazardous substances are in contact with human beings or the environment. This assessment is further explained in section 2.1 of this chapter.

There is no regulation for IBA recycling at EU level so European countries developed their own legislation for IBA recovery and reuse. In the UK, prior further use for IBAA[1], it has to meet with several standards depending on its final use [ENVI14]:

- BS EN 13242:2013 – Aggregates for unbound and hydraulic bound materials for use in civil engineering work and road construction.
- BS EN 13285:2010 – Unbound mixture.
- BS EN 13043:2013 – Aggregates for bituminous mixtures and surfaces treatments for roads, airfields and other trafficked areas.
- BS EN 12620:2013 – Aggregates for concrete
- BS EN 13055-1:2002 – Lightweight aggregates. Lightweight aggregates for concrete, mortar and grout.

(*) For use in road construction it must also meet the Highways Agency specification of Highways works.

But before dealing with these standards, IBAA has to be proven non-hazardous and treated accordingly. In the following sections, it will be explained the hazardous properties assessment process and the standard rules for IBA treatment produced by the EA[2] of the UK Government.

2.1. Hazardous properties

The LIT 10121 Waste Classification document provided by the EA of the UK Government [ENVI15] is a guidance on the classification and assessment of waste. It gives information about how waste must be classified according to 20 chapters in the LoW[3], which contains classification codes. Each code is related to an assessment, divided into three types:

- Wastes that may be hazardous or not hazardous, known as “mirror hazardous” or “mirror non-hazardous”
- Wastes that are always hazardous, known as “absolute hazardous”
- Wastes that are always non-hazardous, known as “absolute non-hazardous”.

According to this classification, IBA and slag from waste management facilities such as Greatmoor EfW is considered mirror hazardous or mirror non-hazardous, so it needs to be sampled and chemically analyzed to determine its composition. In addition, this kind of waste may contain POP[4], which concentration limits are specified in Appendix A.

Sampling is made according to the ESA[5] sampling and testing protocol for the assessment of hazard status of incinerator IBA [ESA14], a voluntary industry protocol produced by ESA with the support of the EA to provide a method for the classification and assessment of IBA from waste incinerators. Samples must be taken periodically to ensure that the IBA produced on plant does not contain hazardous substances or exceed hazardous limits. The sampling procedure consists in 24 samples taken twice a week to create a record of the plant and, if it is considered that the IBA produced in that specific plant is non-hazardous, the number of samples is reduced to two per

[1] Incinerator Bottom Ash Aggregate
[2] Environmental Agency
[3] List of Waste
[4] Persistent Organic Pollutants
[5] Environmental Services Association

month. Waste is assessed according to 15 hazardous properties HP1 to HP15 that have to be considered all times. The complete list of hazardous properties can be seen in Appendix A.

When proven non-hazardous, IBA is ready for further treatment and being commercialized or stored in landfills. This last option is what it is being tried to be avoided for being not environmentally friendly as it leads to emissions and leachates. In addition, the available space is scarce and standard gate fee in UK landfills is £82.60 per ton of waste[6]. Another option is to being stored as "inactive waste" in which case the gate fee would be £2.60 per ton and is intended to be used for road construction but it has a different legislation.

2.2. Treatment of IBA

Once considered non-hazardous, IBA treatment is regulated by the EA though the Standard rules SR2012 No13 document, dealing with the treatment of IBA for Part A installations (treatment capacity more than 75 tons per day) [ENVI13]. These rules are intended to allow to operate a Part A installation for the treatment of IBA inside a building at a specified location, limiting the incoming amount of IBA to 75,000 tons a year.

The purpose of the treatment is to generate material that has the potential for recovery and mechanically separate and collect the ferrous, non-ferrous and precious metals for further recycling. The SR2012 No13 document covers the following aspects of the treatment:

- Management: general management, energy efficiency, efficiency with raw materials and avoidance, recovery and disposal of wastes produced by the activities.
- Operations: authorizes the operator to carry out activities of recycling/reclamation of metals and inorganic materials from non-hazardous IBA and its storage in the specified site. Waste acceptance, operating techniques, emissions and information record/reporting are also regulated in this section.

3. Treatment and further utilization

In grate furnaces like that installed at Greatmoor EfW, IBA falls from the end of the grate directly to the IBA extraction system. Then it is typically conveyed to further treatment that will depend on the final use intended, but generally it is driven to metal separation, ageing or maturing, washing and other treatments. Figure 2.3 shows a generic IBA path.

In the following sections, there is a differentiation between extraction, metal separation and aggregate treatment for use in the industry. All three processes are explained below.

[6] UK Government: https://www.gov.uk/green-taxes-and-reliefs/landfill-tax

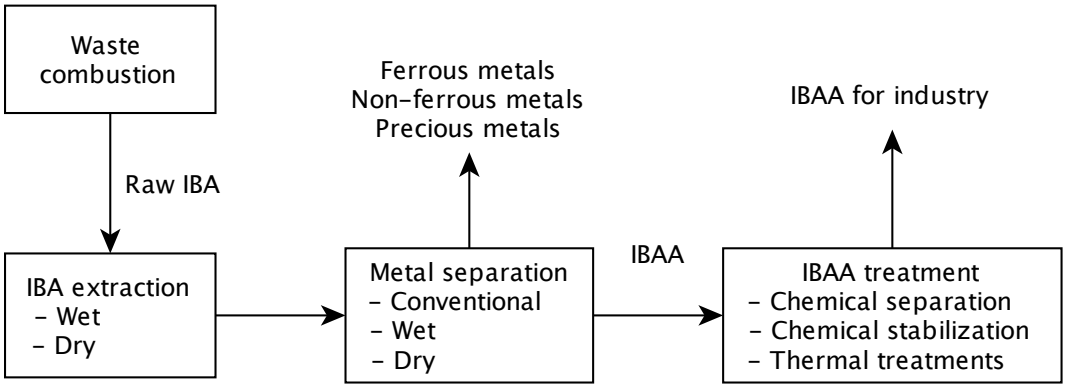

Figure 2.3: Generic IBA path

3.1. Extraction

For grate furnace, wet or dry IBA extraction systems can be applied. Wet discharge is the dominant method currently applied in most EfW facilities worldwide, including Greatmoor EfW. In this case, IBA is quenched in a water bath after it falls from the grate. Even if it is the most common technology used, it has the disadvantage of increasing the moisture of the IBA and thus its mass and leaching. Also thermal shock caused by the immediate contact of metal scrap with water after combustion causes further degradation of the scrap, causing a loss of the potential recoverable mass of those metals.

In 2000, Martin GmbH applied a dry ash discharge technology at the Iwaki Nanbu WTE[7] plant in Japan[8]. Currently six more plants have dry technology in Japan and two in Switzerland [BOUR12]. The dry discharge system makes easier the recovery of metals and minerals from IBA. As no water is used, the cost of disposal is less and there is a reduction of the weight of ash, there is a significant reduction of the leaching of IBA and further chemical reactions for maturing can be controlled. The main disadvantage of this system is the generation of dust emissions that must be controlled whereby a sealed transport system is required.

After extraction, in the case of wet ash it is common to let it dry for a couple of days. An intermediate storage period[9] is required for maturing [ZWAH03], which ensures that IBA meets the standards for utilization. As a result, IBA will solidify into a solid block making necessary for it to be crushed [BUNG15]. This has the side effect that the recoverable metal content is reduced. In the case of Aluminum, the loss of recoverable mass will raise a 20% in the 2-16 mm fraction [DEVR09]. As the purpose of this thesis is to find the best system for metal recovery, for the proposed systems any maturing activity included in the process will be carried out after the metal recovery process.

[7] Waste to Energy
[8] Martin GmbH website: https://www.martingmbh.de
[9] See section 2.3.2 in this chapter

3.2. Metal recovery

In order to obtain a high separation efficiency, instead of trying to recover the metals from the full size range of IBA it is classified[10] to size fractions by screening processes. Figure 2.4 shows a simplified scheme of an IBA processing plant.

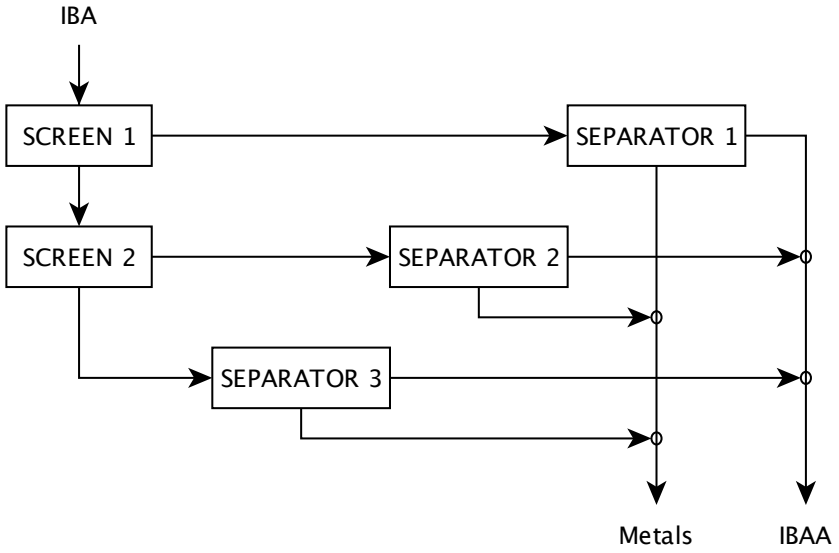

***Figure 2.4**: IBA processing plant*

Classification can be performed either through dry or wet processes. As a result of the wet discharge system installed in Greatmoor EfW and in most of the EfW plants worldwide, ash is a moist, agglomerated material. This makes it difficult to process particles below 8-12 mm. In order to recover metals and minerals from the IBA down to fine particles, the material should either be dried or immersed in water to obtain slurry with freely moving particles. Dry separation operates with standard equipment with typical particle sizes of 10-50 mm and 2-10 mm. Wet separation can be performed through either dense medium separation or attrition washing. It allows the extraction of soluble constituents but generates more fine material to be disposed off and requires water treatment [POLE07].

IBA treatment in Europe has three main possibilities:

- Traditional separation using conventional equipment like coarse screening, size reduction, magnetic separation and eddy current separation. Allows to recover metal particles larger than 10-15 mm from the ash.
- Innovative dry IBA treating technology implemented by INASHCO[11] in collaboration with the Delft University of Technology in 2008 that shifts under 2 mm mineral particles from the IBA input [DEVR09].
- Innovative wet process developed by Rem in Amsterdam (AEB[12] Amsterdam) in 2004 that treats very fine particles down to 0.1 mm [REM04] [MUCH07].

[10] In the context of mechanical process engineering, "classification" consists in a separation according to size.
[11] INASCHO BV: https://www.inachco.com
[12] Afval Energie Bedrijf

The following sections provide a brief explanation of the three technologies.

3.2.1. Conventional separation of metals

Conventional IBA treatment is a dry separation of process applied for the recovery of ferrous metals, coarse Aluminum and Copper-alloy particles larger than 10-15 mm. Only a small part of the metals is recovered, while fine ferrous and non-ferrous metals are not efficiently removed. In most installations the fine fraction is not treated at all. Some facilities pass the fine fraction over the magnets and the eddy current separator, just like they do with the coarse fraction, but due to the high moisture content of the IBA the separation performance is poor for the finer particles. Further explanation of this equipment is given in Chapter 4.

3.2.2. AEB wet separation

This innovative wet process screens the wet IBA into several fractions (0-2 mm, 2-6 mm, 6-20 mm and 20-40 mm) and classifies the 0-2 mm fraction in a cyclone to take out the sludge. Each fraction is treated separately to recover metals by treating a particle size down to 0.1 mm. This process is able to recover up to 80-85% of non-ferrous content of the IBA [BAKK07]. Then, the under 2 mm fraction is treated by a regular soil cleaning process [REM04]. A schematic of the process in shown in Figure 2.5.

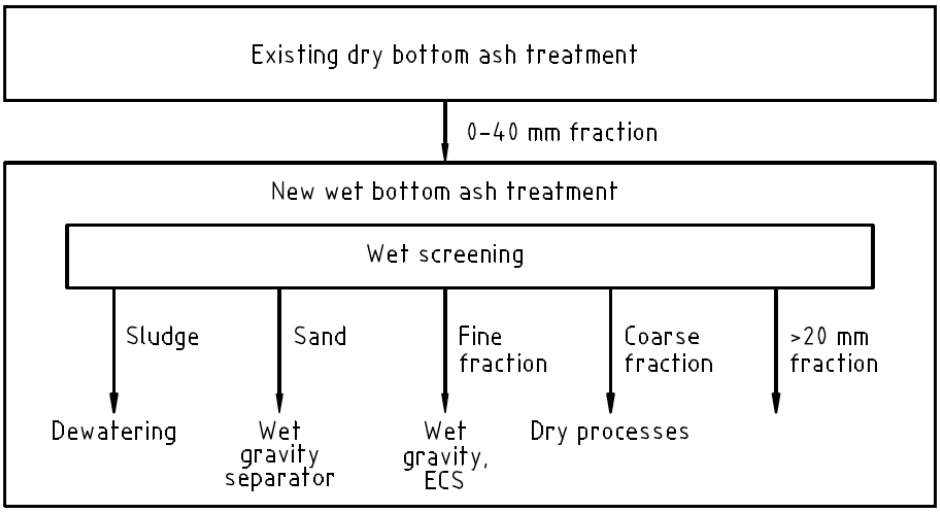

Figure 2.5: AEB IBA treatment [MUCH10]

As it can be seen in the previous figure, IBA at AEB Amsterdam is separated on-site using a conventional IBA treatment prior the wet process. The purpose is to remove the ferrous scrap and reduce the size of the ash to below 40 mm.

3.2.3. INASHCO dry separation

In collaboration with Deflt University of Technology in 2008, INASHCO developed an IBA dry treatment process able to recover metal particles down to 1 mm. The plant can be operated as a stand alone unit or it can serve as an extension to existing installations and can treat IBA with moisture content up to 20% [DEVR09].

IBA is first screened at 12-20 mm and ferrous and non-ferrous metals are removed using conventional systems. The remaining fraction is brought into contact with the INASHCO ADR[13] concentrator where mineral particles under 2 mm are separated by physical classification.

An advantage of this technology is that it can be used as an extension to existing installation as a complement for conventional systems.

3.3. IBAA treatment

The largest fraction of the IBA produced is aggregate (IBAA) and it can be used for several building applications such as foundations, road construction, concrete, bituminous concrete aggregates and others as it has similar composition to raw materials for cement construction as it contains CaO, SiO_2, Fe_2O_3 and Al_2O_3 [REBE95] as it is shown in Table 2.3.

***Table 2.2**: Principal compounds in IBA as a % of the IBA mass [ADEM08]*

Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	N_2O	P_2O_5	SiO_2
8.66 ±6.25	17.68 ±15.37	8.68 ±2.84	1.08 ±0.78	2.52 ±2.10	0.12 ±0.08	4.73 ±2.84	1.26 ±0.88	48.40 ±41.13

Nevertheless, unlike natural construction materials IBAA has a higher concentration of metals. The extraction of this metals is important to improve mechanical properties of the aggregate, as even a small amount of metals can have very adverse consequences in the compression resistance of the formed concrete. This requires a further treatment than the physical separation described in the previous section. Not only to increase its mechanical properties but also to improve its environmental properties, preventing the negative environmental effects due to IBA's high content of heavy metals and polluting content. This concentration is shown in Table 2.3.

***Table 2.3**: Concentration of heavy metals in IBA [μg g-1] [BIGA08]*

As	Cd	Cr	Hg	Ni	Pb	Sb	Zn
1.4–114	0.25–11	0.5–1800	0.06–0.9	28–800	194–5000	10–147.5	300–8890

The mentioned treatments to be described in the following sections are chemical separation, chemical stabilization and thermal treatments. Strategies may vary depending on the objectives.

3.3.1. Chemical separation

The objective is to improve the quality of IBAA and enhance its utilization by treating it to remove salts and heavy metals. Techniques include washing and leaching processes.

- Washing process: aimed at reducing chloride, sodium, sulphate, alkali and heavy metals contents mainly. For this purpose, a leachant liquid like water or some kind of acid is used. However, its efficiency is normally not nigh enough to reach leaching levels

[13] Advanced Dry Recovery

required by the regulation. To improve its efficiency, $NaHCO_3$ or CO_2 can be used for improving the precipitation of Ca as carbonate instead of sulphate forms. For heavy metals the efficiency is also low as the pH of the IBAA is normally between 9.5 and 12, corresponding to the range of low solubility of metals. Controlling of the pH may help to overcome this problem [POLE07].

- Leaching process: aimed to extract heavy metals from IBAA and recover them from the leachant solution. The main problem for heavy metals extraction using this method is the pH. An increasing pH in the leaching solution will lower leachability of heavy metals. To improve metal leaching, CO_2 can be added during water washing. Also using inorganic acids (like hydrochloric, nitric or sulphuric acid), chelating agents (like NTA[14], EDTA[15] or DTPA[16]) and saponins instead of water will make the process to reach a better performance [RAGA04].

The extraction usually involves one to three steps, followed by one to three distilled water washing steps to remove excess of chemical agents.

3.3.2. Chemical stabilization

This process is aimed at minimizing the solubility and toxicity of contaminates by forming low-solubility, thermodynamically and geochemically stable minerals. Natural weathering is commonly used with the addition of chemical species to accelerate the process and improve efficiency.

Natural weathering consists in stockpile IBAA under atmospheric conditions, eventually exposing it to rain and humid environments. Being in contact with water, oxygen and CO_2 results in a series of chemical reactions[17] and promotes the intended transformations of the ash and the decrease of pH from 11-12 to 8-10, which decreases the leaching phenomena [BIGA12].

Weathering can be accelerated by a process named accelerated carbonation [REND05], consisting of adding a gas stream enriched with CO_2. This process has the effect of shorten the weathering time, but when it is carried out under wet conditions the effect is closer to a washing process than to chemical stabilization due to the release of metals [COST07].

Finally, solidification is applied by adding binders like cement to encapsulate the IBAA to immobilize contaminates and reduce the leaching of heavy metals.

3.3.3. Thermal treatments

The aim is to reduce the volume of the residues (up to 60% or more) and to improve their characteristics in terms of mechanical strength, porosity, water adsorption, chemical stability and leaching. The product is more environmentally stable for which applications may be easier [POLE07]. Temperatures up to 1400ºC destroy dioxins, furans and other organic compounds.

[14] Nitrilotriacetate
[15] Ethylendiaminetetraacetate
[16] Diethylentriaminepentaacetate
[17] Hydrolisis, dissolution/precipitation, neutralisation, redox, carbonation, surface complexation, surface precipitation, adsorption, etc.

This process will also allow to reuse of melted slag as a resource [SAKA00]. Two processes commonly used are vitrification and sintering.

- Vitrification transforms IBAA into a homogeneous glassy slag, performed at a temperature between 1000 and 1500ªC. The recovery of heavy metals after this process has been proven in Japan [IZUM96].
- Sintering is performed just below the melting point of the main IBAA constituents, about 900ºC, so the contaminants are bounded into a low porosity and high resistance solid.

Both treatments are high energy consuming and require gas treatment, so related high costs have limited their application.

3.4. IBAA applications

After the recovery of the metals contained in the IBA, ferrous, non-ferrous and precious metals are sold to steel scrap, copper/brass and precious metals smelters and sink-floaters. On the other hand, IBAA is more usable after the treatments commented in the previous section.

A series of studies have been done on IBAA applications in concrete: [CIOF11], [LI12], [MÜLL06], [QUEN00] and [SIDD10]; and there is a history of examples of applications for the IBAA after treatment which is expanding as environmental legislations are hardening and the need of reusable material is increasing. IBAA applicability has been proven as aggregate in concrete in France (up to 50% in composition) and Slovenia (15%), for road base in Spain, as an adsorbent for dyes in India and for concrete in Italy. It has also been used mixed with fly ash for cement clinker in Portugal, Japan and Taiwan and as an aggregate in concrete in Spain [LAM10]. Main applications for IBAA are introduced in the sections below.

- Cement and concrete production. As discussed previously and shown in Table 2.3, IBAA contains CaO, SiO_2, Fe_2O_3 and Al_2O_3 which makes it suitable to be used as a raw material in Portland cement production. Several studies have proven its application and has benefits over conventional concrete processing methods like the reduction of carbon dioxide emissions, but also some problems likely to occur if the remaining metal content in the IBAA is not appropriate [LAM10].
- Road pavement. A possible way to reuse IBAA is to use it in the base course and sub-base in road pavements, the third and second labels in order of construction, where mainly gravel and cement concrete are commonly used. A test road was built in Sweden and it was found that not only the IBAA was able to replace current materials in terms of mechanical capabilities, but also releases of toxins to the environment were not affected and were still below limits [ORE07].
- Glasses and ceramics. As IBAA has a high concentration of SiO_2, Al_2O_3 and CaO, it is possible to use it for replacing part of the clay in the production of ceramics without changes in the behavior of the ceramic body [ANDR01]. Also some studies have proven than glasses obtained from the vitrification of IBAA have leaching and corrosion behavior under exposure to water are below environmental regulations so they are suitable for being use as road base material, construction and decoration materials [PARK04].

4. Characterization of IBA

The IBA composition resulting from the combustion of MSW varies depending on the origin and nature of the waste, combustion technologies and extraction methods. Depending on its composition, options for further utilization also vary. Therefore, IBA characterization prior deciding the utilization strategy is important also with an analysis of the metal market for getting the maximum benefit possible from the materials recovered.

The characterization process includes sampling and analysis. During the sampling process it must be ensured that the results of the analysis are representative of all the IBA produced in Greatmoor EfW for which the appropriate protocol is followed.

The IBA analysis can be carried out in various ways. From the environmental point of view, it is useful to analyze and measure its elemental composition (leaching of harmful elements, heavy metals, etc.) [CHUN07] but it does not provide information of potentially recoverable products contained in the IBA. For this purpose, it is essential to know the size particle distribution in order to have an idea of the recyclability of IBA, that would depend on the capacity of the process, and thus its economic value, that also would be influenced by the situation of the market.

In the following sections, sampling and analysis processes and the characterization of the IBA produced in Greatmoor EfW is explained. This sampling and testing process is aimed at proving that the IBA is non-hazardous. Nevertheless, the elemental composition analysis included in the procedure will be used in this thesis as the composition of the IBA produced as it is discussed in section 4.3 of this chapter.

4.1. Sampling

Generally, there are two points where to collect the samples to be analyzed: after the combustion and before the separation process or after the separation process. In the case of Greatmoor EfW, samples have been taken after the first step of the separation process, where the oversized material (> 300 mm) has already been extracted. This oversized material is constituted almost entirely by metals and for now on in this thesis it will be considered as fully metallic material composed by 90% of ferrous and 10% of non-ferrous metals and taken into account in the final composition of the IBA. Samples are taken accordingly to the ESA Sampling and testing protocol to assess the status of Incinerator IBA of 2014 [ESA14] as explained below.

4.1.1. Purpose

The objective is to take representative samples of IBA. In the particular case of Greatmoot EfW, as it is a new site that does not have historical data, samples are being taken twice a week until 24 samples are taken. If these samples are considered non-hazardous as explained in section 2.1 of this chapter, the number of samples would be reduced to twice a month to keeping track of the status of the IBA produced.

An analysis of any particular portion of sample introduces a statistical error that result from collection of small volumes of material meant to represent a much larger volume [GY99]. Since the sampling methodology is set by the ESA before this thesis began, it will be assumed that this statistical error is controlled and below acceptable levels.

4.1.2. Scale

The aim is to produce a 40 – 50 kg sample that is representative of the IBA as it would be transported from site. This sample is produced in 2 stages: generate a composite sample of approx. 200 kg, cone and quartering down to 40 – 50 kg for laboratory analysis.

4.1.3. Sampling frequency

Samples are taken in different time periods, more concretely twice a month once the first lot is proven non-hazardous, to make sure samples cover all different seasons and periods of activity during the year and avoid inducing bias.

4.1.4. Sample collection

Each 200 kg sample is taken by 20 incremental samples of 10 kg each. This is to make sure that the sample is representative of the total production of ash within the stockpile. The incremental samples are mixed and methodically reduced to avoid analyzing unrepresentative samples. To maintain the the integrity of the sample, samples should be sent to the designated testing house within 48 hours. Figures 2.6 to 2.9 show the sampling procedure and Figure 2.10 shows the sampling process.

***Figure 2.6**: IBA sampling I*

***Figure 2.7**: IBA sampling II*

***Figure 2.8**: IBA sampling III*

***Figure 2.9**: IBA sampling IV*

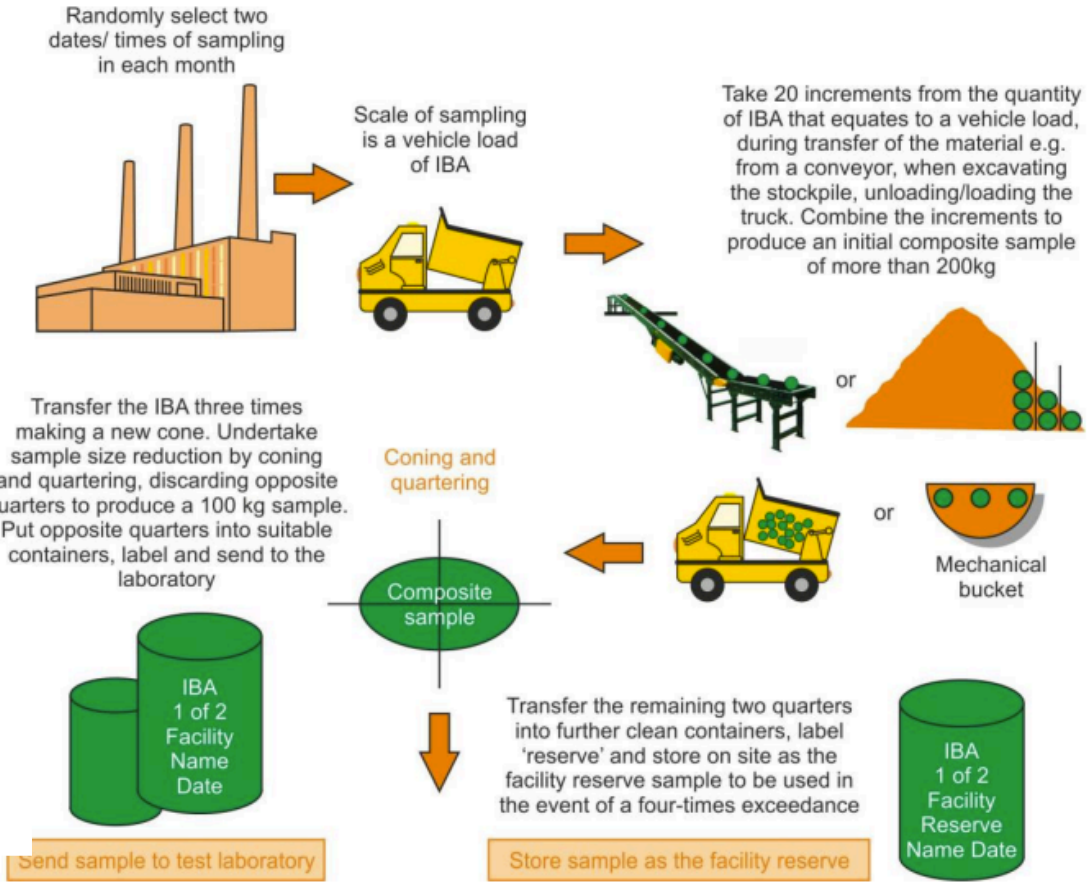

***Figure 2.10**: Summary of sampling steps [ENVI14]*

4.2. Analysis

The objective of the analysis carried out with the IBA produced in Greatmoor EfW is to assess its quality against the 15 hazard properties described in Appendix A. As it includes a complete elemental composition analysis, it will be used to set the composition of the IBA and the amount of material recoverable.

As discussed previously, to get full information of the potentially recoverable products contained in the IBA, a particle size distribution is needed. Since this kind of analysis is not included in the current process, a particle size distribution of the IBA produced in another plant with similar characteristics (combustion technology and MSW origin) will be used as discussed in section 4.2.2 of this chapter.

4.2.1. Greatmoor EfW IBA analysis

Sample preparation

Samples as they arrive at the sampling facility are initially dried at 105ºC[18] until no further weight loss is recorded to facilitate subsequent crushing and/or grinding to an appropriate size. According

[18] Drying at 105ºC will not cause further changed to the sample but it will allow acceleration of sample preparation and data reporting [ESA14]

BS EN 12457 provided by the EA, leaching tests require a particle size of < 4 mm. Meanwhile, for compositional testing a maximum particle size of 0.31 mm is required. It may be necessary to remove non-grindable fractions such as stones, porcelain, ceramics, brick and glass from the sample during crushing. All standard sample preparation techniques require also the removal of cast metal objects, batteries and stones. The percentage of weight should be recorded and taken into account. A summary of the sample preparation and testing programme for IBA is shown in Figure 2.11.

Hazard properties

As Greatmoor EfW is a new facility, assessment for all 15 hazard properties is required. For those facilities that have been part in the on-going monthly assessments between 2011 and 2013 only H4/H8, H7 and H14 assessments are required [ESA14].

Constituents and analysis

Tests include all relevant parameters to allow assessment of all 15 hazard properties [ENVI15]. A full hazard assessment requires determination and assessment of the following:

- pH, alkali reserve.
- Elemental composition: As, Al, Ba, Cd, Co, Cr, Cr(VI), Cu, Fe, Hg, Mn, Mo, Ni, Pb, V, Zn, Mg, Na, K, Li, total CN[19], TPH, dioxins and furans.
- Leachable metals and ions: alkalinity, Cl, Br, F, SO_4, NO_3 and free CN.

IBA control arrangements

IBA produced is separately stored under suitable control until the authorized facility confirms the classification of the ash. This is designed to avoid the reprocessing of IBA that is classified as hazardous.

Data interpretation and reporting

For compositional analysis, analytical data is reported by the analytical laboratory on a dry weight basis but should be assessed on a wet weight ("as received") to represent the ash as it leaves the facility.

[19] Cyadine

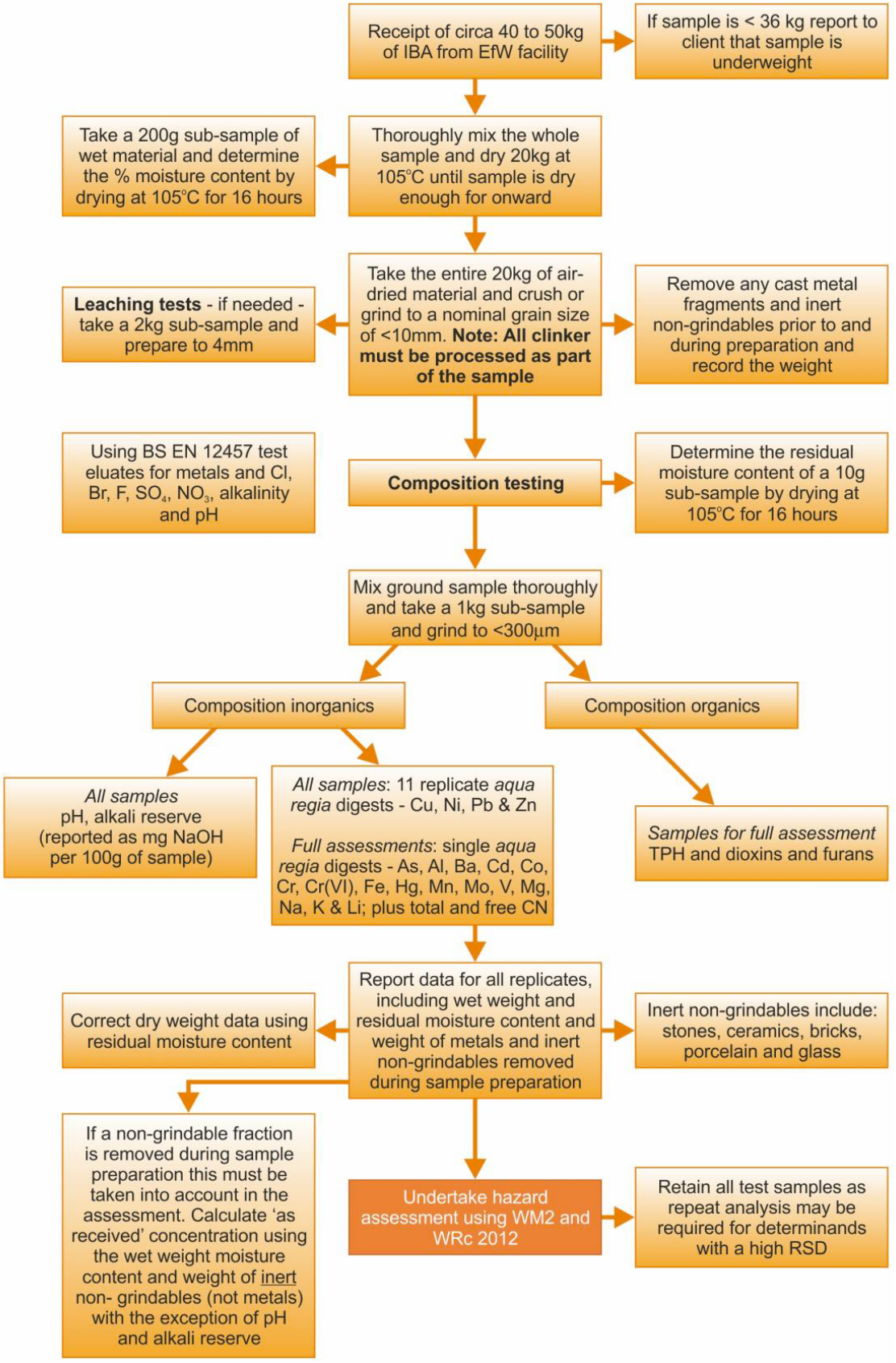

***Figure 2.11**: Laboratory specification for IBA testing [ESA14]*

4.2.2. Particle size distribution

For obtaining a more complete information of the amount of potentially recoverable products contained in the IBA, components should be previously separated in particle size fractions and analyzed separately. Large pieces of materials should be removed before analysis (as it is currently being done on site with the oversized metal > 300 mm). The rest should be screened in size fractions and measured and each fraction should be analyzed separately.

Particle size separation is not being carried out prior analysis of Greatmoor EfW IBA. Considering that MWS of Western Europe has the same composition, a particle size distribution of IBA from another plant is considered in this thesis as similar to Greatmoor EfW IBA particle size distribution and used for further calculations and considerations.

4.3. Characterization of Greatmoor EfW IBA

The average composition of Greatmoor EfW IBA is detailed in Table 2.4. This composition takes into account the amount of oversized metal extracted on site, which percentage has been used for correcting the concentrations provided by the analysis facility. This composition is an average of the 24 samples analyzed for the hazard assessment. The complete IBA characterization tables and calculus can be seen in Appendix A.

***Table 2.4**: Average composition of Greatmoor EfW IBA*

Material	% by mass
Aggregate	82.19
Ferrous Metals	11.53
Non-Ferrous Metals	5.62
Precious Metals	0.001
Organics	0.66

4.3.1. Hazardous assessment

Hazardous assessments are carried out for the 24 samples taken into account in this characterization following the procedure below.

- Samples 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23 are subject to all 15 hazard properties assessments and also TOC, LOI, PAHs, TPH, PCBs, dioxins/furans and leachates are evaluated.
- All 24 samples are subject to assessments H5/H8, H7 and H15[20].

According to what it is specified by the EA of the UK five single exceedances of a relevant hazard threshold are allowed in any 24 samples. It has been proven that Greatmoor EfW IBA is

[20] Appendix A.

non-hazardous as there were no exceedances in any hazard property. The complete list of results can be seen in Appendix A.

4.3.2. Elemental composition

The average elemental composition of the 24 samples taken into account the amount of every component removed prior analysis is specified in Table 2.5. The composition of all the samples and the calculus for corrections can be seen in Appendix A.

From this composition, it can be summarized the amount of non-ferrous and precious metals that may be more interesting to recover, more precisely Aluminum, Copper, Zinc, Lead, Titanium, Tin and Silver. The amount of these materials contained in Greatmoor EfW IBA is summarized in Table 2.6. In addition, it has to be pointed out the high concentration of Calcium contained in the IBA, making approximately 8.12% of mass of IBA, which makes it interesting as a secondary source for building products [MUCH10].

***Table 2.5**: Average elemental composition of Greatmoor EfW IBA*

Element	mg/kg	St. Dev.	Element	mg/kg	St. Dev.
Aluminum	21,613.13	2,267.49	Mercury	0.78	0.11
Antimony	39.35	7.90	Molybdenum	5.85	1.59
Arsenic	4.91	0.80	Nickel	94.22	50.03
Barium	518.07	62.14	Phosphorus	4,292.97	831.29
Beryllium	0.42	0.10	Potassium	2,557.43	296.24
Boron	79.50	23.21	Selenium	0.80	0.17
Cadmium	17.34	42.00	Silver	6.18	5.51
Calcium	82,805.57	11,047.74	Sodium	7,384.19	806.16
Chromium (tot)	78.88	15.96	Strontium	184.06	24.46
Chromium (VI)	0.27	0.25	Thallium	0.77	0.18
Cobalt	34.41	13.56	Tin	125.71	37.41
Copper	2,412.65	646.47	Titanium	1,908.00	169.27
Iron	37,544.25	13,767.27	Vanadium	37.86	4.45
Lead	762.08	192.25	Zinc	2,427.71	479.61
Lithium	17.66	3.88	Metals removed on site	29,351.38	-
Magnesium	6,892.72	745.07	Metals rem. prior anal.	58,100.25	29,119.87
Manganese	1,051.97	764.49			

Table 2.6: Summary of non-ferrous and precious metals

Element	% mass of IBA	kg per hour	ton per year
Aluminum	2.13	185.04	1,620.98
Copper	0.24	20.66	180.95
Zinc	0.24	20.79	182.08
Lead	0.08	6.52	57.16
Titanium	0.19	16.34	143.10
Tin	0.01	1.08	9.43
Silver	0.001	0.05	0.46

4.3.3. Particle size distribution

As discussed previously, a particle size distribution from another plant has been taken and considered similar to Greatmoor EfW IBA particle size distribution. Specifically, Ardley ERF[21] plant has been chosen as it is located in Oxfordshire (UK) which is about 12 miles from Greatmoor EfW so the MSW accepted is similar and the combustion process is also based on a grate furnace[22]. It is taken into account that oversized metals are being removed from Greatmoot EfW IBA on site as part of the IBA extraction process, so the amount of > 300 mm particles is the current value for Greatmoor EfW. Table 2.7[23] shows the amount of material arriving at Calvert Landfill from March 1st to March 24th, which has been used to obtain the percentage of oversized metal removed. The particle size distribution and size fractions used in this thesis are shown in Table 2.8.

Size distribution has a direct influence on value. Larger pieces of material are more valuable than smaller ones and also aggregate for being use as building material has to meet the specific standards for building materials.

Table 2.7: Calvert Landfill income data from March 1st to March 24th period

Oversized metal > 300 mm	146.40 tons
Remaining IBA	4,841.44 tons
Percentage of oversized metal	2.94 %

[21] Energy Recovery Facility
[22] VIRIDOR webpage: https://viridor.co.uk/our-operations/energy/energy-recovery-facilities/ardley-erf
[23] Information obtained from Calvert Landfill records.

Table 2.8: Particle size distribution [RBA15] and size fractions

Size [mm]	% passing	Size [mm]	% passing
300	97.96	4	36
40	95	2.8	32
31.5	91	2	30
20	77	1	23
16	74	0.5	18
14	71	0.25	16
10	60	0.125	9
8	52	0.063	7.1
6.3	46		

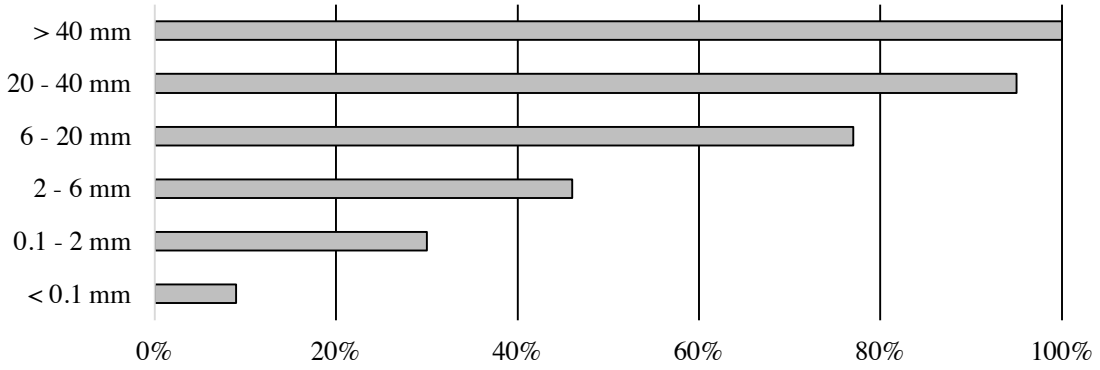

Figure 2.12: Particle size distribution in % of cumulative mass

4.3.4. Material distribution

In addition to the particle size distribution, it is necessary to have an idea of the material distribution of each size fraction before deciding the separation strategy of each section. The amount of each material suitable for recovery contained in each size fraction will justify potential investments in equipment for the specific treatment of each fraction. It has to be taken into account that this amount of material in each fraction is merely indicative as the actual amount of material that can potentially be extracted depends on the equipment and the conditions of the ash. As there is no size distribution analysis being made with Greatmoor EfW IBA, there is also no information about the material distribution in each particle size fraction. For this reason, this information has been taken from an extern study about the IBA of a different plant, assumed similar to Greatmoor

EfW's and adjusted to meet Greatmoor EfW IBA characteristics. This distribution can be seen in Table 2.9 and is calculated as dry material.

Table 2.9: *Material distribution [MUCH10]*

Material [%]	**> 40 mm**	**20 – 40 mm**	**6 – 20 mm**	**2 – 6 mm**	**< 2 mm**	**Total**
Ferrous	4.42	3.53	2.15	0.16	1.23	11.47
Non-Ferrous total	0.58	2.48	1.37	0.62	0.74	5.67
Al		0.99	0.68	0.14	0.34	2.16
Cu		0.11	0.04	0.04	0.10	0.24
Zn		0.15	0.06	0.03	0.01	0.24
Pb		0.04	0.02	0.01	0.01	0.08
Tin		0	0	0.01	0.00	0.01
Ag		0	0.0002	0.0003	0.0001	0.0006
Aggregate	0	11.70	27.35	15.17	27.98	82.20
Organics					0.66	0.66
Total	5	18	31	16	30	100

Size fraction of > 40 mm particles are to be shred and reinserted in the system.

Ferrous metals content

As it can be seen in the previous table, ferrous metals are mainly distributed in > 20 mm size fractions as the melting point of Fe is higher than the combustion temperature applied in the furnace and because the income particle size of ferrous waste items is generally higher. It is also known as magnetic fraction as is the amount of material that is attracted to the magnet separator. The distribution of Fe is shown in Figure 2.12.

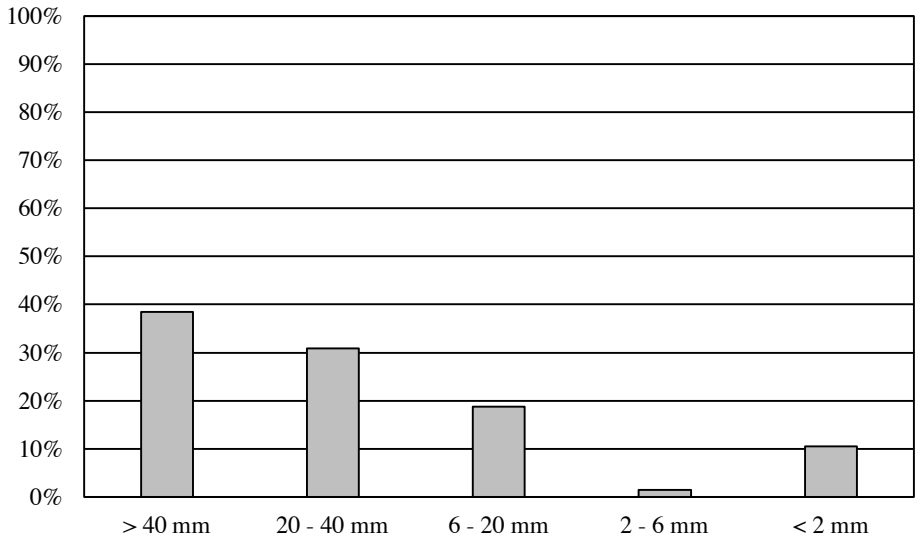

***Figure 2.13**: Ferrous metals distribution [% by mass of Fe]*

Non-ferrous and precious metals content

In Table 2.9 it can be seen that non-ferrous and precious metals are mainly distributed in < 20 mm size fractions as they have a similar melting point to the combustion temperature applied in the furnace and they are used in smaller objects whereas Fe is generally used in larger items. Non-ferrous and precious metals distribution can be seen in Figure 2.13 and 2.14.

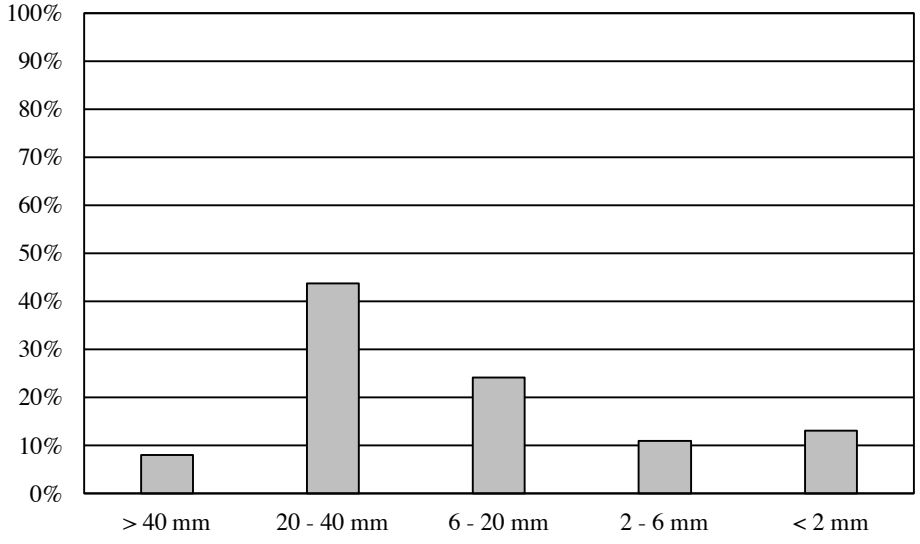

***Figure 2.14**: Non-ferrous metals distribution [% mass of NF]*

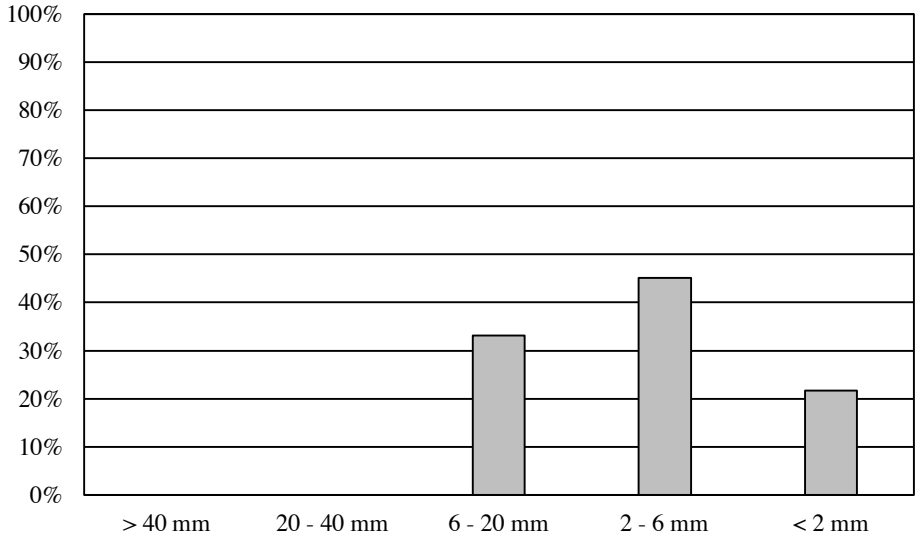

***Figure 2.15**: Precious metals distribution [% mass of precious metals]*

These distributions are used in this thesis for the sizing of the equipment needed for the treatment of each size fraction and also for the justification of the investments this equipment requires.

4.3.5. Organic content

IBA generally contains a portion of unburned organic matter. This content is limited by the EA and directly affects both the engineering and environmental quality (leachates) on the IBAA, so it should be considered and important factor of the quality of the IBAA for further utilization. It is measured by the TOC[24] and LOI[25] contents that can be seen in Table 2.10.

***Table 2.10**: TOC and LOI average measures*

	% of mass	St. Dev	Limit [%]
TOC	0.66	0.18	3
LOI	1.77	1.21	5

4.3.6. Water content

The moisture content directly affects the separation strategy as it sticks to particles of all size and obstructs the size classification and the separation itself. In some cases, it makes impossible to recover valuable material, specially in the fine fraction. It also has influence in the weight of the residue and raises extraction, transport, storage and disposal costs and also the sampling, mass balance and estimated prices. It is a result of the quenching process after burning installed in

[24] Total Organic Carbon: amount of carbon found in the IBA.
[25] Loss On Ignition: test used to determine the amount of volatile substance contained in the IBA.

Greatmoor EfW and also of the temporal storage under atmospheric conditions. IBA is stored under natural open air, so the weather conditions are a significant factor of the IBA water content.

This moisture content is measured by taking a 200 g sub-sample of wet IBA, drying it at 105ºC for 16 hours and measuring its weight before and after drying [ESA14]. The average water content found in Greatmoot EfW IBA is shown in Table 2.11.

***Table 2.11**: Moisture content at 30ºC*

	% of mass	**St. Dev.**
Moisture content at 30ºC	16.28	4.44

Chapter 3

Presentation of the problem

1. Introduction

IBA produced at Greatmoor EfW is a moist material as it contains an average of 16.28% by mass of water. Starting from this point, the objective of this thesis is to work out a treatment process to get the most value from the IBA attending to the materials it contains, possibilities of the market and technologies being developed.

In the previous chapter it is discussed the composition of the IBA that it is intended to be treated. The potential material that can be recovered is significant, which extraction has benefits in two directions:

- Recover high-grade metal fractions. Recycling of ferrous, non-ferrous and precious metals than can be sold to melting industry for further reinsertion in the market, raising the revenues of the plant.
- Improving the quality of the remaining aggregate. For meeting the mechanical and environmental quality required for being used in the building industry, metals have to be removed. Any amount of metal can decrease the compression capacity of building materials like concrete or asphalt and the content of heavy metals increases leaching phenomena which has an impact on the environment.

1.1. High-grade metal recovery

The main purpose is to get a high-grade metal recovery. In the previous chapter it has been discussed the characterization of IBA produced in Greatmoor EfW and the amount of metals potentially recoverable include an amount of 8,648.91 tons of ferrous metals; 4,217.85 tons of non-ferrous metals and 456 kg of precious metals per year. This amounts can barely be recovered applying conventional separation methods and can be improved in several ways that are to be technically and economically analyzed in the following chapters of this thesis.

Financial value of IBA can be improved by selling recovered metal to melting companies for further use, in addition to saving costs from landfill storage and/or disposals. This activity has the potential of raising the revenues of the plant and make it more profitable. This purpose would require investments in equipment and other operational costs that are economically analyzed in Chapter 8 but it makes unnecessary subcontractors for extra treatments and other intermediaries.

In most cases it might result convenient to buy extra machinery and equipment for further IBA treatments others than the conventional ones in order to increase its financial value by improving the amount of recovered material that could be sold.

1.2. Improve IBAA quality

The high content of minerals such as glassy and crystalline silicates, aluminates and oxides makes IBAA an alternative to naturally obtained sands and gravel for use as concrete and road base aggregate. Nevertheless, metals have to be removed to meet required conditions for this use. Raw IBA contains damaging components such as chloride, sulphates and others specified in Chapter 2 that cause leaching problems that can be avoided by treatments also explained in the previous chapter.

This thesis focuses on the metal removal, which content in the IBAA has the potential to cause cracks and spalling in concrete specimens. It may also cause corrosion and the formation of other voluminous products by chemical reaction that lead to concrete damages [KUBN07].

The better quality of the IBAA produced makes it more suitable for being use in the building industry which would generate extra revenue.

2. Approach and basic data

The objective of this thesis is to get the maximum benefit from the IBA production in Greatmoot EfW. For this purpose, a technical and economic study is made in several scenarios, which are explained in next section, to prove if the revenues resulting for better IBA quality related to new technologies and equipment justify related investments to those technologies. Assumptions made in this direction and basis data used are explained below.

2.1. Assumptions

As a consequence of non-accessible information for being of commercial value or non-existing, several assumptions have been made in order to carry out the activities of this thesis:

- As the operating activities of the plant is not a part of this thesis, it will be assumed that the amount IBA produced is constant and which value is shown in Table 3.1.
- The processes designed and equipment selected is to be installed in any energy from waste plant. Data from Greatmoor EfW is used for sizing machinery and obtaining concrete results, but those are likely to be adapted to other plants.
- The proposed plant would only be operating in working hours. No overnight or weekend work required, so mass flows will be calculated according to those hours with an assumed availability of 81% (90% in equipment and 90% in operations). This data is summarized in Table 3.1.
- As a result of non-existing data of IBA size and material distribution, information from other plants has been considered similar to Greatmoor EfW's and adjusted to the characteristics of this facility. This information has been taken from Ardley ERF (Oxfordshire, UK) and the EfW facility AEB Amsterdam (the Netherlands).

2.2. Basic data

The basis data that sets the starting point of the thesis is constituted by the IBA mass flow and summarized in the following Tables 3.1, 3.2 and 3.3.

***Table 3.1**: IBA mass flow and time data*

IBA mass flow		**Time data**	
MSW income	300,000 ton/year	Working days[1]	253 days/year
IBA production (dry[2])	25 % mass of MSW	Working hour	8 h/day
	75,000 ton/year	Availability	90% equipment
	45.75 ton/hour		90% operations
Oversized material removed on site	2.94 % mass of IBA		81% total
	1.34 ton/hour		
Remaining IBA	44.40 ton/hour		

***Table 3.2**: Material content in IBA*

Material	**% by mass of IBA**	**kg/hour**	**ton/year**
Ferrous	11.53	5,274.31	8,646.91
Aluminum	2.13	974.37	1,597.42
Zinc	0.24	110.68	181.45
Copper	0.24	107.98	177.03
Titanium	0.19	87.90	144.10
Lead	0.08	37.00	60.66
Tin	0.01	5.89	9.66
Silver	0.0001	0.28	0.46

[1] Data of the UK, 2016
[2] Gained weight due to moisture content not included

***Table 3.3**: Particle size distribution*

Material	> 40 mm			20 – 40 mm			6 – 20 mm			2 – 6 mm			< 2 mm		
	%	kg/h	ton/y	%	kg/h	ton/y	%	kg/h	ton/y	%	kg/h	ton/y	%	kg/h	ton/y
Ferrous	4.42	2,021	3,313	3.53	1,617	2,651	2.15	984	1,613	0.16	74	121	1.23	563	923
Non-Fe	0.46	209	342	2.48	1,133	1,857	1.37	628	1.029	0.62	285	467	0.74	340	558
IBAA	-	-	-	11.70	5,352	8,774	27.35	12,512	20,513	15.17	6941	11,379	27.98	12,800	20,985
Total	4.87	2,230	3,656	17.71	8,101	13,281	30.87	14,124	23,155	15.96	7,299	11,967	29.95	13,703	22,465

3. Scenarios

The objectives of this thesis are to be met by extent analysis of the technologies proposed. These processes result from state-of-art and market study with further technical and economic analysis and comparison between proposals.

Analysis and comparison are made in three directions or scenarios differentiated between each other in terms of IBA extraction system, treatment process, separation technology and material recovered. These scenarios are explained below and in each case technical analysis will be supported with an economic analysis to compare revenues against expenses.

As it has been explained in previous sections, to enable such a high-grade metal recovery a strict classification according to particle size is necessary prior metal removal. Metal particles > 12 mm (approx.) can be recovered using conventional methods. Problems arises when treating the < 12 mm fraction because of the moisture content in IBA. These problems are caused by the 0 – 2 mm grains that contain the most moisture and makes the entire < 12 mm fraction sticky. In the three scenarios to be analyzed in this thesis, it will be considered several ways to deal with these problems and to raise the metal recovery rate in the IBA produced in Greatmoor EfW.

3.1. Scenario I – Wet discharge and conventional separation

The first scenario for analysis is the current installation and status of the extracted IBA. As discussed previously, it is based on a wet extraction process which includes a quenching tank and conveying system for temporal storage at a concrete pad and further transport to landfill.

No treatment is currently applied to IBA extracted apart from the > 300 mm oversized material that is removed on site. The remaining IBA is conveyed by a redundant conveyors system to a concrete pad where is stockpiled and transported to the Calvert Landfill. At the landfill, raw IBA is stored as it is still being tested for hazardous assessments and no further activities can be carried out until proven non-hazardous.

An IBA separation process will be analyzed based on magnetic and eddy current separation, with no special treatment for the fine fraction.

3.2. Scenario II – Wet discharge, conventional and fine fraction separation

The second scenario for analysis is set by the current installation and status of the extracted IBA which is treated on site by one of the proposed systems to be analyzed. IBA is extracted wet and with the actual equipment, required processes and related equipment for high-grade recovery are to be analyzed. For the > 12 mm (approx.) fraction, conventional methods are to be used as they show good recovery grades. For the fine particle fraction, two alternatives are analyzed in this thesis:

- ADR technology developed by INASHCO in collaboration with TU Delft, that removes the < 2 mm moist particles of the 0 – 12 mm fraction. This will raise the rate of metal recovery that can be performed by conventional methods.
- Wet separation process developed by P. Rem (TU Delft) and performed in AEB Amsterdam. Full wet separation process able to recover particles down to 0.1 mm.

3.3. Scenario 3 – Dry discharge and conventional separation

The third scenario to be analyzed consists on the installation of a new dry discharge system and conventional separation methods. A dry extraction process has the potential to improve quality of the IBA produced and facilitate the material recovery process. It is expected to obtain a higher material recovery rate and the advantage of avoiding complex fine particle treatments. A study of the available technologies will be made and the best alternative chosen for the characteristics of the plant and IBA. Using a dry extraction process, material can be recovered using conventional methods.

Chapter 4

Separation equipment

1. Introduction

The separation techniques to be considered in this thesis can be classified into magnetic separation, eddy current separation and density separation, in addition to general process equipment needed in the value chain. Each technique has its specific field of application depending on the characteristics of the income material and will be combined in order to get the maximum material recovery efficiency.

In the three scenarios to be analyzed, the bulk material would be separated into size fraction to increase recovery efficiency. Those size fractions would be the same as in the size distribution in Chapter 2 since the metal concentrations are know for those fractions.

In the following sections, all three techniques will be defined and the selection criteria will be explained. This chapter has the intention of serving as a reference for further chapters where technical explanations will be avoided.

2. Magnetic separation

2.1. Magnetic separation principle

Magnetic separation is used for the removal of magnetizable particles from fluid streams and it is achieved by passing the mixture of particles through a non-homogeneous magnetic field.

Separation is driven by the magnetic force and the removal depends upon the magnetizable particles motion in response to the magnetic force and to other competing forces, being gravity, inertia, hydrodynamic and centrifugal forces in addition to particle/fluid and particle/particle interactions. A schematic of this phenomena is shown in Figure 4.1.

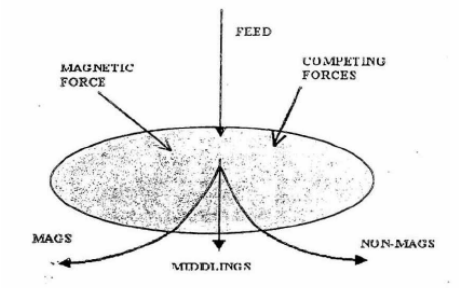

***Figure 4.1**: Schematic of magnetic separation [DAS07]*

For a successful separation of strongly magnetic particles from the rest of the stream that the magnetic force acting on them must be greater than the sum of all the competing forces. In addition, magnetic force acting on less strongly magnetic particles must be smaller than the sum of the corresponding competing forces:

$$F_{mag}^{m} \geq F_{comp}^{im} \text{ and } F_{mag}^{n} \geq F_{comp}^{in};$$

Equation 4.1

but, if this magnetic force is much greater than the sum of the competing forces, selectivity of separation will be poor, making no distinction between strongly and less strongly magnetic particles and thus must be controlled.

All materials are magnetic in some extent. An advantage of material treatment in a magnetic field is that the magnetic force can be controlled effectively in a wide range of values. Magnetic separation is environmentally friendly and can operate in wet and dry modes.

It is possible to determine the force acting on a particle on the basis of potential energy

$$U = \frac{1}{2}(\mu_f - \mu_p)V_p H^2$$

Equation 4.2

where μ_p and μ_f are magnetic permeabilities of the particle and the fluid respectively, V_p is the volume of the particle and H is the value of the magnetic field intensity. Thus, the force acting on the particle can be determined using the principles of the mechanics as

$$\vec{F}_m = -\nabla U = \frac{1}{2}(\mu_p - \mu_f)V_p \nabla H^2$$

Equation 4.3

taking into account that $\mu_j = \mu_0(1 + \kappa_j)$, being κ_j the volume magnetic susceptibility of material j and μ_0 the magnetic permeability of vacuum, and considering that for sufficiently strongly magnetic particles $\kappa_p \gg \kappa_f$, the magnetic force acting on a particle is expressed as

$$\vec{F}_m = \mu_0 V_p M \nabla H$$

Equation 4.4

where ∇ is the operator of the gradient and M is the magnetization of the particle. From this expression it can be inferred that in homogeneous magnetic fields the gradient is zero. In which case there is a just rotating torque affecting the particle.

In non-homogeneous magnetic field values, the gradient is not zero and, in addition to the rotating torque, the magnetic force also affects the particle. According to this the design of magnetic separators has to ensure non-homogeneous magnetic field.

As mentioned before, magnetic force in a magnetic separator competes with external forces such as gravity, inertia, centrifugal and hydrodynamic forces:

$$\vec{F}_g = (\rho_p - \rho_f)V_p\vec{g}$$

Equation 4.5

$$\vec{F}_c = (\rho_p - \rho_f)wV_p\vec{r}$$

Equation 4.6

$$\vec{F}_d = 6\pi\eta b(\vec{v}_f - \vec{v}_p);$$

Equation 4.7

where $\vec{F}_g$, $\vec{F}_c$ and $\vec{F}_d$ are the gravitational, centrifugal and hydrodynamic forces, ρ_p and ρ_f are the densities of the particle and the fluid, $\vec{g}$ is the gravity acceleration, $\vec{r}$ is the radial position of the particle, w is its angular velocity, η is the dynamic viscosity of the fluid, b is the particle radius and $\vec{v}_f$ and $\vec{v}_p$ are the velocities of the fluid and the particle respectively. In this thesis, particle/fluid interactions and interparticle effects will be neglected also with inertia forces as particles velocity will be considered constant.

The working zone of the separator is defined as a region of attraction and holding of the magnetic field. Efficiency of the separator work or separation process is determined on the basis of the speed v which the separated material passes through the separator.

$$v = L\sqrt{\frac{\eta_0 \chi H \nabla H - g}{2h}}$$

Equation 4.8

where L is determined as the distance between the beginning of magnetic attraction and position of discharge of the separated material, χ is the magnetic susceptibility and h is the high of the zone, the distance from the magnet to the place where the magnetic force does not ensure magnetic particles attraction. Then, it is obvious than increasing L increases the efficiency of the separation process.

2.2. Magnetic separation equipment

No single technique is universally applicable to all types of magnetic separation. Accordingly, various classifications schemes exist in which magnetic separators can be divided into categories [SVOB04]. For the purpose and characteristic of this thesis, magnetic separators will be grouped as follows:

- Based on the medium:
  - Dry
  - Wet
- Based on the requirement of the system:

  - Removal of iron for the protection of the machinery
  - Extraction of valuable magnetic constituents
  - Removal of deleterious magnetic impurities
  - Separation of materials based on properties other than magnetics
  - Material handling
- Based on how the magnetic field is generated:
  - Permanent magnets
  - Electromagnets with iron yoke
  - Resistive solenoids
  - Superconducting magnets
- Based on the magnitude of the magnetic field and its gradient:
  - Low-intensity magnetic separators
  - High-intensity magnetic separators
  - High-gradient magnetic separators

The purpose of using magnetic separation in this thesis is the recovery of iron scrap and thus, the magnetic separators explained in the following sections are defined as equipment for the extraction of valuable magnetic constituents, using permanent magnets and classified as low-intensity magnetic separators as iron is a strongly magnetic material. Dry or wet mediums will depend on the characteristics of the process and set in the corresponding chapters.

2.2.1. Suspended magnets

Normally used when the speed of the belt is high and/or if large iron objects are to be removed. They can be found in circular or rectangular configuration, being rectangular the most commonly used as it permits installation of self-cleaning construction. When large amounts of removed material are expected, self-cleaning systems are required. A belt driven across the magnet face allows continuous automatic removal of iron scrap. A schematic of the principle of operation can be seen in Figure 4.2 and a cross-belt suspended magnet is shown in Figure 4.3.

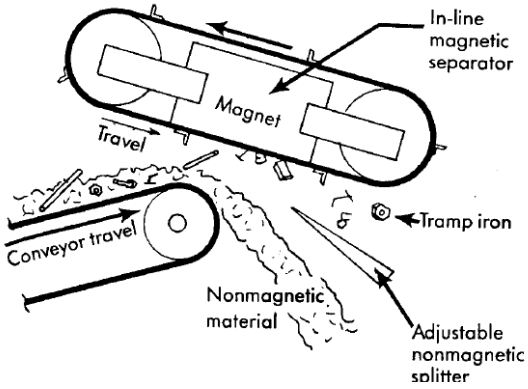

***Figure 4.2**: Suspended magnet principle of operation [MORG88]*

***Figure 4.3**: Cross-belt suspended magnet*

Suspended magnets can be installed at many point in a material handling system: any point of the conveyor belt, at the discharge end of feeders or screens and above chutes or launders.

In the case of self-cleaning cross-belt magnets, the magnet belt moves perpendicular to the conveyor belt. They are usually stronger and larger as particles have to be attracted and turned by 90º. Figure 4.4 show typical values of the magnetic field as function of the suspension distance.

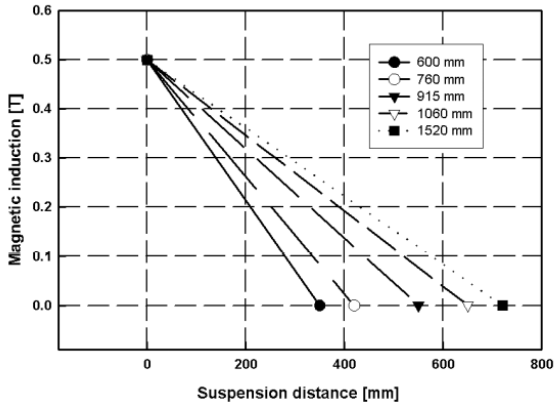

***Figure 4.4**: Magnetic field as function of the suspension distance [SVOB04]*

The main parameters affecting this process, apart from the moisture content, would be the force of the magnetic field, the working zone, the burden depth, the conveyor belt and magnet belt speeds. Speeds are normally easy to adjust while operating and not considered in the feasibility stage.

The equipment selected would be a suspended magnet model OIP 3380 E supplied by Magnapower Equipment Ltd, which is ensured to meet the requirements of all processes by the supplier. This supplier has been selected since it is based in the UK and assuming that the competition would have similar prices. More information can be found in Appendix B.

2.2.2. Drum magnetic separators

Drum magnetic separators are widely used and can be applied to the treatment of particles from several centimeters down to micrometers. Conventional ferrite magnets are used in low-intensity magnetic separation generating up to 0.22 T on the drum and 0.1 T at 50 mm, while rare-earth magnets can perform powerful high-intensity magnetic separation generating up to 1 T on the drum in the case of NdFeB-based drums [SVOB04].

They are normally constituted by three to nine magnetic blocks covering an angle from 90º to 120º of the drum. Ferrite drums are manufactured from 600 mm to 1500 mm diameter and rare-earth drums from 380 mm to 1000 mm diameter, most commonly used are 1500 mm drums.

Ferrite drum separators are used for recovering strongly magnetic materials, like iron scrap. They can operate with top feed or bottom feed configurations as shown in Figure 4.5 and 4.6. Drums with top feed produce highest recovery and are suitable for mixtures with small amounts of magnetic particles. Drums with bottom feed produce a cleaner magnetic concentrate and is used to treat mixtures with a high grade of magnetic particles.

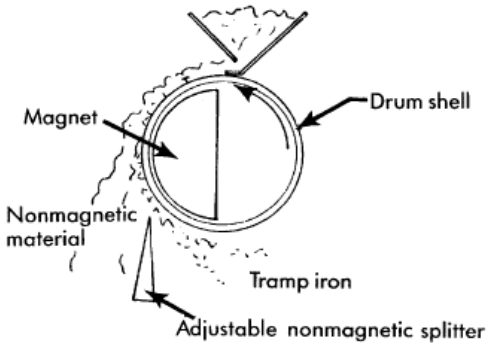

Figure 4.5: Dry drum magnetic separator with top feed [MORG88]

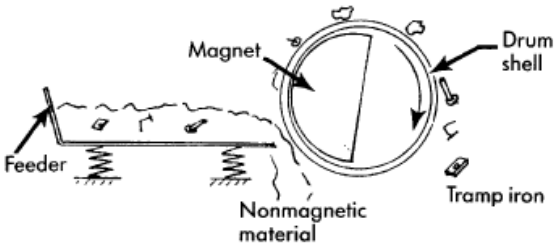

Figure 4.6: Dry drum magnetic separator with bottom feed [MORG88]

The main parameters affecting this process, apart from the moisture content, would be the force of the magnetic field in the drum, the drum radius and length, number of poles, angle covered by the permanent magnet, speed of rotation of the drum and size and shape of the particles. The speed of rotation can be easily adjusted when operating and is not normally included in the feasibility stage.

Generic state-of-art equipment would be used, which assumed fixed and operation costs are specified in Chapter 8.

2.2.3. Wet low-intensity drum magnetic separators

In this case the drum is partially submersed in a tank of water and carries the material to be treated across the face of the magnetic system and the magnetic concentrate out of the tank. The design of the tanks is very important and determined by the objectives of the separation process. There are three basic designs: concurrent tank, used for particles < 5 mm; counter-rotation tanks, for particles < 0.5 mm; and counter-concurrent tanks, for particles < 0.1 mm. For the characteristics of the IBA in Greatmoor EfW and the purpose of the material recovery processes to be proposed, the most suitable configuration is the concurrent tank type, shown in Figure 4.7. Figure 4.8 shows the throughput of drum magnetic separators as function of the drum diameter.

In concurrent tank design, the feed is introduced in the tank and flows in the direction of drum rotation. Strongly magnetic particles are picked up by the magnet and the non-magnetic material is discharged at the bottom through the discharge opening. They can perform high throughput with high quality of the magnetic concentrate.

As in the dry drum magnetic separators, the parameters affecting this process would be the force of the magnetic field in the drum, the drum radius and length, number of poles, angle covered by the permanent magnet, speed of rotation of the drum and size and shape of the particles also adding the water flow in this case.

Generic state-of-art equipment would be used, which assumed fixed and operation costs are specified in Chapter 8.

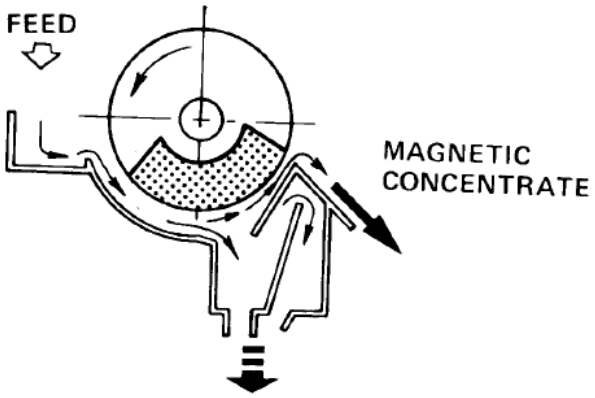

Figure 4.7: Concurrent tank design [MORG88]

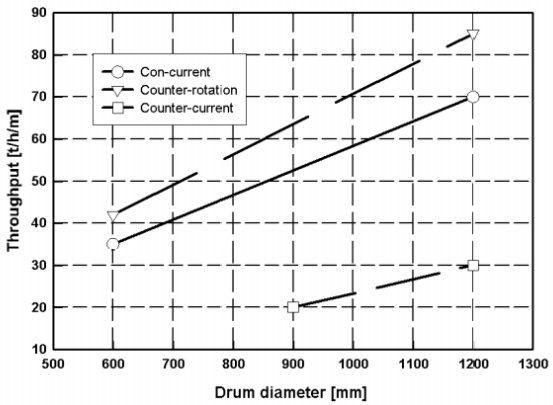

Figure 4.8: Throughput of drum magnetic separators as function of the drum diameter [SVOB04]

3. Eddy current separation

3.1. Eddy current separation principle

Eddy current separation is used to separate non-ferrous metals from streams of mixed materials. The separation is brought about by inducing eddy currents inside the conductive particles of the stream by placing the conductor in a changing magnetic field [REM98]. The rate of change of magnetic flux B affects to the amount of induced voltage, being numerically equal and opposite to the rate of change of magnetic flux according to Faraday's Law:

$$V_L = -N\frac{dB}{dt}$$

Equation 4.9

being V_L the induced voltage in volts and N the number of turns in the coil of the inducer. In addition, Lenz's Law states that the magnetic field of induced current is oppose to the change in magnetic flux that caused this current.

Permanent magnets generate a primary magnetic field. Induced eddy currents generated in the conductive particles generate thus a secondary magnetic field opposite to the primary magnetic

field. Then, these conductive particles are propelled by the gradient field of the magnets [EDIS89]. The magnitude of the eddy current is determined by

$$\vec{\nabla}\times\vec{J} = -\rho\frac{\partial\vec{B}}{\partial t}$$

Equation 4.10

where J is the current density and ρ is the specific conductivity of the particle. The opposite magnetic fields generate a repellent force on the linear surface element ds represented by

$$\vec{F_L} = Id\vec{s}\times\vec{B}$$

Equation 4.11

where I is the induced current on the material. The repellent force in the ECS[1] caused by the variable magnetic field of rotating magnetic drums can be simplified as

$$F_r = H^2\frac{np}{2}\times\frac{m\sigma}{\rho s}$$

Equation 4.12

where F_r is the repellent force, n is the speed of the magnetic drum, p is the number of poles and m, σ, ρ and s are the mass, conductivity, density and shape factor of the particle [WANG05].

Like happens in magnetic separation, these forces compete with other external forces such as gravity, inertia, etc., and conditions expressed in Equation 4.1 adapted to this case have to be met.

The repulsion for a certain material depends on its conductivity and density. A high repulsion figure guarantees a high efficiency by the ECS. Aluminum, for example, with a repulsion of 13,700 $m^2/kg\Omega$ can be easily separated but a lower repulsion figure would need a perfect setup of the ECS to achieve high efficiency rate. Table 4.1 shows significant repulsions values.

Table 4.1: *Significant repulsion values*

Material	Conductivity [1/Ωm]	Density [kg/m³]	Repulsion [m²/kgΩ]
Aluminum	37,000,000	2,700	13,700
Copper	59,900,000	8,960	6,700
Silver	62,100,000	10,500	5,900

3.2. Eddy current separation equipment

The rotary drum is the most widely used type of ECS. The active part is a fast spinning drum with a surface consisting of rows of magnets of alternating polarity. A conveyor belt takes the particles over the drum and the conductive particles are repelled while the non-conductive stay on the belt and drop close to the drum.

[1] Eddy Current Separator

Conventional dry ECS have problems in recovering non-ferrous metal particles with a diameter less than 5 mm [SETT04]. Recently, WECS[2]s have been capable of recovering these fine particles.

3.2.1. Dry drum eddy current separators

The rotor of the ECS is based on a multi-pole magnet, consisting of an even number of poles, rotating at a very high speed in the same direction as the belt. When a metal particle approaches the rotor several processes occur. The fast rotation of the rotor makes the field change very rapidly in such a way that at a certain position it can be experienced as a rotating field. A non-ferrous material particle within a magnetic field tend to keep the magnetic flux inside the particle constant. A particle that approaches the rotor experiences a torque that makes it rotate in the same direction as the field. Besides the torque there are a number of forces working on the metal particle. The normal and tangential forces make the non-ferrous metal particles jump away from the belt, while the torque makes them spin. In this way non-ferrous metals jump further than mineral particles, which fall by gravity closer to the belt while magnetic particles are removed below the belt [MUCH10]. A schematic is shown in Figure 4.9.

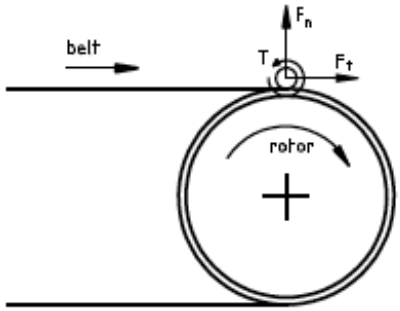

***Figure 4.9**: Dry drum ECS [MUCH10]*

The efficiency of the process would depend on the force of the magnetic field, the drum radius and length, number of pairs of the magnetic in the drum, speed of the belt, rotating speed of the drum and particle parameter such as the shape factor and the characteristic time with which the induced magnetic field decays in the particle, depending on the material.

Generic state-of-art equipment would be used, which assumed fixed and operation costs are specified in Chapter 8.

3.2.2. Wet drum eddy current separators

A WECS is, in contrast with the standard ECS, suitable for particles with sizes below 5 mm. The separator itself is not different from an ECS and any regular ECS can perform this way. The difference is that the feed is slightly wet (moisture around 10-15%) and the rotor of a WECS rotates against the direction of the conveyor belt. The water sticks all the particles to the belt surface and the adhesive force acting on the small particles is similar to gravity. The torque caused by the rotating field of the rotor breaks the adhesive force that makes the non-ferrous metal

[2] Wet Eddy Current Separators

particles adhere to the belt and makes them spin. The same processes affect the ferrous metal particles. However, if the magnetic attraction acting on these ferrous particles is sufficiently strong they will stay on the belt. The non-ferrous metal particles are disengaged from the belt and are collected in front of the separator while the non-metal and ferrous particles remain on the belt and are released below the separator [MUCH10]. A schematic is shown in Figure 4.10.

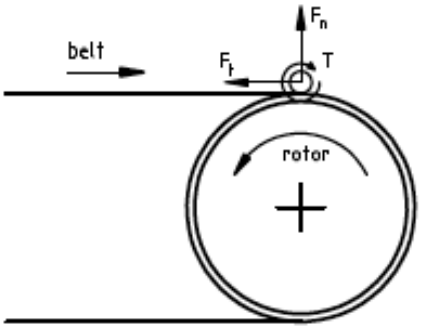

***Figure 4.10**: Wet drum ECS [MUCH10]*

4. Density separation

Also called gravity separation in some contexts, density separation is based on the differences in density in the particles contained in a mixture of materials. Density concentrating operations are characterized by processes that allow particles to be held slightly apart so that they can move relative to each other and therefore to separate into layers of dense and light materials [GUPT06]. The mechanisms to be used in the processes proposed in this thesis are:

- Jig: uses vertical expansion and contraction of a bed of particles by a pulse of fluid.
- Shaking table: employs horizontal motion to the solids-fluids stream to effectively fluidize the particles causing segregation of light and heavy particles and middlings.
- Kinetic gravity separator: particles are separated on the basis of differences in their terminal velocity [VANK04].
- Hydro-cyclone: used to remove sludge from a slurry mixture.

4.1. Jigs

Consisting of two actions. One is the effect of “hindered settling”, meaning that a heavier particle will settle faster than a light particle. The other is the separation process in a “upward flow of water”, which separates the particles by their density. These two actions are combined in a jig by slurry pulses generated mechanically or by air. The principle of the jig separation is explained by a layer of mixed particles lying on a perforated plate or screen creating a “bed”. During the upward and downward stroke of the fluid, parts of the jig bed will be fluidized and particles are able to move. During this stage the heavy particles will have a greater velocity downward than the light particles. After equilibrium is reached, layers with different densities will be present on the screen. The density will increase with decreasing distance from the screen [GUPT06]. A schematic the jigging actions can be seen in Figure 4.11 and a jigging machine in Figure 4.12.

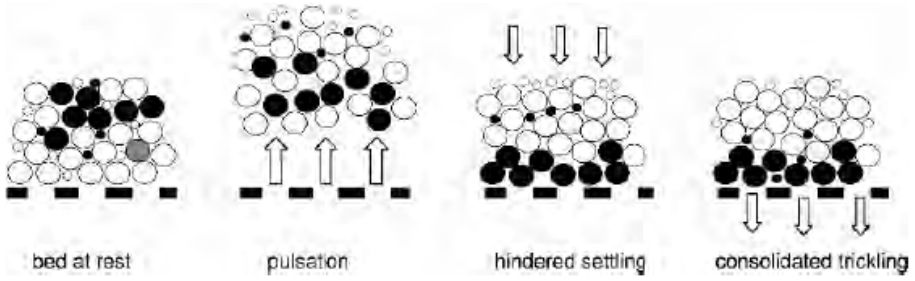

Figure 4.11: Jigging action [GUPT06]

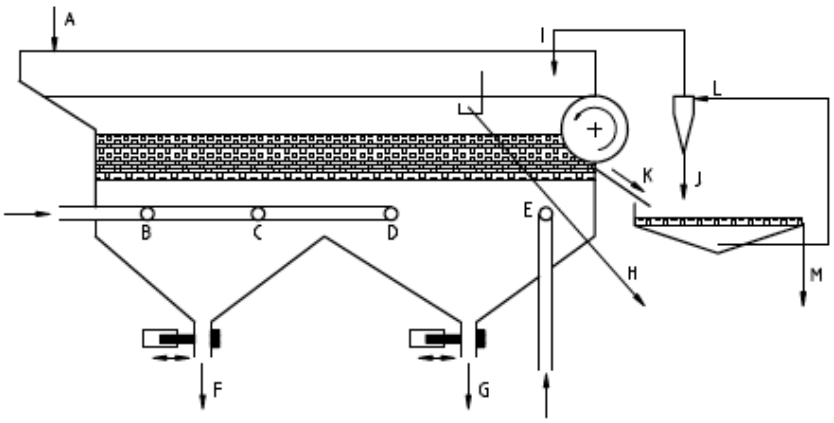

Figure 4.12: Jigging machine [MUCH10]

A	Income material
BCDE	Underflow water exits
FG	Denser particles exits (heavy non-ferrous, ferrous and larger stony particles)
H	Organic and very light particles exit
IJL	Recirculation
K	Sand product exit
M	Water from removal of leaching salts

The jig concentrator selected is the JT4-2 model commercialized by Well-Tech International Mining Equipment. More information in Appendix B. The jig this is a complex machine and there are several factor affecting the separation performance such as the size and material of the ragging, the water flow and the organics removal system.

4.2. Shaking tables

Consisting of small riffles over which a fine slurry is passed. The heavy, dense particles settle into the riffles and through a vibrating action are directed to one side of the table where they are collected. The tailings are passed across the middle of the table or remain in suspension. Middlings, material that is partially settled, may be collected. Heads and middlings are commonly reprocessed on multi-stage tables [GUPT06]. A schematic of the segregation effect due to shaking motion can be seen in Figure 4.13 and a shaking table in Figure 4.14.

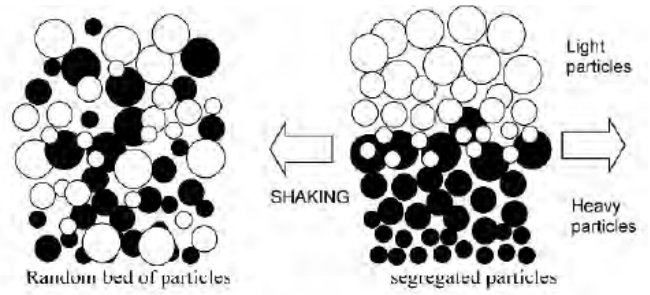

Figure 4.13: Segregation effect [GUPT06]

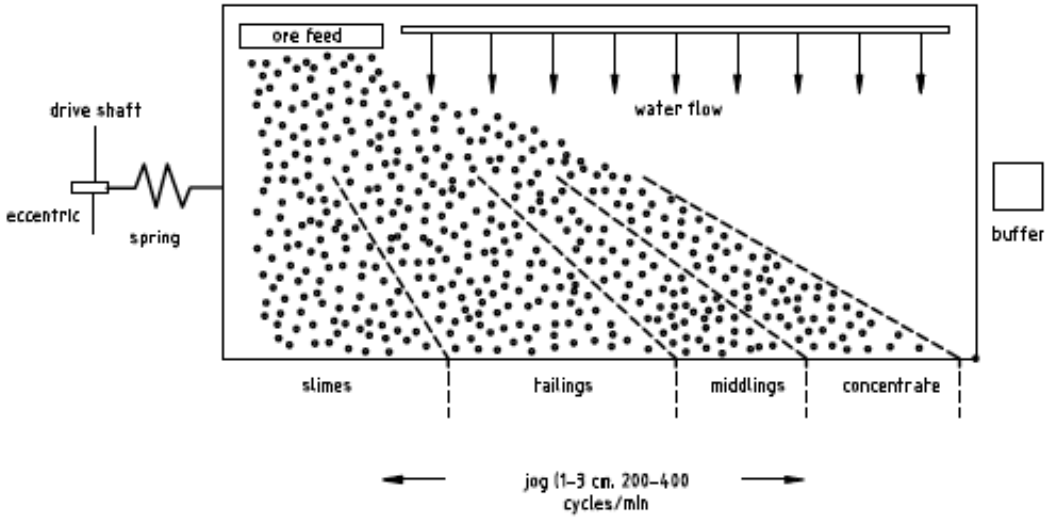

Figure 4.14: Shaking table [MUCH10]

The shaking table chosen would be a shaking table model Holman 3000 supplied by Holman Wilfley, which details can be seen in Appendix B. The accumulation of material in each case would depend on four variables: stroke length, deck angle, wash water flow and position of splitter plates that would be adjust when operating for optimal recovery.

4.3. Kinetic gravity separator

The principle of kinetic gravity separation is that particles that are fed at some point into a horizontal flowing fluid stream reach their terminal velocity rapidly after being released. The particles then have a horizontal velocity component that equals that of the fluid and a vertical velocity component depending on their density, size and shape. The particles with a high terminal velocity end up in the compartment close to the feeding point, while particles settling at a lower speed are collected further downstream. It is practical to use a circular rotating design.

KGS[3] consists of a cylindrical shell with a cylinder placed inside it. Between the cylinders a paddle wheel is placed consisting of several paddles. These paddles are placed close toe ach other to prevent horizontal fluttering of the particles. The paddles rotate around the separator's vertical axis and due to their rotation, water in the separator is forced to move at a constant angular velocity. Particles are fed from the top and based on their specific terminal velocity, the wheel

[3] Kinetic Gravity Separator

speed and the height of the machine, these particles will be separated into several compartments, located at the bottom of the KGS. The speed of the paddle wheel rotation makes the heavy particles fall into the first compartment while the lighter particles are collected in the second and third compartments. The light particles are collected in the fourth, fifth and sixth compartments. The extremely light particles flow over the top where they are collected [MUCH10]. A schematic of the principle can be seen in Figure 4.15.

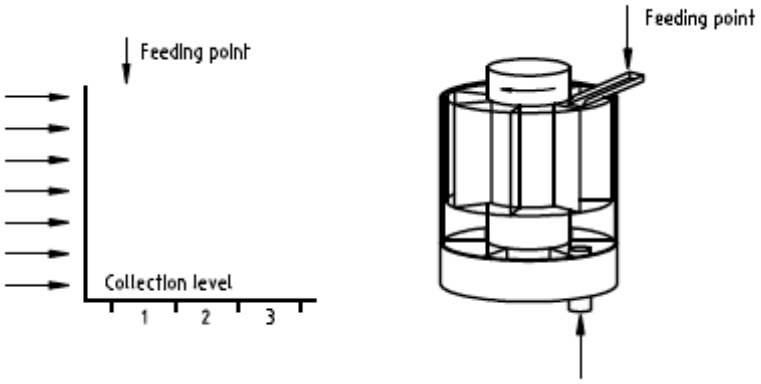

***Figure 4.15**: Kinetic gravity separation principle [MUCH10]*

The KGS is currently performed by INASHCO [WRAP08b]. Figure 4.16 shows the KGS at AEB Amsterdam. Fixed and operational costs associated are detailed in Chapter 8.

***Figure 4.16**: KGS at AEB Amsterdam*

4.4. Hydro-cyclones

Based on the centrifugal effect created within the cyclone body. The cylindrical part is closed at the top by a cover, through which a liquid overflow pipe (vortex finder) protrudes some distance into the cyclone body. The slurry enters the hydro-cyclone through a tangential inlet located near the top of the cyclone. Most of the incoming fluid moves in an outward, downward moving primary vortex. Some of the downward flow that carries most of the solids leaves through the underflow orifice at the bottom of the hydro-cyclone, while vertical direction of the rest reverses and it moves upward in a secondary vortex, exiting via the overflow orifice. The strong centrifugal effect within the cyclone causes the particles in the slurry to migrate to the wall of the cyclone. Working against this is the flow of water from the primary to the secondary vortex, towards the overflow. The result of these opposing factors is that the coarse particles remain at the cyclone

wall whilst the finer particles remain with the water and exit the cyclone in the overflow fraction. The coarse material is forced through the conical section of the cyclone to exit via the spigot [MUCH10]. A schematic of the principle can be seen in Figure 4.16.

The piece of equipment chosen for this task is the CAVEX® Hydro-cyclone model 150CVX6 supplied by Weir Minerals Ltd. with capacity up to 45 t/h in mass of water. More details of this equipment can be seen in Appendix B.

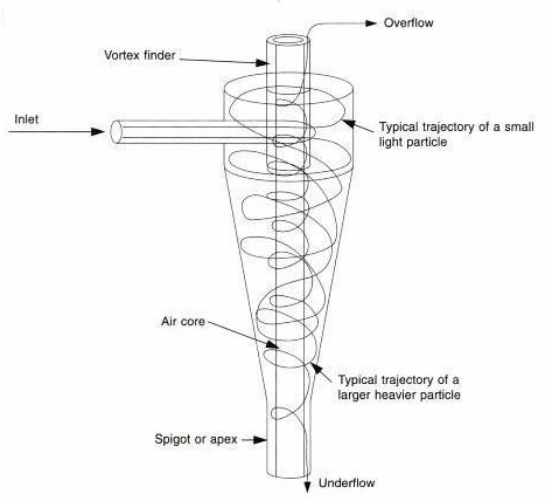

***Figure 4.17**: Hydro-cyclone principle, Lenntech BV*

5. General process equipment

In this group, necessary equipment for the separation process that is not metal separation equipment itself is included. This equipment consists of screening equipment, crushers and conveyors.

5.1. Screening equipment

As mentioned before, size classification is essential for a high-rate metal recovery. In the processes proposed in the following sections, a first screen is performed where the oversized > 300 mm materials are removed from the bulk IBA stream. This first screen is currently being performed on site by a fixed finger screening system after the IBA extractor and before being conveyed off site. Figure 4.17 shows the exterior of the mentioned screening system.

Figure 4.18: Fixed fingers screen on site and oversized container

Further in the processes proposed in the following chapters of this thesis, at least one more screening stage would be required. A widely used technique in the industry is the vibrating screen system. It differs from the one mentioned above in that in this case, a vibrating motion of the fingers would help the classification process. The deck provides several apertures that can be of different shapes and dimensions, depending on the process needs. Figures 4.18 and 4.19 show the vibrating screen principle and an example of a commercialized unit.

In all cases, generic state-of-art equipment would be used. Information about their associated fixed an operating costs, together with the number of pieces of equipment required are detailed in Chapter 8 for each case.

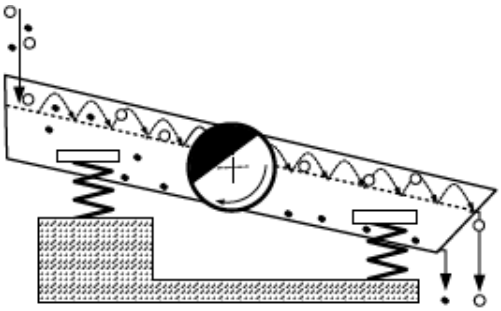

Figure 4.19: Vibrating screen principle

Figure 4.20: Vibrating screen unit

5.2. Crusher

In all cases, the oversized material would be crushed and reinserted in the system to improve the efficiency of the metal recovery process. The cut-off size and the amount of material to be crushed is specified in every process proposed. Figure 4.20 shows the principle of the crushing process.

***Figure 4.21**: Jaw crusher, Kleemann*[4]

An example of crushing equipment and the one to be used for the economic feasibility analysis is the C96 Jaw Crusher supplied by Metso, which capacity is ensured to meet the requirements of all scenarios by the supplier. Further details can be seen in Appendix B.

5.3. Conveyor

Several conveyors would be required to cover the distance between pieces of equipment automatically. The speed of these conveyor belts would affect the recovery rates and needs to be adjusted. It would depend on the material presentation and composition, type and orientation of the equipment and material size fraction. It is normally easy to adjust while operating and not considered in the feasibility stage. It shall be a speed that allows the material to set into a one-layer thick configuration to ensure effective and clean removal. An example of an IBA processing plant is shown in Figure 4.21.

***Figure 4.22**: IBA processing plant, Raymond Brown*[5]

In all cases, generic state-of-art equipment would be used. Information about their associated fixed an operating costs, together with the number of pieces of equipment required are detailed in Chapter 8 for each case.

[4] Kleemann: https://www.kleemann.info
[5] Raymond Brown Aggregates: https://www.rbaggregates.co.uk

Chapter 5

Scenario I – Wet discharge and conventional separation

1. Introduction

The first scenario analyzed consists on the current wet IBA discharge installed in Greatmoor EfW with further IBA treatment and material recovery using conventional methods. The separation process would be conditioned by the moist status of the IBA and the efficiencies in metal recovery marked by the limitations of the equipment.

No special treatment for the fine fractions would be performed but the bulk material would still be screened into size fractions to increase efficiency. Recovery rates would be acceptable for particles > 8 mm approximately but poor for smaller fractions.

2. Process

2.1. Base base

A schematic of the process is shown in Figure 5.1 which includes the mass flows calculated. IBA would be wet discharged and conveyed to a first screen to separate the > 300 mm objects that would be shredded and reinserted in the system. Then, a second screen would be performed to separate > 40 mm particles for further shredding and being reinserted in the system too. This would make sure that all particles have a correct size to be efficiently separated. Particles < 40 mm would be screened into three fractions 0-6 mm, 6-20 mm and 20-40 mm, that would increase the efficiency of the process and allow a better positioning of the material on the conveyor belts.

The three fractions are to be treated evenly. Firstly, magnetic separation would extract the ferrous metal content and secondly, ECSs would remove the non-ferrous metal fraction. The rest would be considered aggregate that would have to be further analyzed and treated accordingly for further use due to the heavy metals and moisture contained in the residue.

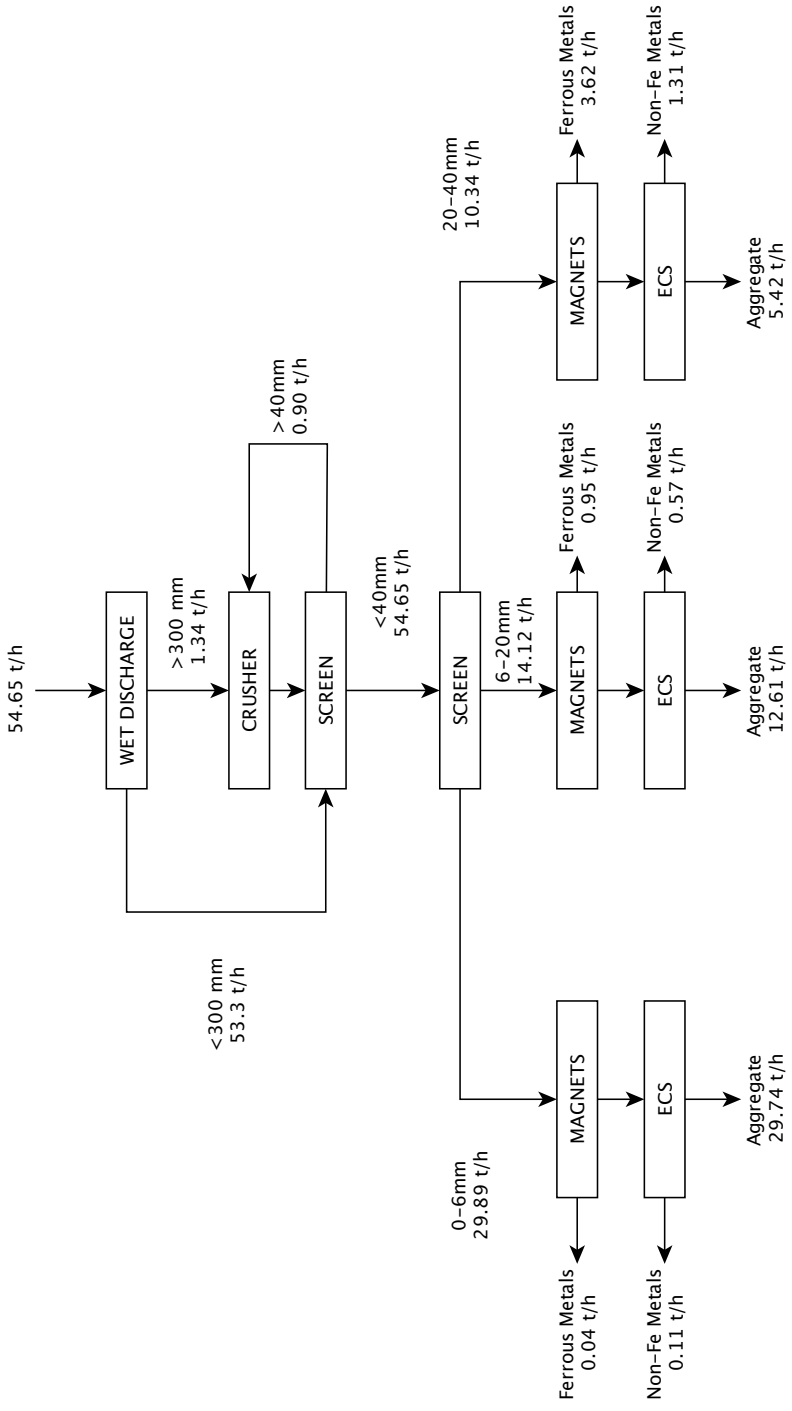

***Figure 5.1**: Scenario I base case*

2.1.1. Wet discharge

The IBA would be discharged wet by the IBA extraction system currently installed at Greatmoor EfW explained in Chapter 1. This process us used to cool down the ash coming from the grate, avoids problems related with dust emissions and produces a slurry that is easier to transport than dusty mixtures. Nevertheless, it also makes the fine particles to stick together, which makes if difficult to separate, and increase the weight of the material to be extracted and transported.

As an effect of this process, Greatmoor EfW IBA has an average moisture content of 16.28%. This content makes the production of IBA increase its throughput from 45.75 to 54.65 t/h. Subsequently, the IBA composition changes its mass concentrations. Table 5.1 shows this composition, considering that the moist particles would be contained in the fine fraction.

After discharge, a first separation of > 300 mm objects would be carried out by finger screening as it is currently performed on site. This fraction would be conveyed to be crushed to < 40 mm carried to the second screen. A second screen for the < 300 mm fraction separate IBA into > 40 mm and < 40 mm fractions, being the first one crushed down to < 40 mm. Once all particles would be < 40 mm, the bulk material would be screened again into 0-6 mm, 6-20 mm and 20-40 mm fractions for being treated separately which would increase the efficiency of the metal recovery process.

***Table 5.1**: IBA composition considering moist particles*

Material [%]	**Total**	**> 40 mm**	**20-40 mm**	**6-20 mm**	**2-6 mm**	**< 2 mm**
Ferrous	9.65	3.72	2.97	1.81	0.14	1.03
Non-Ferrous	4.71	0.38	2.05	1.14	0.52	0.62
Cu	0.20		0.09	0.03	0.03	0.04
Zn	0.20		0.12	0.05	0.03	0.01
Pb	0.07		0.04	0.01	0.01	0.00
Al	1.78		0.82	0.56	0.12	0.28
Ag	0.00		0.00	0.0002	0.0002	0.0001
Sn	0.01		0.00	0.00	0.01	0.00
Mix	2.45	0.38	0.98	0.48	0.32	0.28
Aggregate	85.09		9.81	22.89	12.70	39.70
Organics	0.55	0.00	0.00	0.00	0.00	0.55
Total	100	4.10	14.83	25.84	13.35	41.90

2.1.2. 0-6 mm fraction

The 0-6 mm fraction is the largest fraction from IBA constituting 55.25% of the total wet production. It contains ferrous and non-ferrous metals which would not be recovered effectively

since moist particles are also contained in this fraction and would make the rest sticky. Material separation would be performed by magnetic separation first, to recover ferrous metals, and eddy current separation second, to recover non-ferrous metals, leaving a residue that would contain a large amount of metals so it shall be further treated by any of the processes mentioned in Chapter 2. Since non-ferrous metal fraction would not be further separated, its composition is not considered and the entire fraction would be sold as a mix.

Magnetic separation

The ferrous metal fraction would be separated by a top-feed drum magnetic separator. This configuration is suitable for the small size of the particles and also for mixtures with small amounts of magnetic particles, 2.11% in this case.

Experimental data for this magnetic separation technique in wet discharged IBA shows a rate of recovery of about 1.5% for 0-2 mm particles and 40% for 2-6 mm particles [DEVR09]. These are poor rates that indicates that this process may not be worth to be installed. Anyway, for it would be included in this base configuration, leaving alternative configurations for section 2.2 of this chapter. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 5.2.

***Table 5.2**: Scenario I 0-6 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T[1]	%F[2]	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.17	2.11	0.64	0.07	100	0.04	1.10	1.99	0.60
Non-Fe	1.14	2.06	0.62				1.14	2.06	0.62
Agg.	52.39	94.84	28.63				52.39	94.96	28.63
Organics	0.55	1.00	0.30				0.55	1.00	0.30
Total	55.25	100	30.19	0.07	100	0.04	55.18	100	30.15

Eddy current separation

Non-ferrous metal fraction separation would be performed by an ECS. Experimental data in wet discharged IBA shows a rate of recovery of 1.27% for 0-2 mm particles and 37.10% for 2-6 mm particles [DEVR09]. As happened in magnetic separation, this efficiency indicates that this process may not worth to be included for this fraction. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 5.3.

[1] Percentage by total mass produced
[2] Percentage by mass of the fraction

Table 5.3: Scenario I 0-6 mm ECS amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.10	1.99	0.60				1.10	2.01	0.60
Non-Fe	1.14	2.06	0.62	0.20	100	0.11	0.94	1.72	0.51
Agg.	52.39	94.96	28.63				52.39	94.26	28.63
Organics	0.55	1.00	0.30				0.55	1.01	0.30
Total	55.18	100	30.15	0.20	100	0.11	55.18	100	29.74

2.1.3. 6-20 mm fraction

The 6-20 mm fraction constitutes 25.84% of the total wet IBA production. Interesting materials in this fraction are the ferrous and non-ferrous metals that are to be separated the same way as the 0-6 mm fraction but with a notable increase in efficiency rates. Magnetic separation would be performed to remove ferrous metals from the bulk material and eddy current separation for the non-ferrous fraction. The remaining material would be considered aggregate.

Magnetic separation

Magnetic separation would also be performed by a top-feed drum magnetic separator since the ferrous content is low (7.00%) and it is suitable for this particle size.

Experimental data for this magnetic separation technique in wet discharged IBA shows a rate of recovery of 96% for this size fraction [DEVR09], which is much higher than in the previous fraction. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 5.4.

Table 5.4: Scenario I 6-20 mm magnetic separation amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.81	7.00	0.99	1.74	100	0.95	0.07	0.30	0.04
Non-Fe	1.14	4.42	0.62				1.14	4.74	0.62
Agg.	22.89	88.58	12.51				22.89	94.96	12.51
Total	25.84	100	14.12	1.74	100	0.95	24.10	100	13.17

Eddy current separation

Non-ferrous metal fraction separation would be performed by a generic state-of-art ECS. Experimental data for this ECS technique in wet discharged IBA shows a rate of recovery of 90.80% for this size fraction [DEVR09], which is much higher than in the previous fraction. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 5.5.

***Table 5.5**: Scenario I 6-20 mm ECS amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.07	0.30	0.04				0.07	0.30	0.04
Non-Fe	1.14	4.74	0.62	1.04	100	0.57	0.11	0.46	0.06
Agg.	22.89	94.96	12.51				22.89	99.23	12.51
Total	24.10	100	14.12	1.04	100	0.57	55.18	100	13.17

2.1.4. 20-40 mm fraction

The 20-40 mm fraction constitutes 18.93% of the total wet IBA production. Interesting materials in this fraction are again the ferrous and non-ferrous metals that are to be separated the same way as in the previous fractions. Magnetic separation would be performed to remove ferrous metals from the bulk material and eddy current separation for the non-ferrous fraction. The remaining material would be considered aggregate.

Magnetic separation

Due to the higher concentration of ferrous metals in this fraction, their removal would be performed by a cross-belt suspended magnet, more suitable for large objects and a high content (35.35% of this fraction) than drum separators as explained in Chapter 4.

For this configuration and material size fraction, very high recovery rates would be obtained up to 99% [SVOB04]. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 5.6.

Table 5.6: Scenario I 20-40 mm magnetic separation amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	% tot	%F	t/h	%T	%F	t/h
Ferrous	6.69	35.35	3.66	6.62	100	3.62	0.07	0.54	0.04
Non-Fe	2.43	12.84	1.33				2.43	19.75	1.33
Agg.	9.81	51.81	5.36				9.81	79.71	5.36
Total	18.93	100	10.34	6.62	100	3.62	12.30	100	6.72

Eddy current separator

As happens in the magnetic separation, this size fraction allows high recovery rates with regular ECS equipment [SVOB04].

Generic state-of-art equipment would be used, which assumed fixed and operation costs are specified in Chapter 8.

For this configuration and material size fraction, recovery rates would be obtained up to 98.40% [SVOB04]. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 5.7.

Table 5.7: Scenario I 20-40 mm ECS amounts

Material	Income			Removed			Remaining		
	% tot	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.07	0.54	0.04				0.07	0.67	0.04
Non-Fe	2.43	19.75	1.33	2.39	100	1.31	0.04	0.39	0.02
Agg.	9.81	79.71	5.36				9.81	98.93	5.36
Total	12.30	100	6.72	2.39	100	1.31	9.92	100	5.42

2.1.5. Summary

The total amount of products and overall recovery rates of this process is summarized in Table 5.8. From the total amount of ferrous metals contained originally in the IBA, 87.35% can be recovered and sold whereas in the case of non-ferrous metals would be 77.03%. This relatively poor rates are due to the moist particles as it has been discussed before, making the recovery for the fine fraction almost null.

Table 5.8: Scenario I base case total products and overall recovery rates

Material	% total	t/y	% recovery
Ferrous	8.43	7,549.52	87.35
Non-ferrous	3.63	3,238.40	77.03
Aggregate	87.96	78,807.48	
Total	100	89,595.40[3]	

2.2. Alternative case

An alternative option due to the low recovery rates shown in the 0-6 mm fraction would be not to treat that fraction. This would drive into a situation where the amount of material recovered would be lower and also the revenues associated but also the required initial investment would decrease too. A schematic of this process is shown in Figure 5.7.

From this schematic it can be inferred that the ferrous and non-ferrous metals contained in the 0-6 mm fraction would not be recovered and thus the total amounts of these metals recovered together with the overall rates of recovery would decrease.

The total amount of products and overall recovery rates of this process is summarized in Table 5.9. From the total amount of ferrous metals contained originally in the IBA, 86.62% would be recovered and sold whereas in the case of non-ferrous metals would be 72.79%.

Table 5.9: Scenario I alternative case total products and overall recovery rates

Material	% total	t/y	% recovery
Ferrous	8.36	7,490.13	86.62
Non-ferrous	3.43	3,070.42	72.79
Aggregate	88.23	79,034.85	
Total	100	89,595.40	

[3] Production of IBA per year including the moisture content

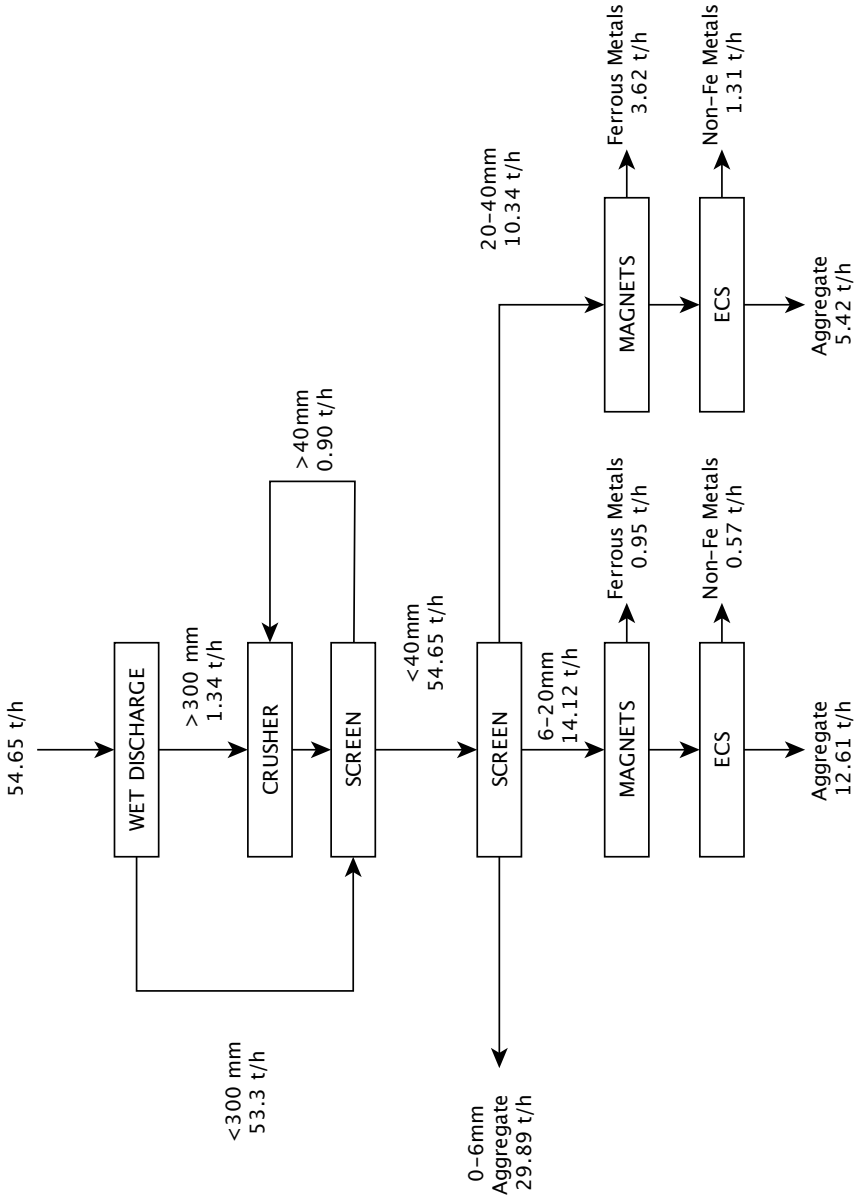

***Figure 5.2**: Scenario I alternative case*

2.3. Optimal case

The final results of both cases are shown in Table 5.10.

***Table 5.10**: Scenario I summary*

	Base case	**Alternative case**
Ferrous metals recovery rate	87.35%	86.62%
Non-ferrous metals recovery rate	77.03%	72.79%

From the technical point of view, it is obvious that the best case would be that which maximizes the amount of material recovered, which in this scenario is the base case. Nevertheless, this selection has to be supported by the economic feasibility which is analyzed in Chapter 8.

Chapter 6

Scenario II – Wet discharge, conventional and fine fraction separation

1. Introduction

This second scenario differs from the first one in the addition of specific treatments for the fine particles that would allow to recover metals of sizes down to < 1 mm. The medium and coarse size fractions would be treated the same way as in the previous scenario since acceptable rates of recovery would be reached and the IBA contained in those fractions has the same characteristics as in the previous scenario.

Two models for fine fraction separation process are to be proposed. The first proposal is the ADR system developed by INASCHO and installed, for example, in Sluiskil (the Netherlands) [DEVR09], that would involve the 0-12 mm fraction, and the second one is the wet physical separation process installed in AEB Amsterdam, focusing on the 0-6 mm fraction. Both technologies have been introduced in Chapter 2.

As mentioned, the medium and coarse fractions would be treated equally to as in the first scenario by performing magnetic and eddy current separation so they will not be explained but mentioned, since the recovery amounts and equipment required would be even.

2. Advanced Dry Recovery

The ADR system focuses on the 0-12 mm fraction. The process screens the wet IBA into < 12 mm and > 12 mm size fractions and passes the first one through the ADR concentrator before metals recovery. The main goal is to reduce the amount of fines, which contain the moist particles, within the waste materials. The ADR concentrator uses kinetic energy[1] to break the water bond that is formed by the moisture associated with the fine particles. Figure 6.1 and 6.2 show the fine fraction and the concentrate obtained in the ADR. When the wet fraction is released from the

[1] See Chapter 4

coarse material, the latter becomes suitable for being treated using magnetic, eddy current and density separation equipment.

***Figure 6.1**: Mineral fines 0-2 mm [INAS14]*

***Figure 6.2**: ADR concentrate [INAS14]*

2.1. Base case

A schematic of the process is shown in Figure 6.3 which includes the mass flows calculated. IBA would be wet discharged and conveyed to a first screen to separate the > 300 mm objects that would be shredded and reinserted in the system. Then, a second screen would be performed to separate > 40 mm particles for further shredding and being reinserted in the system too. This would make sure that all particles have a correct size to be efficiently separated. Particles < 40 mm would be screened into two size fractions 0-12 mm and 12-40 mm that would be treated separately.

The 0-12 mm would be treated in the ADR concentrator that would remove the moist < 2 mm mineral particles from the fraction. Some products (ferrous and non-ferrous metals) would be contained in the moist fraction removed as residue and would not be recovered [DEVR09]. The remaining dry fraction would be conveyed through magnetic and eddy current separation as in the previous scenario and finally the products from the ECS would be screened to 0-2 mm, 2-6 mm and 6-12 mm fractions. The first two would be treated by density separation for separating the light fraction, mainly Aluminum; middlings, a non-ferrous metal mix; and the heavy fraction, mainly Copper and Silver. The 6-12 mm would not further be separated since a very poor recovery rate is obtained for > 5 mm particles [WRAP08].

The 12-40 mm fraction would be first treated by magnetic separation for ferrous metal removal prior eddy current separation for recovery of non-ferrous metal fraction that would not be further separated.

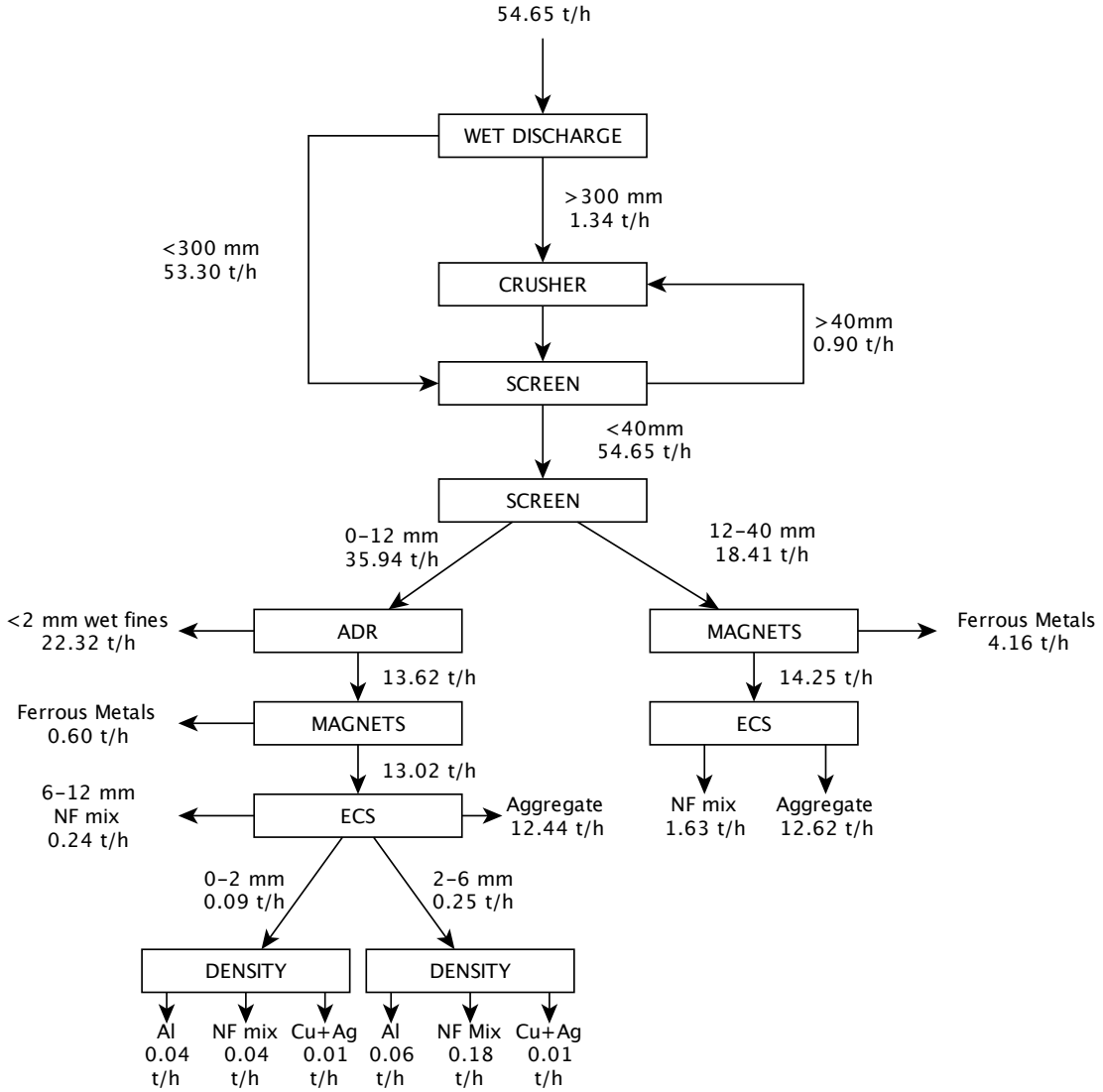

Figure 6.3: Scenario II ADR base case

2.1.1. Wet discharge

Wet IBA discharge would be performed as in the previous scenario and concurring with the current installation at Greatmoor EfW. This process would have the same effect on the IBA as explained before, due to the moisture content of 16.28%, the IBA throughput would increase from 45.75 to 54.65 t/h. Subsequently, the IBA changes its mass composition as shown in Table 5.1[2].

After discharge, a first separation of > 300 mm objects would be carried out by finger screening as it is currently performed on site. This fraction would be conveyed to be crushed to < 40 mm carried to the second screen. A second screen for the < 300 mm fraction separate IBA into > 40 mm and < 40 mm fractions, being the first one crushed down to < 40 mm. Once all particles would be < 40 mm, the bulk material would be screened again into 0-12 and 12-40 mm fractions for being treated separately which would increase the efficiency of the metal recovery process.

2.1.2. 0-12 mm fraction

The 0-12 mm fraction contains 65.77% of the total production of wet IBA. It contains valuable materials such as ferrous and non-ferrous metals which in turn contains very valuable heavy metals like Copper and Silver. It also contains the fine moist particles that makes the entire section sticky and hinders metal recovery. In order to get the maximum recovery from this fraction, the ADR concentrator would remove the fine moist particles from the bulk material. Then, this bulk material would be suitable for being further treated by magnetic, eddy current and density separators.

ADR concentrator

As explained before, the ADR concentrator uses kinetic gravity to remove the 0-2 mm moist mineral particles. It accelerates the bulk IBA income, being the lighter particles the first to precipitate. A consequence of this process is that a notable amount of valuable material would be lost in the extracted fraction but would enable high-rate recovery for the remaining 2-12 mm fraction.

INASHCO (Figure 6.4) supplies a mobile unit of the ADR separator to be added to an existing process. This unit can be seen in Figure 6.5. According to performance reports [RESO16], an operating cost of about 2.5€ (£1.74) per ton of IBA treated is related to this mobile unit and is taken into account in Chapter 8.

***Figure 6.4**: INASHCO logo*

[2] Chapter 5

***Figure 6.5**: ADR separator mobile unit*

Performance reports for the ADR operation details a rate of recovery of 15.9% for the 0-2 mm fraction [DEVR09], so it was assumed that 70% of the valuable materials content in the 0-2 mm is lost in the extraction process. According to this, extracted and remaining amounts of this process is shown in Table 6.1.

From these amounts it can be inferred that the 0-2 mm mineral particles, moisture and organics would be removed together with 70% of the amount of ferrous and non-ferrous metals of the 0-2 mm, which represents 37.14% of ferrous metals and 26.66% of non-ferrous metals of the entire 0-12 mm fraction. As a consequence, the amount of valuable heavy non-ferrous metals that would be separated by density separation might not be worth the investment in equipment. Nevertheless, this process is included in the base case and further considerations will be made in section 2.2 of this chapter.

***Table 6.1:** Scenario II ADR concentrator amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.94	2.95	1.06	0.72	1.76	0.39	1.22	4.90	0.67
Non-Fe	1.63	2.47	0.89	0.43	1.06	0.24	1.19	4.79	0.65
Al	0.64	0.98	0.35	0.20	0.49	0.11	0.44	1.78	0.24
Cu	0.09	0.13	0.05	0.03	0.07	0.02	0.06	0.23	0.03
Ag	0.0004	0.0006	0.0002	0.0001	0.0002	0.00	0.0003	0.0013	0.0002
Mix	0.90	1.36	0.49	0.21	0.50	0.11	0.69	2.77	0.38
Agg.	62.20	94.58	33.99	39.70	97.17	21.69	22.51	90.32	12.30
Organics	0.55	0.84	0.30	0.55	1.35	0.30	0	0	0
Total	65.77	100	35.94	41.40	100	22.32	24.92	100	13.62

Magnetic separation

After the removal of the moist particles, ferrous metals would be efficiently recovered using a single top-feed drum magnetic separator as in the previous scenario but, in this case, recovery efficiency would be expected to be up to 90% [DEVR09]. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 6.2.

***Table 6.2**: Scenario II ADR 0-12 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.22	4.90	0.67	1.10	100	0.60	0.12	0.51	0.07
Non-Fe	1.19	4.79	0.65				1.19	5.01	0.65
Agg.	22.51	90.32	12.30				22.51	94.48	12.30
Total	24.92	100	13.62	1.10	100	0.60	23.82	100	13.02

Eddy current separation

Same as in the magnetic separation, in the absence of moist particles the non-ferrous metals would be efficiently recovered by an eddy current separator which efficiency would be 89.20% according to experimental data from an ADR plant [DEVR09]. Based on this recovery rates, extracted and remaining material amounts of this process are shown in Table 6.3.

***Table 6.3**: Scenario II ADR 0-12 mm eddy current separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.12	0.51	0.07				0.12	0.54	0.07
Non-Fe	1.19	5.01	0.65	1.06	100	0.58	0.13	0.57	0.07
Agg.	22.51	94.48	12.30				22.51	98.80	12.30
Total	23.82	100	13.02	1.06	100	0.58	22.76	100	12.44

Density separation

Prior treatment, the entire fraction would be screened into three fractions 0-2 mm, 2-6 mm and 6-12 for improving the separation efficiency. The latter would not be further separated since the size of the particles exceeds the density separation limitations for acceptable recoveries and would be sold as a non-ferrous mix at an agreed price. Higher efficiency is to be obtained in the 0-2 mm fraction due to the equipment characteristics.

The process would require two shaking tables, each one with a different configuration according to the fraction characteristics. Each one would separate the income mixture into 3

fractions according to the difference in density of the materials contained. This fractions would be fines, Aluminum (2,700 kg/m^3); heavies, Cu (8,960 kg/m^3) and Ag (10,500 kg/m^3); and middlings containing the rest of non-ferrous metals. The heavy fraction would have a major fraction of Copper and a small amount of Silver but, due to the high value of Silver in the metal market, a refining process would be performed and sold separately.

Experiments performed with a wet shaking table for the 0-2 mm fraction demonstrate an accumulation of Copper in the heavy fraction up to 95% [WRAP08a], that will also be considered for Silver as it has a similar density. Aluminum accumulation is also demonstrated to be 98% [BÖNI13]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 6.4.

***Table 6.4**: Scenario II ADR 0-2 mm density separation amounts*

Material	**Income**			**Lights**		
	%T	**%F**	**t/h**	**%T**	**%F**	**t/h**
Al	0.08	45.69	0.04	0.07	100	0.04
Cu	0.01	7.00	0.01			
Ag	0.00	0.02	0.00			
Mix	0.08	47.29	0.04			
NF Total	0.17	100	0.09	0.07	100	0.04
Material	**Middlings**			**Heavies**		
	%T	**%F**	**t/h**	**%T**	**%F**	**t/h**
Al	0.00	2.07	0.00			
Cu	0.00	0.72	0.00	0.01	99.75	0.01
Ag	0.00	0.002	0.00	0.00	0.25	0.00
Mix	0.08	97.21	0.04			
NF Total	0.08	100	0.04	0.01	100	0.01

For the 2-6 mm fraction, experimental data details an accumulation rate of 98% for Aluminum and about 80% for Cu and Ag [BÖNI13]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 6.5.

Table 6.5: Scenario II ADR 2-6 mm density separation amounts

Material	Income			Lights		
	%T	%F	t/h	%T	%F	t/h
Al	0.10	22.68	0.06	0.10	100	0.06
Cu	0.03	5.90	0.02			
Ag	0.0002	0.04	0.0001			
Mix	0.33	71.38	0.18			
NF Total	0.46	100	0.25	0.10	100	0.06
Material	**Middlings**			**Heavies**		
	%T	%F	t/h	%T	%F	t/h
Al	0.002	0.69	0.00			
Cu	0.004	1.22	0.00	0.02	99.29	0.01
Ag	0.00	0.01	0.00	0.0002	0.71	0.0001
Mix	0.33	98.08	0.18			
NF Total	0.34	100	0.18	0.02	100	0.01

2.1.3. 12-40 mm

The 12-40 mm fraction constitutes 33.69% of the total wet IBA production. Interesting materials in this fraction are again the ferrous and non-ferrous metals that are to be separated the same way as in the coarse fraction of the previous scenario. Magnetic separation would be performed to remove ferrous metals from the bulk material and eddy current separation for the non-ferrous fraction. The remaining material would be considered aggregate.

Magnetic separation

Ferrous metal separation would be performed by a single cross-belt suspended magnet, more suitable for large objects and a high content of ferrous metals (22.93% of total fraction) than the drum separators. The configuration for this piece of equipment would be the same as in Scenario I.

For this configuration and material size fraction, very high recovery rates are obtained. As an average an efficiency of 99% for the > 20 mm particles and 96% for the 12-20 mm fraction will be taken [SVOB04]. Based on a combination this recovery rates, extracted and remaining amounts of this process are shown in Table 6.6.

Table 6.6: Scenario II ADR 12-40 mm magnetic separation amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	% tot	%F	t/h
Ferrous	7.72	22.93	4.22	7.62	100	4.16	0.11	0.42	0.06
Non-Fe	3.08	9.15	1.68				3.08	11.82	1.68
Agg.	22.89	67.93	12.51				22.89	87.77	12.51
Total	33.69	100	18.41	7.62	100	4.16	26.08	100	14.25

Eddy current separation

As happens in the case of the ferrous metals, this particle size fraction allows acceptable recovery rates with a single dry ECS [SVOB04].

Experimental reports of ECS performing in this size fraction detail a recovery rate of 90.80% for the 12-20 mm fraction and 98.40% for > 20 mm particles [DEVR09]. Based on the combination of this recovery rates, extracted and remaining amounts of this process are shown in Table 6.7.

Table 6.7: Scenario II ADR 12-40 mm ECS amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.11	0.42	0.06				0.11	0.47	0.06
Non-Fe	3.08	11.82	1.68	2.98	100	1.63	0.10	0.43	0.05
Agg.	22.89	87.77	12.51				22.89	99.10	12.51
Total	26.08	100	14.25	2.98	100	1.63	23.09	100	12.62

2.1.4. Summary

The total amount of products and overall recovery rate of this process is summarized in Table 6.8. Note that the amount of Al, Cu and Ag include in the table is the one to be sold does not meet the total amount recovered since the non-ferrous fraction would be only separated in the 0-2 and 2-6 mm fractions. The difference is distributed in the non-ferrous metal mix of the other two fractions.

***Table 6.8**: Scenario II – ADR base case total products and overall recovery rates*

Material	**%T**	**t/y**	**% recovery**
Ferrous	8.71	7,807.13	90.29
Non-ferrous	4.05	3,625.24	85.95
Al	0.18	158.14	9.90
Cu	0.03	30.59	17.28
Ag	0.0002	0.18	37.83
Mix	3.84	3,436.33	
Aggregate	45.85	41,079.49	
Sludge	40.85	37,083.54	
Total	100	89,595.40	

From the total amount of ferrous metals contained originally in the IBA, 90.29% is to be sold. In the case of non-ferrous metals 85.95% is to be sold, where the rate of "pure" Al, Cu and Ag to be sold separately are 9.90%, 17.28% and 37.83% respectively. The rest is contained in the non-ferrous mix and would be sold as it is being 1.74 t/h. 45.85% of the initial amount considered aggregate and 40.85% in mass of IBA would be sludge extracted by the ADR concentrator.

2.2. Alternative case

Since the ADR concentrator extracts a notable amount of valuable material from the 0-2 mm fraction, the alternative case considered consists removing the density separation treatment for that fraction. This configuration would increase the amount of non-ferrous metals sold as a mix and would decrease the amount of Al, Cu and Ag sold as "pure" together with the initial investment required. A schematic of this case is shown in Figure 6.6.

In this case, the total amount of products and overall recovery rate of this process is summarized in Table 6.9. Note that the amount of Al, Cu and Ag include in the table is the one to be sold does not meet the total amount recovered since the non-ferrous fraction would be only separated in the 2-6 mm fraction. The difference is distributed in the non-ferrous metal mix of the other two fractions.

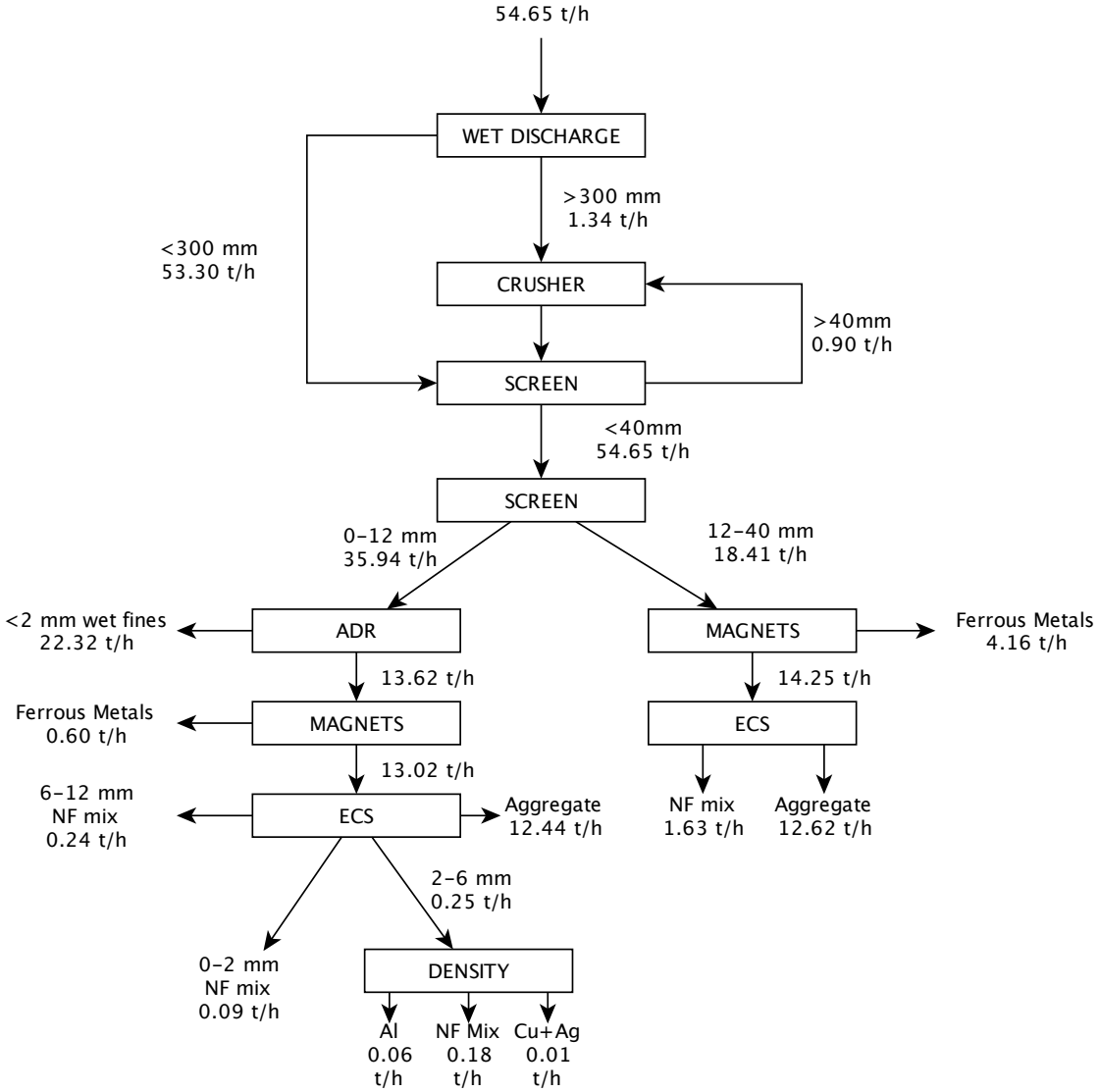

Figure 6.6: *Scenario II - ADR alternative case*

Table 6.9: Scenario II – ADR alternative case total products and overall recovery rates

Material	%T	t/y	% recovery
Ferrous	8.71	7,807.13	90.29
Non-ferrous	4.05	3,625.24	85.95
Al	0.10	91.69	5.74
Cu	0.02	20.71	11.70
Ag	0.0002	0.15	32.32
Mix	3.92	3,512.69	
Aggregate	45.85	41,079.49	
Sludge	40.85	37,083.54	
Total	100	89,595.40	

2.3. Optimal case

The final results of both cases are shown in Table 6.10.

Table 6.10: Scenario II - ADR summary

	Base case	Alternative case
Ferrous metals recovery rate	90.29%	90.29%
Non-ferrous metals recovery rate	85.95%	85.95%
Pure Aluminum recovery rate	9.90%	5.74%
Pure Copper recovery rate	17.28%	11,70%
Pure Silver recovery rate	37.83%	32.32%

From the technical point of view, for this case in this scenario the base case would also be the optimal case. In Chapter 8 the economic feasibility of both cases is analyzed and compared.

3. Wet separation

Wet separation process proposed in this section is based on the IBA wet separation plant installed at AEB Amsterdam WTE plant which can be seen in Figure 6.7. It is performed together with a dry conventional separation plant which operates the coarse > 20 mm fraction leaving the < 20 mm particles for wet separation. Wet treatments are preferable to dry methods since they allow more efficient and accurate classification in size and density, being able to recover metals down to 0.3 mm [MUCH10]. In addition, organics are washed out from the aggregate which improves the environmental quality of building products. Contaminants are contained in the sludge stream, so it is recommended to being dewatered and landfilled.

This wet process needs the addition of water in several parts of the system. This water is recycled, being collected in the process water tank and reintroduced as input water. The 0-2 mm fraction is treated by equipment used in the mining industry but not common in the IBA processing such as a cyclone and a jig and more conventional processes as magnetic density separators. Meanwhile, the 2-6 mm fraction is treated by density, eddy current and magnetic wet separators. Finally, the > 6 mm particles are treated as in the previous scenarios by conventional magnetic and eddy current separation.

Figure 6.7: AEB Amsterdam wet separation plant

3.1. Base case

A schematic of the base configuration of this process is shown in Figure 6.8 which includes the mass flows calculated. These mass flows were calculated as “dry” material, without including water mass flows. IBA would be wet discharged and water-cooled as it is currently performed at Greatmoor EfW. Then a first screen would be performed to separate the > 300 mm materials that would be shredded and reinserted in the system. Then, a second screen would do the same with > 40 mm particles for further shredding and being reinserted in the system too. This would make sure that all particles have a correct size to be processed. Particles < 40 mm would be then screened into four fractions: 0-2 mm, 2-6 mm, 6-20 mm and 20-40 mm.

The 0-2 mm fraction would be first passed through a hydro-cyclone that would remove particles smaller than its cut size (CCS[3]) in form of sludge. The remaining fraction is then driven to a jig that would remove sand particles, leaving a mix of ferrous and non-ferrous metals. The ferrous metal fraction would be recovered by magnetic separation and a density separator would separate the non-ferrous metal fraction into light particles (Aluminum), middlings and heavy particles (Copper and Silver).

The 2-6 mm fraction would be first treated by a KGS that would remove the organic fraction and would separate the bulk material into a light fraction (Aluminum and aggregate) and a heavy fraction (ferrous and heavy non-ferrous metals) and both fractions would be treated separately. The light fraction would be passed through a WECS to separate the Aluminum and the heavy fraction through a magnetic separator to remove the ferrous metal fraction.

The 6-20 mm fraction and the 20-40 mm fraction would be treated as in the previous cases by magnetic and ECSs.

As mentioned before, this process would require continuous water mass flow. This process water balance is not included in the extracted and remaining material mass flows that was calculated as dry material. According to experimental data, a total amount of input data of 160 t/h is required for 50 t/h of IBA input [MUCH10], so an amount of input water of 175 t/h would be required for the 54.65 t/h of wet IBA produced at Greatmoor EfW.

[3] Cyclone Cut Size

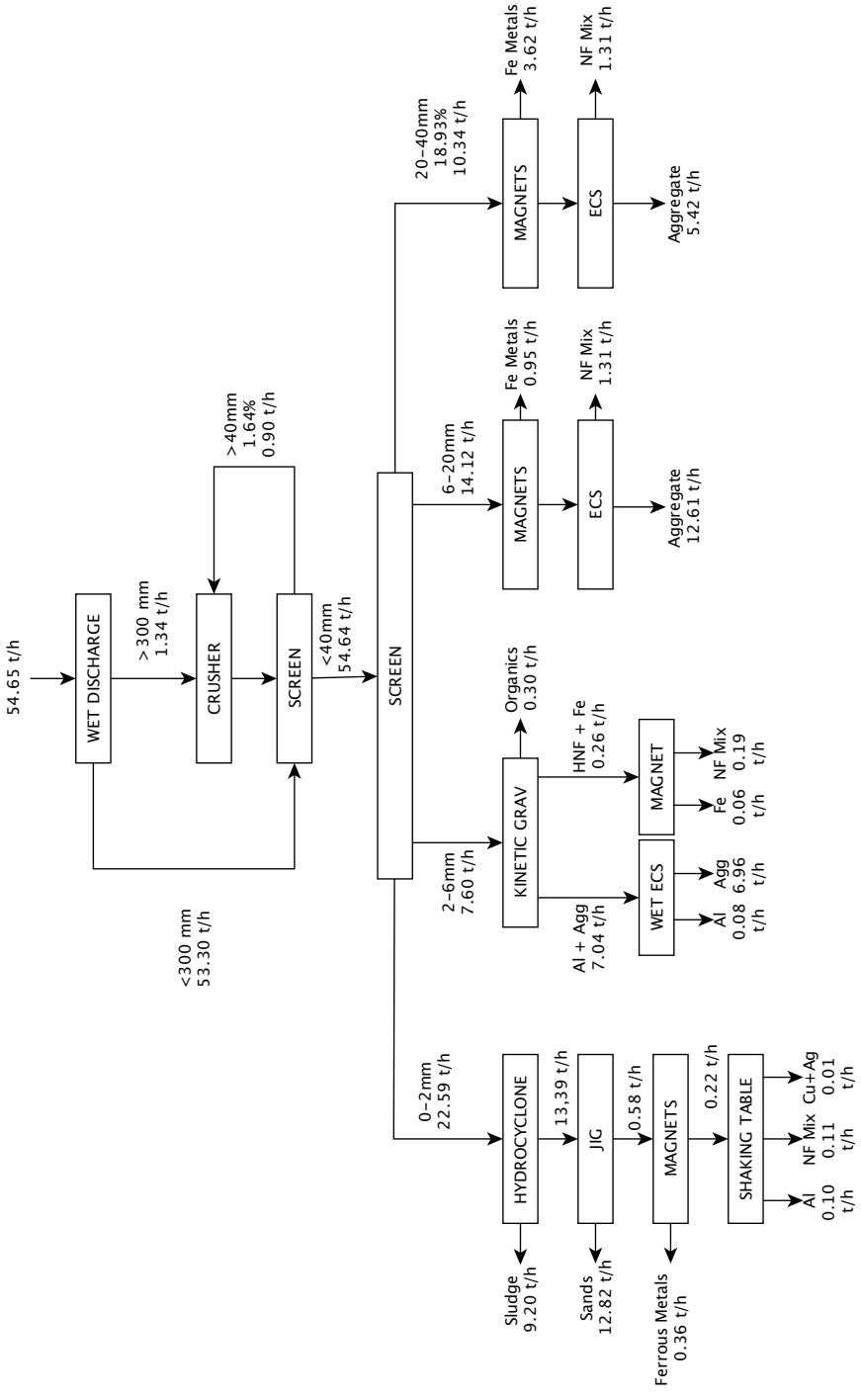

***Figure 6.8**: Scenario II wet separation base case*

3.1.1. Wet discharge

Wet IBA discharge would be performed as in the previous scenario and concurring with the current installation at Greatmoor EfW. This process would have the same effect on the IBA as explained before, due to the moisture content of 16.28%, the IBA throughput would increase from 45.75 to 54.65 t/h. Subsequently, the IBA changes its mass composition as shown in Table 5.1.

After discharge, a first separation of > 300 mm objects would be carried out by finger screening as it is currently performed on site. This fraction would be conveyed to be crushed to < 40 mm carried to the second screen. A second screen for the < 300 mm fraction separate IBA into > 40 mm and < 40 mm fractions, being the first one crushed down to < 40 mm. Once all particles would be < 40 mm, the bulk material would be screened again into 0-12 and 12-40 mm fractions for being treated separately which would increase the efficiency of the metal recovery process.

3.1.2. 0-2 mm fraction

The 0-2 mm fraction is the largest fraction from IBA containing 41.35% of the total wet IBA production. It contains valuable materials such as ferrous and non-ferrous metals which in turn contains very valuable heavy metals like Copper and Silver. The first issue would be to extract the <CCS material in the hydro-cyclone. The rest would then be driven to a jig prior magnetic and density separation.

Hydro-cyclone

As explained in Chapter 4, section 4.4 and commented earlier in this chapter, the hydro-cyclone would separate the very fine <CCS material that cannot be used as a building material. This fraction is extracted as sludge that should be further dewatered and landfilled. To calculate the mass flow, it was considered that the moist particles resulting from the wet discharge would be contained in this fraction. Extracted and remaining amounts are shown in Table 6.11.

***Table 6.11**: Scenario II wet separation 0-2 mm hydro-cyclone amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.03	2.49	0.56				1.03	4.15	0.56
Non-Fe	0.62	1.50	0.34				0.62	2.50	0.34
Agg.	39.70	96.01	21.69	16.28	98.34	8.90	23.41	94.46	12.79
Organics	0.27	0.66	0.15	0.27	1.66	0.15	0	0	0
Total	41.35	100	22.59	2.98	100	9.05	24.79	100	13.55

Jig

The remaining CCS-2 mm fraction would be then fed into the jig[4]. The denser particle would fall through the ragging and the screen whereas the sand products would flow over the jig and and would be separated by the cylindrical drum which helps to separate the light particles. The sand product should then be dewatered to decrease the leaching phenomena.

Experimental data from AEB Amsterdam show a separation efficiency for the heavy fraction of 65% [MUCH10]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.12.

***Table 6.12**: Scenario II wet separation 0-2 mm jig amounts*

Material	Income			Removed			Remaining		
	%T	**%F**	**t/h**	**%T**	**%F**	**t/h**	**%T**	**%F**	**t/h**
Ferrous	1.03	4.15	0.56	0.66	62.43	0.36	0.37	1.56	0.20
Non-Fe	0.62	2.50	0.34	0.40	37.57	0.22	0.22	0.94	0.12
Agg.	23.41	94.46	12.79				23.41	98.66	12.79
Total	24.79	100	13.55	1.06	100	0.58	24.79	100	12.97

Magnetic separation

The ferrous metals fraction would be separated by a wet concurrent tank drum magnetic separator, which principle has been explained in Chapter 4, section 2.2.3. This configuration is commonly used for particles from 0.5 up to 5 mm.

Experimental data from AEB Amsterdam show a rate recovery of 99% [MUCH10]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.13.

***Table 6.13**: Scenario II wet separation 0-2 mm magnetic separation amounts*

Material	**Income**			**Removed**			**Remaining**		
	%T	**%F**	**t/h**	**%T**	**%F**	**t/h**	**%T**	**%F**	**t/h**
Ferrous	0.66	62.43	0.36	0.65	100	0.36	0.01	1.63	0.00
Non-Fe	0.40	37.57	0.22				0.40	98.37	0.22
Total	1.06	100	0.58	0.65	100	0.36	0.40	100	0.22

Density separation

Density separation in this scenario would have similar characteristics as in the previous case. This density separation process would be performed a wet shaking that would separate the income mixture into 3 fractions according to the difference in density of the materials contained.

[4] See Chapter 5, section 4,1

Experiments performed with a wet shaking table for the 0-2 mm fraction demonstrate an accumulation of Copper up to 95% [WRAP08a], that will also be considered for Silver as it has a similar density. Aluminum accumulation is also demonstrated to be 98% [BÖNI13]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 6.14.

***Table 6.14**: Scenario II wet separation 0-2 mm density separation amounts*

Material	Income			Lights		
	%T	%F	t/h	%T	%F	t/h
Ferrous	0.01	1.63	0.00			
Non-Fe	0.40	98.37	0.22	0.18	100	0.10
Al	0.18	44.94	0.10	0.18	100	0.10
Cu	0.03	6.89	0.02			
Ag	0.0001	0.02	0.00			
Mix	0.19	46.52	0.10			
Total	0.40	100	0.22	0.18	100	0.10
Material	**Middlings**			**Heavies**		
	%T	%F	t/h	%T	%F	t/h
Ferrous	0.01	3.30	0.00			
Non-Fe	0.19	96.70	0.11	0.03	100	0.01
Al	0.00	2.00	0.002			
Cu	0.00	0.70	0.001	0.03	99.75	0.01
Ag	0.00	0.002	0.00	0.0001	0.25	0.00
Mix	0.19	94.00	0.10			
Total	0.20	100	0.11	0.03	100	0.01

3.1.3. 2-6 mm fraction

From the 2-6 mm fraction, which constitutes 13.63% in mass of the production of wet IBA, valuable products to be recovered would also be ferrous and non-ferrous metals, from which two streams would be obtained: Aluminum and a heavy non-ferrous metals mix. This fraction would be first treated by a KGS producing two streams: one containing Aluminum and aggregate that would be treated by a WECS and another consisting on ferrous and heavy non-ferrous metals that would be separated by a magnetic separator.

Kinetic gravity separation

As mentioned, the KGS would remove the organics from the bulk material and produce two different streams: a heavy metal stream (ferrous and heavy non-ferrous metals) and an Aluminum/aggregate stream. The KGS operating principle is based on the difference in the particles terminal velocity, which depends on the density, size and shape of those particles.

Experiments performed by Delft University with a KGS at AEB Amsterdam show a rate of recovery of the heavy metals fraction of 88% [MUCH10], being the rest contained in the Aluminum/aggregate fraction. Organics would be fully removed in the light fraction. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.15.

***Table 6.15**: Scenario II wet separation 2-6 mm KGS amounts*

Material	Income			Organics		
	%T	%F	t/h	%T	%F	t/h
Ferrous	0.14	1.00	0.07			
Non-Fe	0.52	3.80	0.28			
Al	0.12	0.86	0.06			
Cu	0.03	0.22	0.02			
Ag	0.0002	0.002	0.0001			
Mix	0.37	2.71	0.20			
Agg.	12.70	93.18	6.94			
Organics	0.28	2.02	0.15	0.28	100	0.15
Total	13.63	100	7.45	0.28	100	0.10

Material	Al + Agg.			Heavies		
	%T	%F	t/h	%T	%F	t/h
Ferrous	0.02	0.13	0.01	0.12	25.35	0.07
Non-Fe	0.17	1.28	0.09	0.35	74.65	0.19
Al	0.12	0.91	0.06			
Cu	0.00	0.03	0.00	0.03	5.69	0.01
Ag	0.00	0.00	0.00	0.0002	0.04	0.0001
Mix	0.04	0.34	0.02	0.33	68.91	0.18
Agg.	12.70	98.59	6.94			
Organics						
Total	12.88	100	7.04	0.47	100	0.26

Wet eddy current separation

The Aluminum/aggregate fraction would be treated by a WECS, which shows higher recovery rates for small fractions than dry eddy current separators [REM98]. The principle is to add water at the feeding point to stick all the small particles to the belt surface. This adhesive force is of the same order as gravity. The rotating magnetic field would make the conductive particles spin, breaking the water bonds between these particles and the belt. The principle of operation is detailed in Chapter 4, section 3.2.2.

Experimental data shows an efficiency of 85% in this process for the recovery of Aluminum [MUCH10]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.16.

***Table 6.16**: Scenario II wet separation 2-6 mm WECS amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.02	0.13	0.01				0.02	0.13	0.01
Non-Fe	0.17	1.28	0.09	0.14	100	0.08	0.02	0.19	0.01
Agg.	12.70	98.59	6.94				12.70	99.68	6.94
Total	12.88	100	0.58	0.14	100	0.08	12.74	100	6.96

Magnetic separation

The ferrous metals fraction would be separated from the heavy metals stream by a wet concurrent tank drum magnetic separator as used in the 0-2 mm fraction.

Experimental data from AEB Amsterdam show a rate recovery of 99% [MUCH10]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.17.

***Table 6.17**: Scenario II wet separation 2-6 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.12	25.35	0.07	0.12	100	0.06	0.00	0.34	0.00
Non-Fe	0.35	74.65	0.19				0.35	99.66	0.19
Total	0.47	100	0.26	0.12	100	0.06	0.35	100	0.19

3.1.4. 6-20 mm fraction

The 6-20 mm fraction represents 25.84% in mass of total production of wet IBA. Ferrous and non-ferrous metals from this fraction would be separated by conventional magnetic and eddy current separation since the size of the particles allows acceptable rates of recovery.

Magnetic separation

Extraction of the magnetic, ferrous fraction will be performed by a single ferrite dry top feed drum separator since the particle size allows high-rate recovery with this equipment and this configuration is suitable for small amounts of ferrous metals in the mixture (about 7%).

An average rate of recovery for this equipment and this particle size fraction is 96% [MUCH10]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.18.

***Table 6.18**: Scenario II wet separation 6-20 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.81	7.00	0.99	1.74	100	0.95	0.07	0.28	0.04
Non-Fe	1.14	4.42	0.62				1.14	4.38	0.62
Agg.	22.89	88.58	12.51				22.89	87.78	12.51
Total	25.84	100	14.12	1.74	100	0.95	24.10	100	13.17

Eddy current separation

As happens in the case of the ferrous metals, this particle size fraction allows acceptable recovery rates with a regular dry ECS.

Experimental reports of ECS performing in this size fraction detail a recovery rate of 88% [MUCH10]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 6.19.

Table 6.19: Scenario II wet separation 6-20 mm ECS amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.07	0.28	0.04				0.07	0.31	0.04
Non-Fe	1.14	4.38	0.62	1.04	100	0.57	0.11	0.46	0.06
Agg.	22.89	87.78	12.51				22.89	99.23	12.51
Total	24.10	100	13.17	1.04	100	0.57	23.07	100	12.61

3.1.5. 20-40 mm fraction

The 20-40 mm represents 18.93% of the total wet IBA production. The main interest resides on the removal of metals, ferrous and non-ferrous. Like in the 6-20 mm fraction, the particle size does not allow to perform further separation of the non-ferrous metal fraction.

Magnetic separation

Ferrous metal separation would be performed by a single cross-belt suspended magnet, more suitable for large objects and a high content of ferrous metals (35% of total fraction) than drum separators. The configuration for this piece of equipment would be the same as in the other scenarios.

For this configuration and material size fraction, very high recovery rates are obtained. As an average an efficiency of 99% will be taken [SVOB04]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 6.20.

Table 6.20: Scenario II wet separation 20-40 mm magnetic separation amounts

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	6.69	35.35	3.66	6.62	100	3.62	0.07	0.54	0.04
Non-Fe	2.43	12.84	1.33				2.43	19.75	1.33
Agg.	9.81	51.81	5.36				9.81	79.71	5.36
Total	18.93	100	10.34	6.62	100	3.62	14.70	100	6.72

Eddy current separation

As happens in the case of the ferrous metals, this particle size fraction allows acceptable recovery rates with a regular ECS [SVOB04].

Experimental reports of ECS performing in this size fraction detail a recovery rate of 98.40% [DEVR09]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 6.21.

***Table 6.21**: Scenario II wet separation 20-40 mm ECS amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.07	0.54	0.04				0.07	0.67	0.04
Non-Fe	2.43	19.75	1.33	2.39	100	1.31	0.04	0.39	0.02
Agg.	9.81	79.71	5.36				9.81	98.93	5.36
Total	14.70	100	6.72	2.39	100	1.31	9.91	100	5.42

3.1.6. Summary

The total amount of products and overall recovery rate of this process is summarized in Table 6.23. Note that the amount of Al, Cu and Ag include in the table is the one to be sold does not meet the total amount recovered since the non-ferrous fraction would be only separated in the 0-2 and 0-6 mm fractions. The difference is distributed in the non-ferrous metal mix of the other two fractions.

***Table 6.22**: Scenario II wet separation total products and overall recovery rates*

Material	%T	t/y	% recovery
Ferrous	9.13	8,180.72	94.61
Non-ferrous	4.18	3,744.40	88.69
Al	0.28	248.15	15.53
Cu	0.03	23.63	13.35
Ag	0.0001	0.06	13.19
Mix	3.87	3,472.56	
Aggregate	69.72	62,465.91	
Sludge	16.56	15,204.37	
Total	100	89,595.40	

From the total amount of ferrous metals contained originally in the IBA, the 94.61% is to be sold. In the case of non-ferrous metals 88.69% is to be sold, where the rates of "pure" Al, Cu and Ag to be sold separately are 15.53%, 13.35% and 13.19% respectively. The rest is contained in the non-ferrous mix and would be sold as it is being 1.71 t/h. 69.72% of the initial amount considered aggregate and 16.56% in mass of IBA would be sludge extracted by the hydro-cyclone and the jig.

Since this case is already the optimized configuration for the wet separation process [MUCH10], no alternative case was considered. Economic feasibility analysis is detailed in Chapter 8.

3.2. Extra considerations

This wet separation process differs from the previous ones in that water would be added in several steps of the process. This would cause and alteration in the leaching data of the aggregate to be landfilled changing the emission values to the soil.

Leaching values are strongly influenced by the quality of the process water and the amount of water used [MUCH10]. Levels of the critical leaching elements in Greatmoor EfW IBA aggregate can be reduced to below the leaching limits by reducing the amount of free ions, organics and fine particles that can me performed by increasing the amount of water used in the process, and using an extra washing system at the end of each separation of materials to be landfilled. The quality of the water should be also controlled by measuring its conductivity (which is currently being done at Greatmoor EfW).

In addition, a sludge treatment stage is installed at AEB Amsterdam to recover sand products that are suitable to being used in construction. Since the matter of study of this thesis is metal recovery, this stage was not analyzed.

These considerations have to be studied deeply if this process is intended to be installed. Leaching values can be predicted based on the existing historical data but just as an indicator, being the real operational values obtained once the process is installed the ones to be used for calculating water flows and other parameters affecting the process.

Chapter 7

Scenario III – Dry discharge and conventional separation

1. Introduction

The third scenario analyzed consists on the installation of a dry discharge process instead of the existing wet discharge. Then, due to the absence of moist particles in the IBA, separation process can be performed using conventional methods reaching high-grade recoveries even for < 1 mm particles.

This technology is mainly beneficial in the extraction of metals from the fine fraction where, as it can be seen in Scenario I and Scenario II, problems appear due to the moisture content that would be avoided in this scenario. In addition, this process would have further benefits:

- No wastage of water as cooling process is performed by air.
- Lower organic content in the bottom ash as combustion is not stopped by quenching process.
- Significant reduction of the leaching rate of stockpiled bottom ash.
- Transport costs reduced as there is no water content.
- Chemical reactions (maturing, ageing, etc.) can be activated when required by adding water under controlled circumstances.

As usual, it also has disadvantages as the dust emission generated by the very fine dry bottom ash particles that required special treatment. However, it is a minor problem as most of dry discharge suppliers provide solutions to this problem as a closed transport system.

The model for IBA extraction and treatment to be proposed in the following sections is similar to the process currently installed in KEZO[1] Hinwill plant (Switzerland). This waste management authority was founded in 1961 and covers an area with around 322,000 inhabitants generating 200,000 tons of waste per year. The original design counted with a wet discharge system as it is commonly used in the industry but, due its low efficiency in metal recovery, a dry discharge

[1] Kehrichtverbrennung Zürcher Oberland

process was installed resulting in a metal separating efficiency that exceeds 95% in comparison with around 30% obtained with wet discharge for the small fraction [ZAR12].

2. Operating principle

The treatment process in KEZO consists on a dry extractor prior the separation plant, where metals are separated from the 0.7 – 5 mm IBA fraction. An additional plant for > 5 mm IBA treatment is being built at the moment also with investigations for recovering metals from the 0.1 – 0.7 mm fraction. Figure 7.1 shows a flowchart with the current IBA path in KEZO. Each step is to be explained in the following sub-sections.

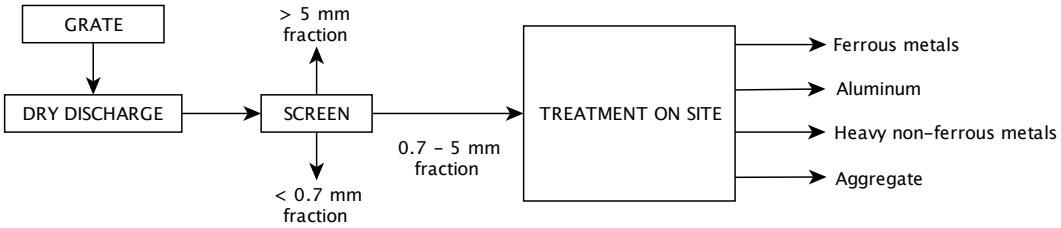

Figure 7.1: KEZO IBA path

2.1. Dry discharge

IBA passes through an ash drum and a set of flaps that serves to reduce the air flow through the system. The ash is then discharged onto a vibrating conveyor[2] designed to withstand the high temperatures with which IBA exits the furnace.

IBA is air-cooled during discharge by injection of "tertiary air", an additional process variable for this system. However, the air in the furnace is not increased as the secondary air is reduced by the amount of tertiary air used in the dry process. Tertiary air also supports further burning of unburned particles in the IBA which, in the case of Greatmoor EfW IBA is 0.66% mass of IBA using wet discharge. Very fine particles causing dust are returned to the furnace by the tertiary air flow. The dry discharge air-cooling principle is shown in Figure 7.2.

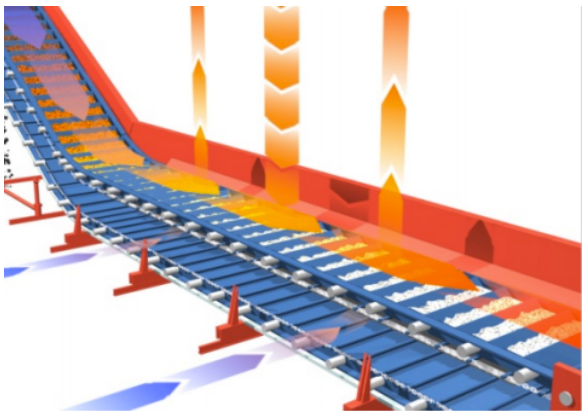

Figure 7.2: Dry discharge air-cooling principle, Clyde Bergemann

[2] There are also belt conveyor solutions in the market.

The vibrating conveyor transports the IBA at the end of the discharge to a first screen that separates coarse > 5 mm particles to be further treated off site. A second screen separates the < 0.7 mm fraction that is temporary stored in a silo. The 0.7 – 5 mm is treated on site and metals are recovered in high-rate.

2.2. IBA treatment on site

The IBA separation treatment is based on conventional magnet and eddy current separators, for ferrous and non-ferrous metals separation respectively, with density separators at the end to further separation of light and heavy non-ferrous metals.

The 0.7 – 5 mm fraction passes to two in-series neodymium magnets, which is proven to increase efficiency [ZAR11], to remove all the ferrous particles. It is important to remove these particles as they would disturb the magnetic field in the eddy current separators and lower their efficiency consequently.

The remaining non-ferrous metals and mineral fraction passes to two in-series eddy current separators which separates the non-ferrous metals. The mineral fraction is transported to a storage silo and the non-ferrous metals fraction conveyed for further treatment.

Non-ferrous metals fraction is screened in two fractions, 0.7 – 3 mm and 3 – 5 mm, for better efficiency and then passed to density separation tables, which separates non-ferrous metals in a light fraction (Aluminum) and a heavy fraction (precious metals).

The entire facility is a “tunnel-type” separation process with the objective of controlling dust emissions. Figure 7.3 shows the last steps of the separation process.

***Figure 7.3**: KEZO metal recovery facility [ZAR11]*

In the following section, an adaptation of this process for Greatmoor EfW facility is analyzed. All efficiencies have been obtained from experiments carried out for KEZO IBA treatment and applied for Greatmoor EfW IBA to evaluate its results and support the analysis.

3. Process

3.1. Base case

A schematic of the base case of this process is shown in Figure 7.4 which includes the mass flows calculated. IBA would be dry discharged and air-cooled while conveyed prior treatment for metal recovery. Then a first screen would be performed to separate the > 300 mm materials that would be shredded and reinserted in the system. Then, a second screen would do the same with > 40 mm particles for further shredding and being reinserted in the system too. This would make sure that all particles have a correct size to be processed. Particles < 40 mm would be then screened into three fractions: 0-6 mm, 6-20 mm and 20-40 mm.

The 0-6 mm fraction would be first treated by magnetic separation for ferrous metal removal. Then it would be driven to ECSs for non-ferrous metal removal. The residue of this process would not be further treated. The non-ferrous metal fraction extracted would be screened into 0-2 mm and 2-6 mm fractions for obtaining better efficiency and then treated separately by density separators to separate the light fraction, mainly Aluminum; middlings, a non-ferrous metal mix; and the heavy fraction, mainly Copper and Silver.

The 6-20 mm fraction would be first treated by magnetic separation for ferrous metal removal prior eddy current separation for recovery of non-ferrous metal fraction which would not be further separated.

The 20-40 mm fraction treatment would be the same as for the 6-20 mm fractions. The reason for being treated separately is to increase recovery efficiency. Since both ferrous and non-ferrous metal concentrations is higher for this fraction and bigger practices are to be recovered, magnetic separation technique would be different than the one used in other fractions.

In all cases, recovered material is calculated as “pure” as there is no way to predict the amount of impurities contained in each fraction. The grade of the material recovered can affect its price and has to be considered before selling.

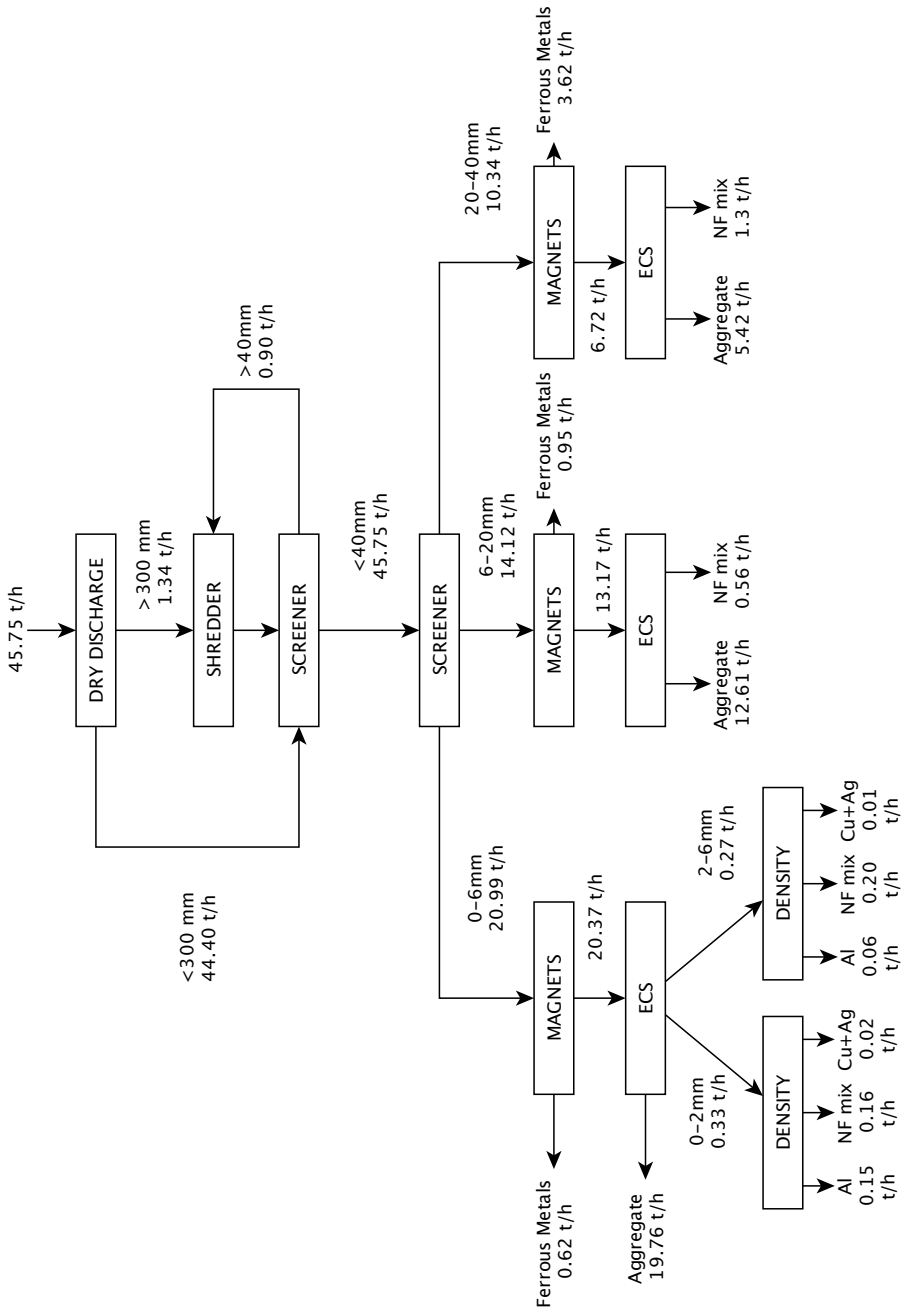

***Figure 7.4**: Scenario III base configuration*

3.1.1. Dry discharge

There are several options in the market for dry IBA discharge (Magaldi Group, United Conveyor Corporation, HZI, …). As an example, information of the Magaldi ECOBELT® supplied by Magaldi Group was obtained. This extraction system would perform in the same way as explained in section 2.1 of this chapter and its detailed information can be seen in Appendix B.

Figure 7.5: Magaldi ECOBELT®

After discharge, a first separation of > 300 mm objects would be carried out by finger screening as it is currently performed on site. This fraction would be conveyed to be crushed to < 40 mm carried to the second screen. A second screen for the < 300 mm fraction separate IBA into > 40 mm and < 40 mm fractions, being the first one crushed down to < 40 mm. Once all particles would be < 40 mm, the bulk material would be screened again into 0-6 mm, 6-20 mm and 20-40 mm fractions for being treated separately which would increase the efficiency of the metal recovery process.

3.1.2. 0-6 mm fraction

The 0-6 mm fraction is the largest fraction from IBA constituting over 45% of the total production. It contains valuable materials such as ferrous, non-ferrous metals and, in a major concentration, aggregate but also some undesired components like organics. The most interesting products of this fraction is the Aluminum and heavy metals content, such as Copper and Silver. In order to obtain the maximum amount possible of the mentioned products, magnetic, eddy current and density separation processes would be performed.

Magnetic separation

The ferrous metals fraction, also called magnetic fraction, would be separated by two in series NdFeB-based top feed drum magnetic separators. This configuration is due to the small size of the particles in this fractions that would be hinder the recovery. It would double the length of the working zone[3] of the process and thus increase its efficiency and is the most suitable for mixtures with small amounts of magnetic particles (about 3% in this case).

[3] See Chapter 4, section 2.1

Experiments performed by ZAR[4] at KEZO plant ensures a metal recovery efficiency of 98% [ZAR12]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 7.1.

***Table 7.1**: Scenario III 0-6 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	1.39	2.99	0.64	1.36	100	0.62	0.03	0.06	0.01
Non-Fe	1.36	2.92	0.62				1.36	3.01	0.62
Agg.	43.13	94.00	19.73				43.13	95.48	19.73
Organics	0.66	0.00	0.00				0.66	1.45	0.30
Total	46.54	100	21.29	1.36	100	0.62	44.52	100	20.37

Eddy current separation

Non-ferrous metals fraction separation would be performed by two in-series dry eddy current separators. Experiments performed at KEZO plant demonstrate that this configuration, also with an inclined position of the ECS increase notably the efficiency of the process and will be taken as a base configuration [ZAR11]. This configuration is shown in Figure 7.6.

Experiments performed by ZAR at KEZO plant ensures a metal recovery efficiency of 96.83% [ZAR11]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 7.2.

***Figure 7.6**: Two in series inclined ECS configuration [ZAR11]*

[4] Zentrum Für Nachhaltige Abfall-Und Ressourcennutzung

***Table 7.2**: Scenario III 0-6 mm ECS separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.03	0.06	0.01				0.03	0.06	0.01
Non-Fe	1.36	3.01	0.62	1.32	100	0.60	0.04	0.10	0.02
Agg.	43.13	95.48	19.73				43.13	98.34	19.73
Organics	0.66	1.45	0.30				0.66	1.50	0.30
Total	45.18	100	20.67	1.32	100	0.60	43.86	100	20.07

Density separation

Density separation in this scenario would have similar characteristics as in the previous cases. Prior treatment, the entire fraction would be screened into two fractions, 0-2 mm and 2-6 mm, for improving the separation efficiency which would be higher in the 0-2 mm fraction due to the equipment characteristics.

Experiments performed with a wet shaking table for the 0-2 mm fraction demonstrate an accumulation of Copper in the heavy fraction up to 95% [WRAP08a], that will also be considered for Silver as it has a similar density. Aluminum accumulation is also demonstrated to be 98% [BÖNI13]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 7.3.

Table 7.3: Scenario III 0-2 mm density separation amounts

Material	Income			Lights		
	%T	%F	t/h	%T	%F	t/h
Al	0.33	45.69	0.15	0.32	100	0.15
Cu	0.05	7.00	0.02			
Ag	0.0001	0.02	0.0001			
Mix	0.34	47.29	0.16			
NF Total	0.72	100	0.33	0.32	100	0.15
Material	**Middlings**			**Heavies**		
	%T	%F	t/h	%T	%F	t/h
Al	0.01	2.07	0.00			
Cu	0.00	0.72	0.00	0.05	99.75	0.02
Ag	0.00	0.002	0.00	0.0001	0.25	0.0001
Mix	0.34	97.21	0.16			
NF Total	0.35	100	0.16	0.05	100	0.02

For the 2-6 mm fraction, experimental data details an accumulation rate of 98% for Aluminum and about 80% for Cu and Ag [BÖNI13]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 7.4.

Table 7.4: Scenario III 2-6 mm density separation amounts

Material	Income			Lights		
	%T	%F	t/h	%T	%F	t/h
Al	0.14	22.68	0.06	0.13	100	0.06
Cu	0.04	5.90	0.02			
Ag	0.0003	0.04	0.0001			
Mix	0.43	71.38	0.20			
NF Total	0.60	100	0.27	0.13	100	0.06

Material	Middlings			Heavies		
	%T	%F	t/h	%T	%F	t/h
Al	0.00	0.68	0.00			
Cu	0.01	1.61	0.00	0.03	99.25	0.01
Ag	0.0001	0.01	0.00	0.0002	0.75	0.0001
Mix	0.43	97.69	0.20			
NF Total	0.44	100	0.20	0.03	100	0.01

3.1.3. 6-20 mm fraction

The 6-20 mm fraction is the second in amount of material with about 30.87% of the total IBA production. The interest of this fraction resides in the ferrous and non-ferrous metal fractions. The non-ferrous metal fraction is not further separated since the size of the particles exceeds the density separation limitations for acceptable recoveries and would be sold as a non-ferrous mix at an agreed price. The remaining material is considered aggregate.

Magnetic separation

Extraction of the magnetic, ferrous fraction will be performed by a single ferrite dry top feed drum separator since the particle size allows high-rate recovery with this equipment and this configuration is suitable for small amounts of ferrous metals in the mixture (about a 4.5%).

An average rate of recovery for this equipment and this particle size fraction is 96% [SVOB04]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 7.5.

***Table 7.5**: Scenario III 6-20 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	2.16	7.00	0.64	1.74	100	0.95	0.09	0.30	0.04
Non-Fe	1.36	4.42	0.62				1.36	4.74	0.62
Agg.	27.34	88.58	12.51				27.34	94.96	12.51
Total	30.87	100	14.12	1.74	100	0.95	28.79	100	13.17

Eddy current separation

As happens in the case of the ferrous metals, this particle size fraction allows acceptable recovery rates with a single dry ECS [SVOB04].

Experimental reports of ECS performing in this size fraction detail a recovery rate of 90.8% for a single piece of equipment [DEVR09]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 7.6.

***Table 7.6**: Scenario III 6-20 mm ECS amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.09	0.30	0.04				0.09	0.31	0.04
Non-Fe	1.36	4.74	0.62	1.23	100	0.56	0.14	0.49	0.06
Agg.	27.34	94.96	12.51				27.34	99.19	12.51
Total	28.79	100	13.17	1.23	100	0.56	27.56	100	12.61

3.1.4. 20-40 mm fraction

The 20-40 mm represents 22.61% of the total IBA production. The main interest resides on the removal of metals, ferrous and non-ferrous. Like in the 6-20 mm fraction, the particle size does not allow to perform further separation of the non-ferrous metal fraction.

Magnetic separation

Ferrous metal separation would be performed by a single cross-belt suspended magnet, more suitable for large objects and a high content of ferrous metals (35% of total fraction) than the drum separators.

For this configuration and material size fraction, very high recovery rates are obtained. As an average an efficiency of 99% will be taken [SVOB04]. Based on this recovery rate, extracted and remaining amounts of this process are shown in Table 7.7.

***Table 7.7**: Scenario III 20-40 mm magnetic separation amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	7.99	35.35	3.66	7.91	100	3.62	0.08	0.54	0.04
Non-Fe	2.90	12.84	1.33				2.90	19.75	1.33
Agg.	11.71	51.81	5.36				11.71	79.71	5.36
Total	22.61	100	10.34	7.91	100	3.62	14.70	100	6.72

Eddy current separation

As happens in the case of the ferrous metals, this particle size fraction allows acceptable recovery rates with a single dry ECS [SVOB04].

Generic state-of-art equipment would be used, which assumed fixed and operation costs are specified in Chapter 8.

Experimental reports of ECS performing in this size fraction detail a recovery rate of 98.40% for a single machine [DEVR09]. Based on this recovery rates, extracted and remaining amounts of this process are shown in Table 7.8.

***Table 7.8**: Scenario III 20-40 mm ECS amounts*

Material	Income			Removed			Remaining		
	%T	%F	t/h	%T	%F	t/h	%T	%F	t/h
Ferrous	0.08	0.54	0.04				0.08	0.67	0.04
Non-Fe	2.90	19.75	1.33	2.84	100	1.30	0.06	0.49	0.03
Agg.	11.71	79.71	5.36				11.71	98.84	5.36
Total	14.70	100	6.72	2.84	100	1.30	11.85	100	5.42

3.1.5. Summary

The total amount of products and overall recovery rates of this process are summarized in Table 7.9. As is previous cases, the amount of Al, Cu and Ag include in the table is the one to be sold does not meet the total amount recovered since the non-ferrous fraction would be only separated in the 0-6 mm fraction. The difference is distributed in the non-ferrous metal mix of the other two fractions.

***Table 7.9**: Scenario III total products and overall recovery rates*

Material	%T	t/y	% recovery
Ferrous	11.35	8,513.52	98.46
Non-ferrous	5.39	4,039.87	95.78
Al	0.45	339.77	21.27
Cu	0.08	56.95	32.17
Ag	0.0003	0.26	54.95
Mix	4.86	3,642.89	
Aggregate	83.28	62,446.61	
Total	100	75,000	

From the total amount of ferrous metals contained originally in the IBA, the 98.46% is to be sold. In the case of non-ferrous metals 95.78% is to be sold, where the rates of “pure” Al, Cu and

Ag to be sold separately are 21.27%, 32.17% and 54.95% respectively. The rest is contained in the non-ferrous mix and would be sold as it is being 1.79 t/h. The remaining 83.28% of the products is considered aggregate.

3.2. Alternative case

In the base case, the 0-6 mm fraction would pass through two in series magnetic separators and two in series ECSs, which is proven to raise efficiency. An alternative configuration, where those two in series separation equipment in each case would be switched for just one. This configuration would make the recovery efficiencies of those process from 98% to 85.86% in magnetic separation and from 96.83% to 82.20% in eddy current separation but would also decrease the initial investment. A schematic for this configuration is shown in Figure 7.7. Total amounts of products recovered is shown in Table 7.10.

***Table 7.10**: Scenario III alternative case total products and overall recovery rates*

Material	**%T**	**t/y**	**% recovery**
Ferrous	11.18	8,386.64	96.99
Non-ferrous	5.19	3,890.54	92.24
Al	0.38	288.49	18.06
Cu	0.06	48.35	27.31
Ag	0.0003	0.22	46.65
Mix	4.09	3,553.48	
Aggregate	83.65	62,722.82	
Total	100	75,000	

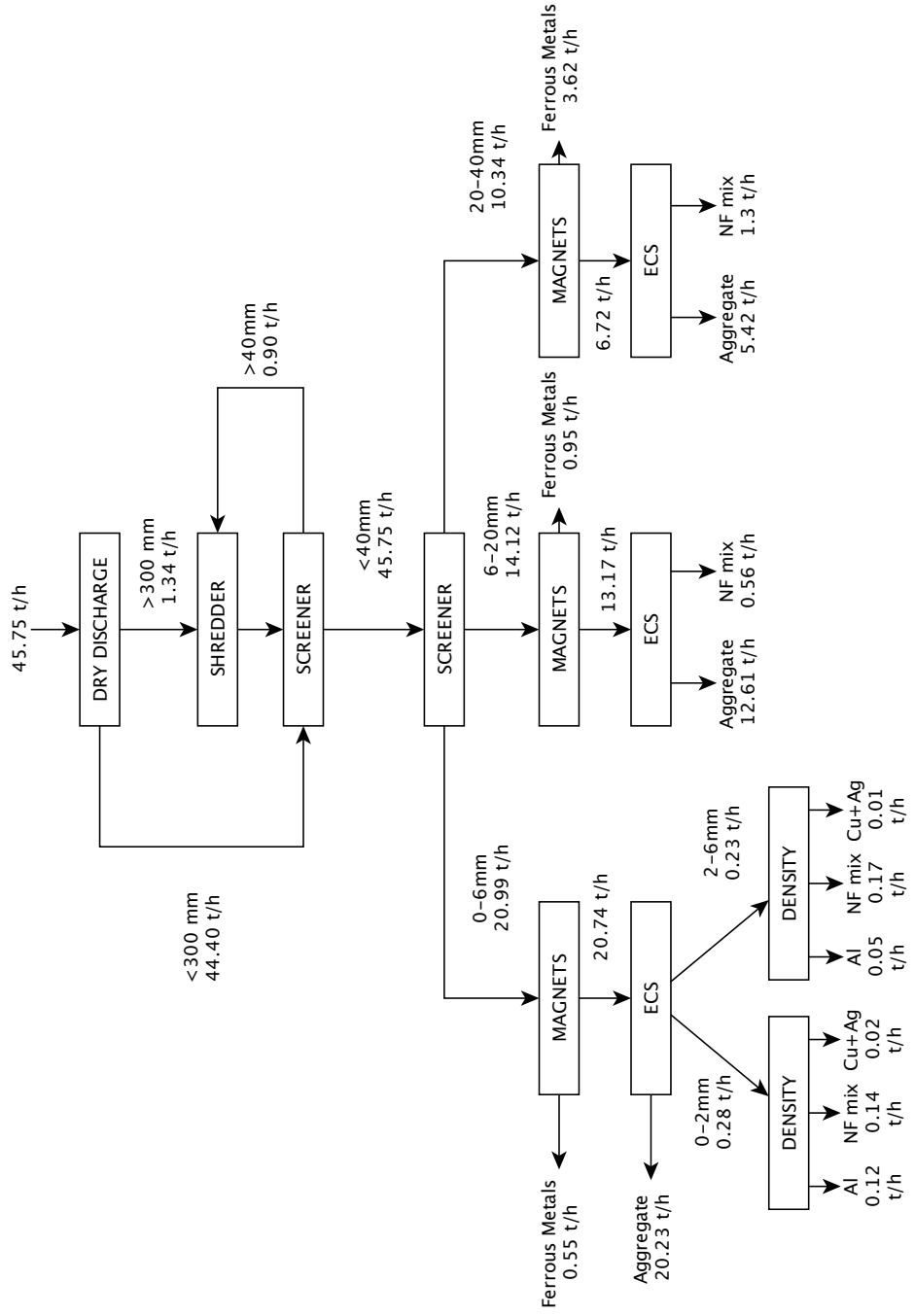

Figure 7.7: Scenario III alternative case schematic

3.3. Optimal case

The final results of both cases are shown in Table 7.11.

Table 7.11: Scenario III summary

	Base case	Alternative case
Ferrous metals recovery rate	98.46%	96.99%
Non-ferrous metals recovery rate	95.78%	92.24%
Pure Aluminum recovery rate	21.27%	18.06%
Pure Copper recovery rate	32.17%	27.31%
Pure Silver recovery rate	54.95%	46.65%

Once again, from the technical point of view the best case is the base case since it has higher rates of recovery. Economic feasibility analysis is detailed in the following chapter and is used to support this selection.

Chapter 8

Economic analysis

1. Introduction

This chapter includes the economic feasibility analysis of each scenario. Its importance resides in the fact that no project is appropriate if it is not profitable, even if it satisfies the required technical performance. Accordingly, it is very common in project engineering that the engineering unit is monetary and not in means of power.

1.1. Assumptions

In order to carry out this economic feasibility analysis and due to the limited information available, the following assumptions have been taken:

- Due to the transferability of the processes, specific costs related to the characteristics of the plant have been calculated using different ratios but not in an exact manner. These include:
  - Civil costs.
  - Staff costs.
  - Planning and permitting costs.
  - Power installation costs, electrical equipment, alternative diesel supply, etc.
  - Costs related with vehicles.
  - Specific tools costs.
  - Basic spares costs.
  - Transport costs.
  - Land costs.
  - Dust, noise and other assessments costs.
  - Other costs specifically related with the characteristics of the plant or the land where the process is to be installed.
- Currency exchange market analysis not included and constant pound sterling value taken is 1.44 US$/£. All cash flows calculated in pound sterling units.
- Maintenance access, purchase, delivery, positioning and other costs related to equipment not analyzed and calculated as “contingency costs” as a percentage of the related investment and specified in the corresponding section.

- Maintenance and life cycle costs calculated as a percentage of the related investment and specified in the corresponding section.
- Metal pricing included in this analysis is indicative. The final price at which recovered material is to be sold will depend on the contract with the purchasers.
- Equipment pricing included in this analysis is indicative and will depend on the contract with the corresponding supplier.

All assumptions are suitable to change if considered. As they are equally applied to all cases, any change would affect proportionally.

1.2. Case 0

The initial case which will be considered as a starting point in the calculations of the cash flows in each scenario would be the current installations and activities at Greatmoor EfW. Characteristics of this case are detailed below:

- IBA extraction system (either wet or dry) included in the plant's budget and thus not considered in the IBA treatment plant required investment. Also its power, maintenance and other operating costs are not considered.
- Extracted IBA is entirely landfilled and thus the amount of material recovered would have an extra revenue being this last the saved cost of this material to be landfilled.
- The rest (investments, operating costs, specific revenues, taxes, etc.) would be included in the cash flows of each scenario.

2. Costs

2.1. Fixed costs

Fixed costs in each scenario would include the investments in the required equipment for each process. Those investments would be made at the beginning of the project (year 0) in order to obtain long-term profitability and is also known as the CAPEX[1] of the project.

In the term CAPEX it has to be distinguished between fixed assets, INV[2], and total investment, which will be named as CAPEX for now on, which ads commissioning, working capital and intangible costs to INV among others. INV has two components:

- Direct costs, DC, which include all costs related to permanent equipment. It has two components:
  - Site costs, SC: equipment, instrumentation and control and electrical installations.
  - Not site costs, NSC: ground, civil, structures and architecture costs.
- Indirect costs, IC, which include engineering, supervision, construction and contingency costs.

[1] Capital Expenditures
[2] Investment

For the economic calculations in this thesis, several ratios based on experience will be used [BEJA96]:

$$CAPEX = 1.47 \cdot INV$$

Equation 8.1

$$INV = DC + IC$$

Equation 8.2

$$IC = 0.25 \cdot DC$$

Equation 8.3

$$DC = SC + NSC$$

Equation 8.4

$$NSC = 0.45 \cdot SC$$

Equation 8.5

Combining the previous three equations,

$$CAPEX = 2.66 \cdot DC$$

Equation 8.6

2.2. Variable costs

Variable costs would include operating costs required for each IBA treatment plant to perform. This costs would be distributed yearly during the length of the project. Variable costs include:

- Power costs, depending on the installed power of each scenario.
- Maintenance costs, calculated in each case as

$$MC = 0.1 \cdot CAPEX$$

Equation 8.7

- Life cycle costs, which is required for the waste management assessment, calculated in each case as

$$LC = 0.04 \cdot CAPEX$$

Equation 8.8

- Water costs, which will be taken into account in the wet separation process proposed in Scenario II.
- Silver refining, based on an average price per ton.

2.3. Depreciation

Depreciation is the decrease in value of an asset (equipment in this case) during the length of the project. It is non-cash expense and only relevant due to tax affects. It allows a tax deduction each year, usually referred to as a capital allowance, outlined in the Capital Allowances Act 2001[3].

[3] Parliament of the United Kingdom

In this thesis, depreciation will be considered using a 7-years MACRS[4] model, commonly used in industrial equipment. It is performed by multiplying the CAPEX by the percentages specified in Table 8.1.

Table 8.1: 7-years MACRS depreciation model

Year	%	Year	%
1	14.29	5	8.93
2	24.49	6	8.93
3	17.49	7	8.93
4	12.49	8	4.46

3. Revenues

3.1. Revenues from metals

Selling the recovered metals for further use is the main source of revenue from the selected IBA processing technology. Its importance resides in the fact that it will set whether it is worth to invest on it or not.

Metal pricing is, with the amount of metal recovered, the most important variable of this section. In these terms, a forecast for the price of the main materials have been done taking into account the price time series, tendency and seasonality in each case.

In the following section it will be explained the followed method for the development of the best predictive model in each case.

3.1.1. Metal price forecasting model

Prices forecasting model has been developed by analyzing the time series of the prices of each material likely to be sold: Fe, Al, Ag and Cu. A time series is a sequence of observations which are ordered in time and collected at regular intervals. In this case, the observations are the market prices at the end of each year [LME16] [TWB16] [TRAD16] [LETS16] [USDI99]. Time series analysis is a statistical tool that allows to set a model of behavior in time of, in this case, an economic variable.

The main purpose is to make a prediction of the values of metal prices according to their past behavior. The horizon validity is normally quite short and it gets longer as the amount of past observations considered in the modeling process increases. According to literature, acceptable forecasting can be made for a temporal horizon from 1/7 to 3/7 of the time during which observations are taken [LINA03]. Then, metal prices at the end of the year have been taken from 1980 to 2015 including the closing price for March 2016 as the last value, which allows to perform

[4] Modified Accelerated Cost Recovery System

good forecasting for 5-15 years. The ferrous metal fraction is to be sold as light Iron scrap which collected data includes year from 2000 to 2016. In that case, good forecasting can be calculated from 2 to 7 years.

It has been followed a quantitative methodology taking into account the tendencies (fundamental evolution of the variable) and its seasonality (oscillatory movements around the tendency with a fixed period).

As it can be seen in Figures 8.1 to 8.4, prices evolutions in time show tendency to increase in all cases. In contrast, there is no clear seasonality and it will not be considered as it would depend on economic variables that are not subject of study in this thesis. Complete data of these graphs can be seen in Appendix C.

Accordingly, linear tendency models without seasonality are considered. More specifically, double exponential smoothing, moving mean with linear regression and Holt models for each case were calculated, selecting the one that minimizes the quadratic error. To avoid repetitive calculations, the general calculation process will be explained for each model and only final results will be shown. Complete developments can be seen in Appendix C.

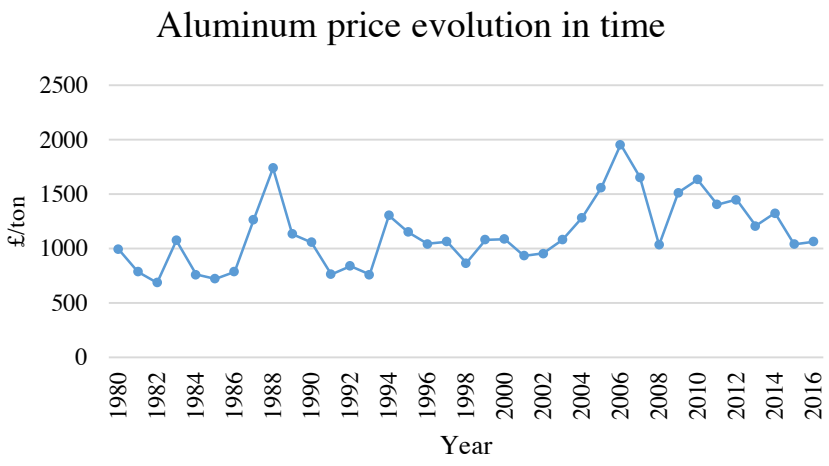

***Figure 8.1**: Aluminum price evolution in time*

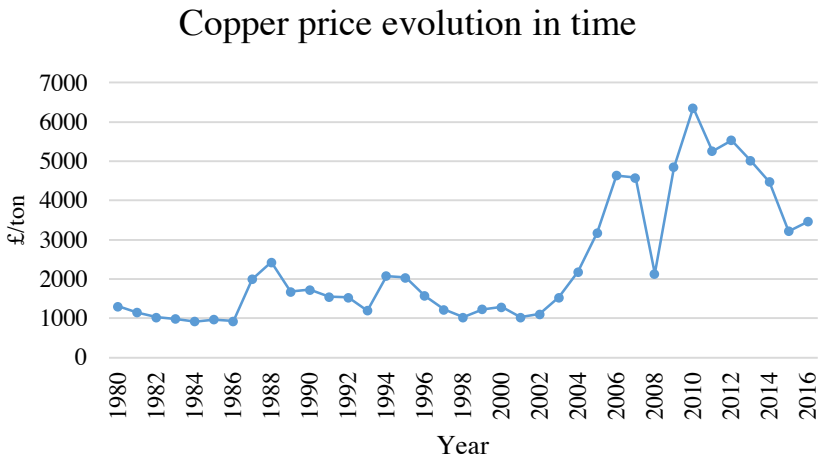

***Figure 8.2**: Copper price evolution in time*

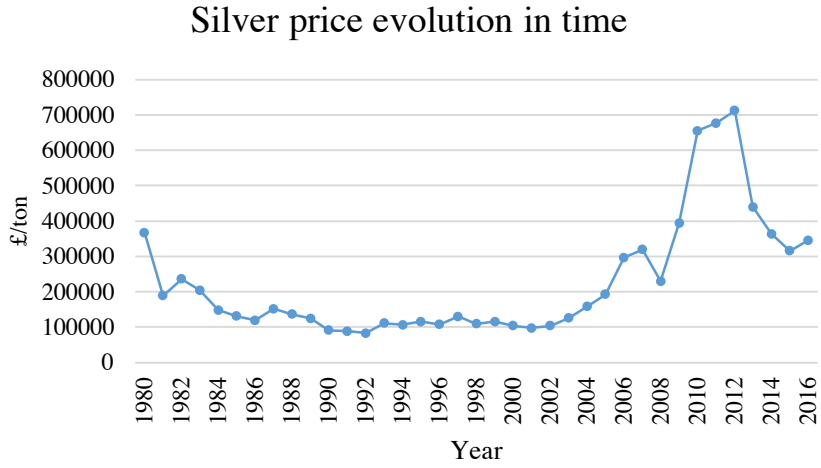

***Figure 8.3**: Silver price evolution in time*

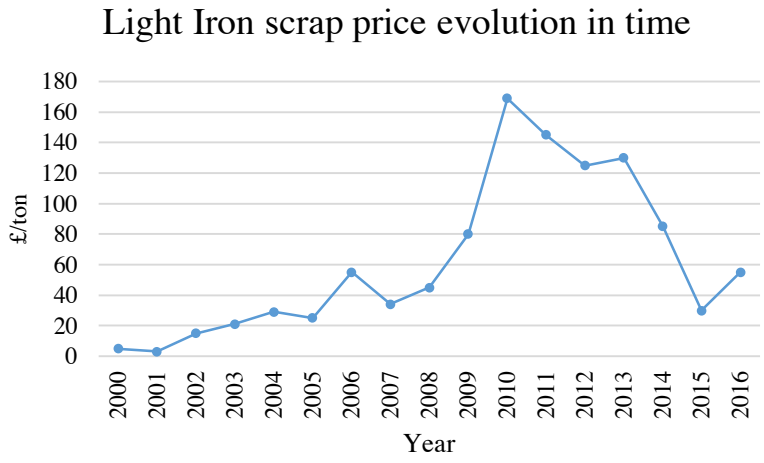

***Figure 8.4**: Light iron scrap price evolution in time*

Moving Mean with Linear Trend model (MMLT)

Method based on the calculus of arithmetic means for a set of values located in a time window that moves along the time period where data are available and taken into account the constant tendency. In all cases, a time window of size 3 values has been considered so the moving mean MM is calculated as

$$MM(H=3)_t = \frac{y_{t-1} + y_t + y_{t+1}}{H}$$

Equation 8.9

for which a linear regression is adjusted that allows to forecast future values. The regression line is calculated as

$$\hat{y}_t = \overline{MM} + \frac{Cov(MM,t)}{Var(t)} \cdot (t - \bar{t})$$

Equation 8.10

where,

$\hat{y}_t$ is the prediction at time t,

$\overline{MM}$ is the mean value of the moving means,

$Cov(MM,t)$ is the covariance between the moving means and the times used calculated as

$$Cov(MM,t) = \frac{\sum_1^n (MM - \overline{MM}) \cdot (t - \bar{t})}{n}$$

Equation 8.11

$Var(t)$ is the variance of t calculated as

$$Var(t) = \frac{\sum_1^n (t - \bar{t})^2}{n}$$

Equation 8.12

n is the number of observations equal to 37[5],

t is the time valued from 1 to 37[6] (number of observations between 1980[7] and 2016),

$\bar{t}$ is the mean value of t.

Double exponential smoothing

This method allows to rank the importance of the data depending on the proximity to the time at which it is predicted, according to the value of the smoothing coefficient α situated in the interval

[5] 17 for light iron
[6] 17 for light iron
[7] 2000 for light iron

[0,1]. The closest α gets to 1, the most importance is given to the data situated close to the variable. The double smoothing consists on making a first smoothing to the original data and then a second one to the previous results. The expressions for this smoothing are

$$Z_t = \alpha \cdot y_t + (1 - \alpha) \cdot Z_{t-1}$$
$$\hat{y}_t = \alpha \cdot Z_t + (1 - \alpha) \cdot \hat{y}_{t-1}$$

Equation 8.13

where Z_t is the result for the first smoothing at time t.

The prediction for $t + h$ consists on applying the point-slope equation using the parameters $b0_t$ and $b1_t$ as in the Equation 9.11.

$$\hat{y}_{t+h,\ t} = b0_t + b1_t \cdot h$$

Equation 8.14

being,

$$b0_t = 2 \cdot Z_t - \hat{y}_t$$

Equation 8.15

$$b1_t = \frac{\alpha}{1 - \alpha} \cdot (Z_t - \hat{y}_t)$$

Equation 8.16

Initialization by assigning to Z_0 and $\hat{y}_0$ the value of the first observation y_1.

Holt method

This method is a variant of the previous one but using two different smoothing coefficients, α and β, for predicting the evolution of a variable according to a line with its point-slope expression. This expression is calculated as

$$\hat{y}_{t+h,\ t} = L_t + b_t \cdot h$$

Equation 8.17

being L_t the point and b_t the slope calculated as

$$L_t = \alpha \cdot y_t + (1 - \alpha) \cdot (L_{t-1} + b_{t-1})$$

Equation 8.18

$$b_t = \beta \cdot (L_t - L_{t-1}) + (1 - \beta) \cdot b_{t-1}$$

Equation 8.19

Initialization by $L_1 = y_1$ and $b_1 = y_2 - y_1$.

Error analysis

Adjustment errors allow to detect a poor times series adjustment. A correctly adjusted time series will show a series adjustment errors distributed around a null mean and a uniform separation from it along time.

In addition, it can be determined a confidence interval of the prediction with a determined confidence level which is set as 95%. The adjustment errors need to be adjusted to a normal probability distribution. Then, the confidence interval is calculated as

$$\left[\hat{y}_t - Z_{1-\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}, \hat{y}_t + Z_{1-\alpha/2} \cdot \frac{\sigma}{\sqrt{n}}\right]$$

Equation 8.20

where,

$Z_{1-\alpha/2}$ is the value for the normal distribution with a confidence level α being 1.96 in this case[8],

σ is the standard deviation of the errors in this case, calculated as

$$\sigma = \sqrt{\frac{\sum_1^n (y_t - \hat{y}_t)^2}{n}}$$

Equation 8.21

3.1.2. Metal price forecasting results

Aluminum

Results of the three modeling methods previously explained are shown in Figure 8.5. In this case, the Moving Means with Linear Trend (MMLT) model had the minimum mean square error (MSE) so it has been chosen as the one that adjust best to the price time series of the Aluminum and used for forecasting.

The adjustment errors displayed in Figure 8.6 show that the mean of adjustment errors is approximately 0 and the distance between then and the mean is practically uniform, apart from some punctual cases, so the adjustment is correctly performed.

Then, the prediction for the values of the price of Aluminum for the next 5 years is shown in Table 8.2. Note that the confidence interval is included, which will be used in the sensibility analysis later in this chapter.

[8] Z table can be obtained easily in any statistics book.

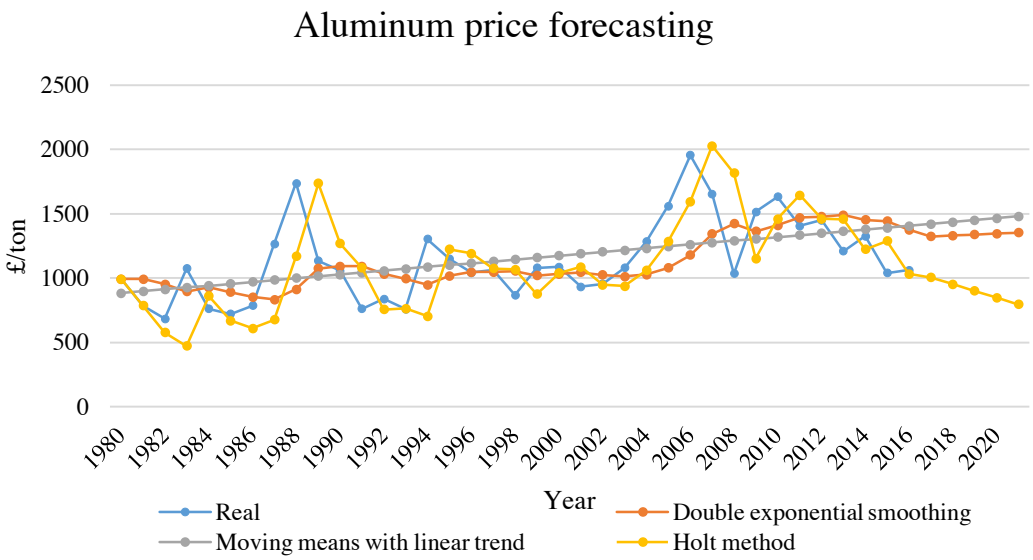

***Figure 8.5**: Aluminum price forecasting results*

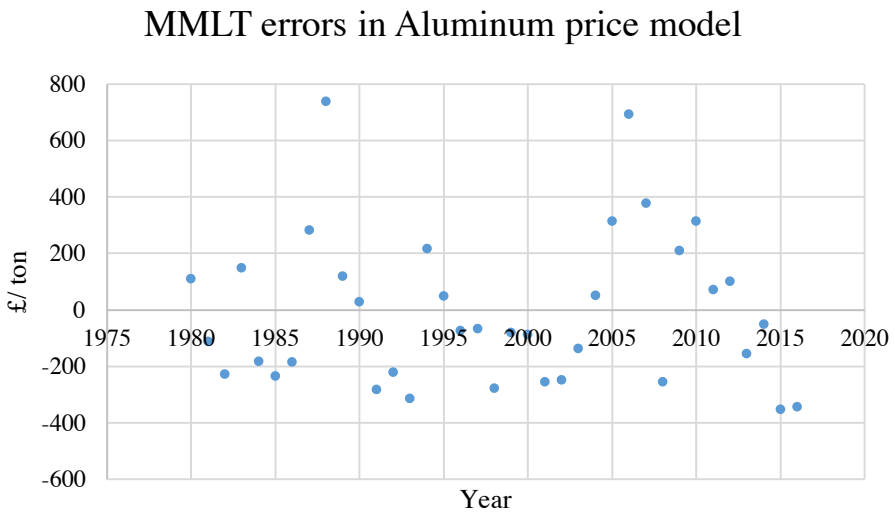

***Figure 8.6**: MMLT errors in Aluminum price model*

Table 8.2: Predicted Aluminum prices

2017	1,420.84 ± 85.29 £/ton
2018	1,435.36 ± 85.29 £/ton
2019	1,449.88 ± 85.29 £/ton
2020	1,464.41 ± 85.29 £/ton
2021	1,478.93 ± 85.29 £/ton

Copper

Results of the three modeling methods previously explained are shown in Figure 8.7. In this case, the Holt method model smoothing coefficients of $\alpha = 0.8$ and $\beta = 0.1$ had the minimum mean square error (MSE) so it has been chosen as the one that adjust best to the price time series of the Copper and used for forecasting.

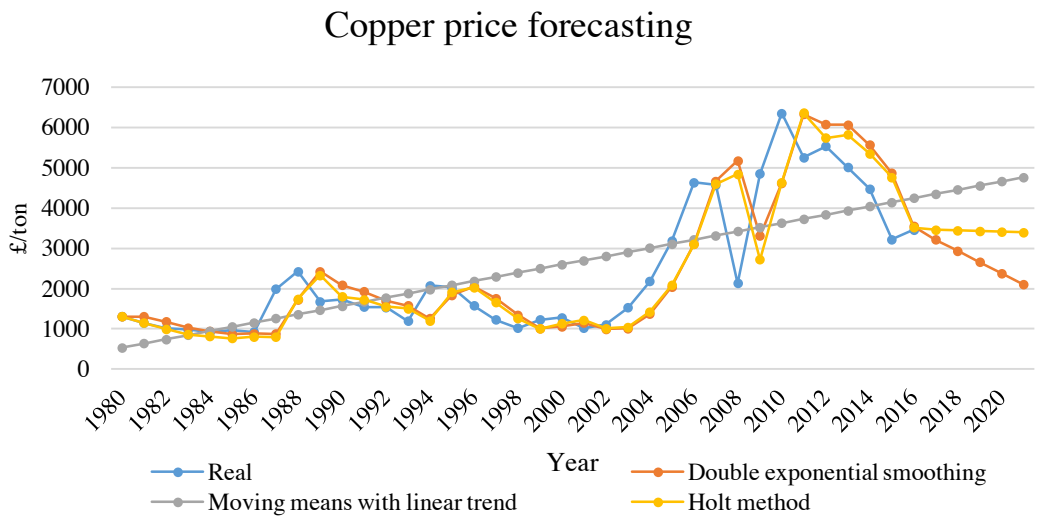

Figure 8.7: Copper price forecasting results

The adjustment errors displayed in Figure 8.8 show that the mean of adjustment errors is approximately 0 and the distance between then and the mean is practically uniform, apart from some punctual cases, so the adjustment is correctly performed.

Then, the prediction for the values of the price of Copper for the next 5 years is shown in Table 8.3. Note that the confidence interval is included, which will be used in the sensibility analysis later in this chapter.

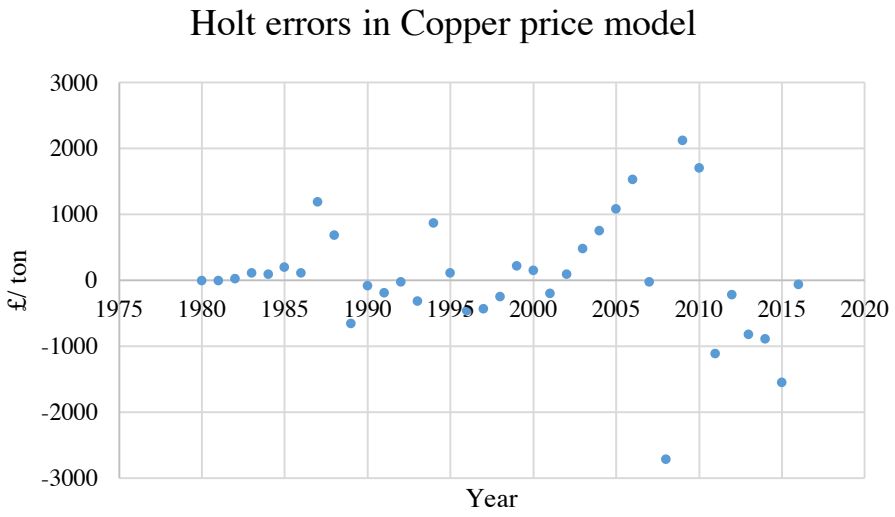

***Figure 8.8**: Holt errors in Copper price model*

***Table 8.3**: Predicted Copper prices*

2017	3,457.43 ± 280.57 £/ton
2018	3,442.15 ± 280.57 £/ton
2019	3,426.87 ± 280.57 £/ton
2020	3,411.59 ± 280.57 £/ton
2021	3,396.31 ± 280.57 £/ton

Silver

Results of the three modeling methods previously explained are shown in Figure 8.9. In this case, the Double Exponential Smoothing (DES) model with smoothing coefficient of $\alpha = 0.7$ had the minimum mean square error (MSE) so it has been chosen as the one that adjust best to the price time series of the Silver and used for forecasting.

The adjustment errors displayed in Figure 8.10 show that the mean of adjustment errors is approximately 0 and the distance between then and the mean is practically uniform, apart from some punctual cases, so the adjustment is correctly performed.

Then, the prediction for the values of the price of Silver for the next 5 years is shown in Table 8.4. Note that the confidence interval is included, which will be used in the sensibility analysis later in this chapter.

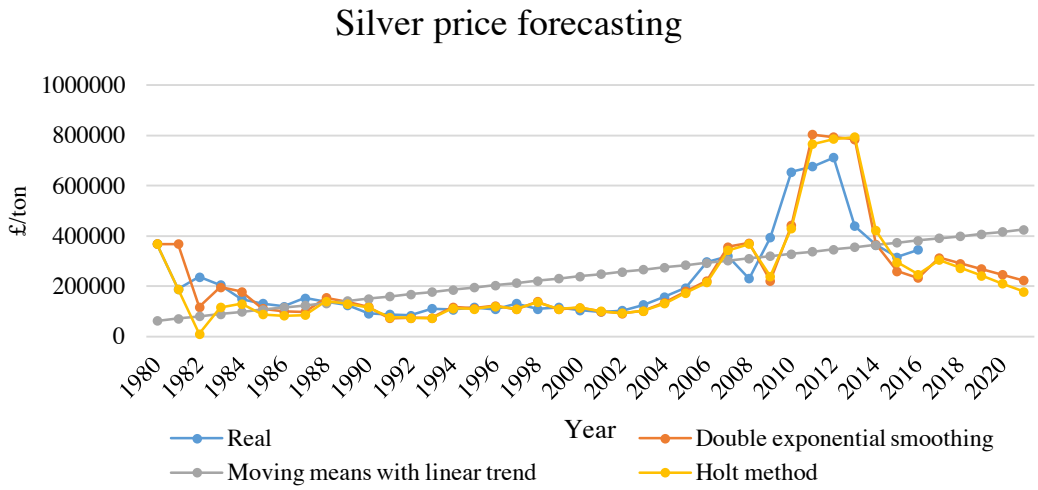

***Figure 8.9**: Silver price forecasting results*

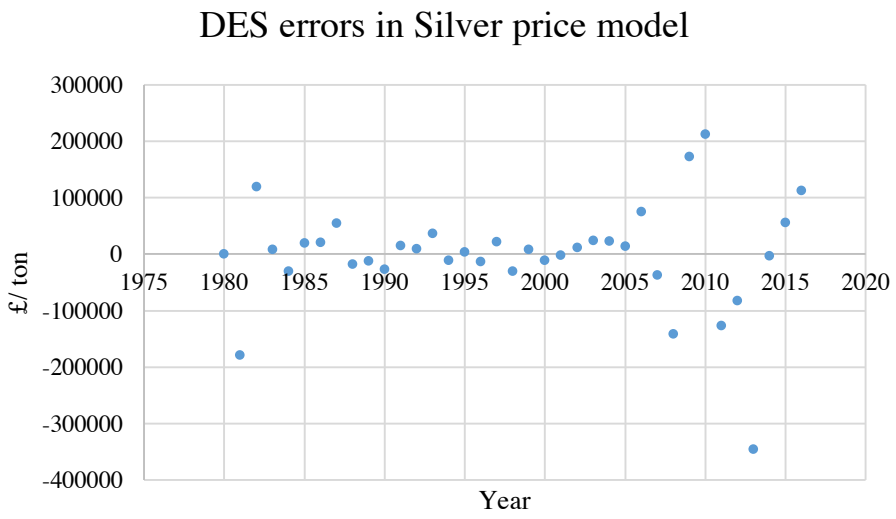

***Figure 8.10**: DES errors in Silver price model*

***Table 8.4**: Predicted Silver prices*

2017	312,639.47 ± 29,811.82 £/ton
2018	290,201.50 ± 29,811.82 £/ton
2019	267,763.54 ± 29,811.82 £/ton
2020	245,325.57 ± 29,811.82 £/ton
2021	222,887.60 ± 29,811.82 £/ton

Light iron scrap

Results of the three modeling methods previously explained are shown in Figure 8.11. In this case, the Holt method model smoothing coefficients of $\alpha = 0.9$ and $\beta = 0.1$ had the minimum mean square error (MSE) so it has been chosen as the one that adjust best to the price time series of the Iron ore and used for forecasting. In addition, double exponential smoothing model has been discarded in the first place as it takes to negative values for 2020 and 2021.

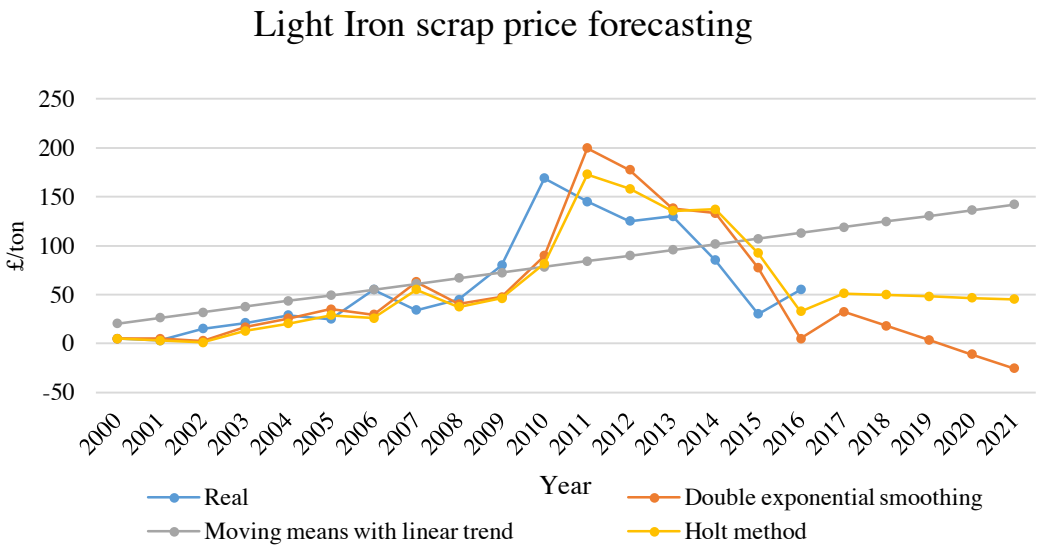

***Figure 8.11**: Light Iron scrap price forecasting results*

The adjustment errors displayed in Figure 8.12 show that the mean of adjustment errors is approximately 0 and the distance between then and the mean is practically uniform, apart from some punctual cases, so the adjustment is correctly performed.

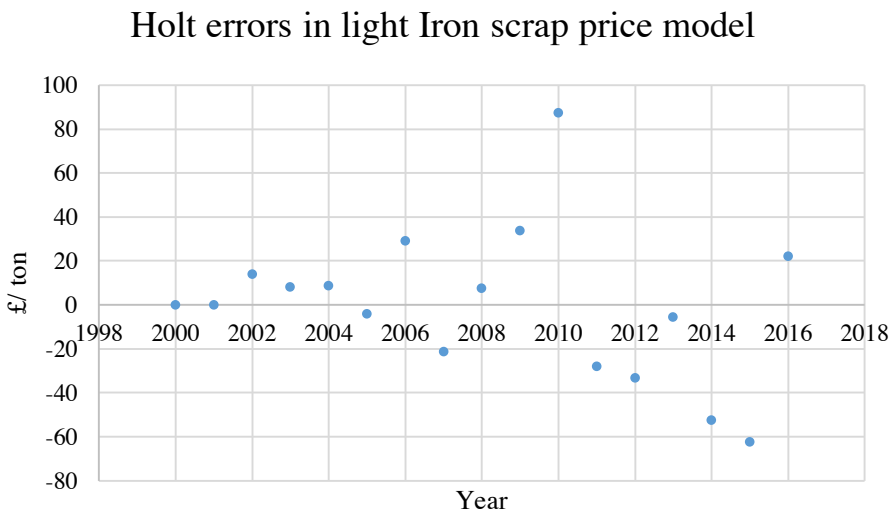

***Figure 8.12**: Holt errors in light Iron scrap price model*

Then, the prediction for the values of the price of light Iron scrap for the next 5 years is shown in Table 8.5. Note that the confidence interval is included, which will be used in the sensibility analysis later in this chapter.

***Table 8.5**: Predicted light Iron scrap prices*

2017	51.24 ± 16.12 £/ton
2018	49.71 ± 16.12 £/ton
2019	48.18 ± 16.12 £/ton
2020	46.64 ± 16.12 £/ton
2021	45.11 ± 16.12 £/ton

Comments

As it can be seen in the figures and tables in all cases, fluctuations became bigger in value during the 2006 – 2014 period according to the worldwide economic situation. It can also be seen that those values are turning to the trend they had in previous years and that is reflected in the predicted values for the prices in each case.

In addition, the remaining mixed non-ferrous fraction price will be taken as the contractual value at which it is sold by the Calvert Landfill, 360 £/ton.

3.2. Saved costs in landfilled material

As mentioned in section 1.2, saving costs associated to the recovered material that would not be landfilled is included as part of the revenue since it is direct consequence of the operation of each process. This amount would depend on the recovery efficiency in each scenario and calculated as

$$Saved\ landfill\ costs = \\ = (Current\ landfilled\ material - Recovered\ material) * Landfill\ rate$$

Equation 8.22

where the current landfilled material is the total production of 75,000 tons of IBA per year that including the moisture content turns to 89,587 tons of wet IBA per year and the recovered material depends directly on the process.

4. Project cash flows calculation

As mentioned in section 1.2, project cash flows will only include relevant cash flows that will only occur if the project is accepted. These cash flows have been calculated as

$$OCF = EBIT + Depreciation - Taxes$$

Equation 8.23

where

$$EBIT = Revenues - Costs - Depreciation$$

Equation 8.24

$$Taxes = Tax\ Rate \cdot EBIT$$

Equation 8.25

being $EBIT$ the Earnings Before Interest and Taxes and OCF the Operating Cash Flow.

The comparison between scenarios will be made according to their net present value, NPV, that takes into account the time value of money associated to a discount rate i at a year k. This NPV of the OCF of N years is compound as

$$NPV = \sum_{0}^{N} \frac{OCF_k}{(1+i)^k}$$

Equation 8.26

In addition, the internal rate of return IRR will be considered. This IRR is defined as the discount rate that would make the NPV null. It is commonly used to compare the profitability of investments. The higher the project's IRR, the more desirable it is to undertake the project.

5. Results

The results for the economic feasibility analysis based on the NPV and the IRR of each scenario is specified below. Table 8.6 contains a series of values shared in every scenario.

***Table 8.6**: Economic analysis common values*

Corporation Tax Rate[9] [TR]	20 %
Discount Rate[10] [i]	10.62 %
Water Price	0.00195 £/L
Power Price	0.01 £/KWh
Landfill Rate	82.60 £/ton

The maximum payback period (PBP) observed is about 1.5 years. A common criteria adopted in the industry is to use a PBP between 1/2 and 1/3 of the length of the project [LINA16] and thus, the length of the project for economic calculations chosen is 4 years.

[9] UK Government May 2016

[10] FCC Environment own criteria

5.1. Scenario I

5.1.1. Base case

As explained in Chapter 5, the IBA treatment process proposed on the base case of Scenario I would require the equipment summarized in Table 8.7, which also include power requirements and price. It was assumed that one piece of equipment would require one conveyor, which data below is an average of the market. Generic state-of-art prices and power requirements for magnetic drum separators, drum ECS, screening equipment and conveyors are chosen as an average of the market and will be the same in all cases.

***Table 8.7**: Scenario I base case equipment*

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	2
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	3
Conveyor	15	25,000	9

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.8. From these cash flows, the resulting NPV is £3,151,311.94 with a IRR of 65%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £2,337,322.97 which would be entirely recovered in 1.33 years.

***Table 8.8**: Scenario I base case cash flows*

Year	0	1	2	3	4
CAPEX	£ (2,337,322.97)				
Revenues		£ 2,441,493.07	£ 2,429,929.62	£ 2,418,366.18	£ 2,406,802.74
Variable costs		(333,347.82)	(333,347.82)	(333,347.82)	(333,347.82)
Depreciation		(334,003.45)	(572,410.40)	(408,797.79)	(291,931.64)
EBIT		1,774,141.80	1,524,171.41	1,676,220.58	1,781,523.29
Taxes		(334,003.45)	(304,834.28)	(335,244.12)	(356,304.66)
Net Income		1,419,313.44	1,219,337.13	1,340,976.46	1,425,218.63
Depreciation		334,003.45	572,410.40	408,797.79	291,931.64
Total cash flow	£ (2,337,322.97)	£ 1,753,316.89	£ 1,791,747.53	£ 1,749,774.25	£ 1,717,150.27
Cumulative cash flows	£ (2,337,322.97)	£ (584,006.08)	£ 1,207,741.45	£ 2,957,515.70	£ 4,674,665.97

5.1.2. Alternative case

An alternative option due to the low recovery rates shown in the 0-6 mm fraction would be not to treat that fraction. This would drive into a situation where the amount of material landfilled would be higher, total revenues would be lower but also the required initial investment would decrease. In this case, the required equipment is shown in Table 8.9.

***Table 8.9**: Scenario I alternative case required equipment*

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	1
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	2
Conveyor	15	25,000	7

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.10. From these cash flows, the resulting NPV is £3,447,757.16 with a IRR of 81%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £1,924,344.84 which would be entirely recovered in 1.12 years.

***Table 8.10**: Scenario I alternative case cash flows*

Year	0	1	2	3	4
CAPEX	£ (1,924,344.84)				
Revenues		£ 2,353,987.20	£ 2,342,519.52	£ 2,331,051.84	£ 2,319,584.17
Variable costs		(274,660.56)	(274,660.56)	(274,660.56)	(274,660.56)
Depreciation		(274,988.88)	(471,272.05)	(336,567.91)	(240,350.67)
EBIT		1,804,337.76	1,596,586.91	1,719,823.37	1,804,572.94
Taxes		(360,867.55)	(319,317.38)	(343,964.67)	(360,914.59)
Net Income		1,443,470.21	1,277,269.53	1,375,858.70	1,443,658.35
Depreciation		274,988.88	471,272.05	336,567.91	240,350.67
Total cash flow	£ (1,924,344.84)	£ 1,718,459.09	£ 1,748,541.58	£ 1,712,426.61	£ 1,684,009.02
Cumulative cash flows	£ (1,924,344.84)	£ (205,885.75)	£ 1,542,655.83	£ 3,255,082.44	£ 4,939,091.46

5.1.3. Optimal case

Cumulative cash flows lines can be seen in Figure 8.13 for both cases and Table 8.11 shows a summary of the economic results. As this alternative case proposed is more profitable for a 4-year project life than the base case, it will be considered as the optimized configuration for Scenario I.

However, the growth rate of the base case is higher than the growth rate of the alternative case. This growth rate is considered as the mean of the individual cash flows in each case. More concretely, in the base case is £1,740,649.34 per year and in the alternative case £1,704,913.97 per year meaning that if a longer project life was considered, the base case would be more profitable.

Table 8.11: Scenario I economic results summary

	Base case	Alternative case
CAPEX	£ 2,337,322.97	£1,924,344.84
NPV	£ 3,151,311.94	£3,447,757.16
IRR	65%	81%
PBP	1.33 years	1.12 years

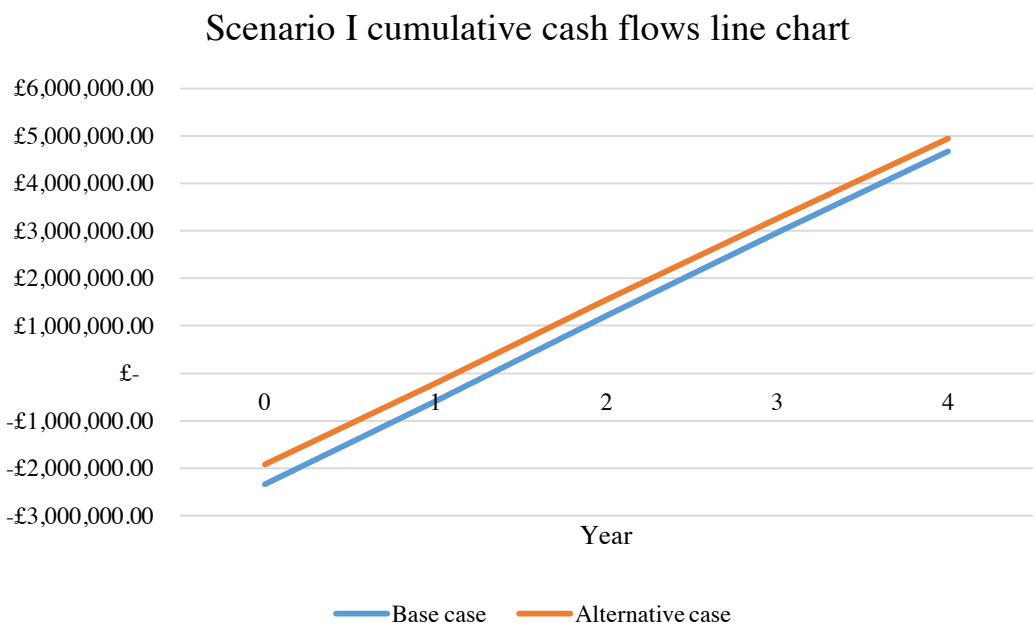

Figure 8.13: Scenario I cumulative cash flow line chart

5.2. Scenario II – ADR

5.2.1. Base case

As explained in Chapter 6, the IBA treatment process proposed on the base case of Scenario II - ADR would require the equipment summarized in Table 8.12.

Table 8.12: Scenario II – ADR base case required equipment

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	1
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	2
Shaking table	1.5	14,100	2
Additional screen	20	100,000	1
Conveyor	15	25,000	11

As mentioned in Chapter 6, estimated costs for the ADR concentrator would be £1.74 per ton of IBA treated, all costs included.

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.13. From these cash flows, the resulting NPV is £3,887,018.49 with a IRR of 71%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £2,573,653.03 which would be entirely recovered in 1.24 years.

***Table 8.13**: Scenario II – ADR base case cash flows*

Year	0	1	2	3	4
CAPEX	£ (2,573,653.03)				
Revenues		£ 2,992,879.18	£ 2,978,884.90	£ 2,924,252.99	£ 2,950,896.34
Variable costs		(493,563.81)	(493,563.81)	(493,563.81)	(493,563.81)
Depreciation		(367,775.02)	(630,287.63)	(450,131.92)	(321,449.26)
EBIT		2,131.540.35	1,855,033.46	1,980,557.27	2,135,883.27
Taxes		(426,308.07)	(371,006.69)	(396,111.45)	(427,176.65)
Net Income		1,705,232.28	1,484,026.77	1,584,445.81	1,708,706.62
Depreciation		367,775.02	630,287.63	450,131.92	321,449.26
Total cash flow	£ (2,573,653.03)	£ 2,073,007,30	£ 2,114,314.40	£ 2,034,577.73	£ 2,030,155.88
Cumulative cash flows	£ (2,573,653.03)	£ (500,645.73)	£ 1,613,668.66	£ 3,648,246.39	£ 5,678,402.27

5.2.2. Alternative case

Since the ADR concentrator extracts a notable amount of valuable material from the 0-2 mm fraction, the alternative case considered consists removing the density separation treatment for that fraction. This configuration would increase the amount of non-ferrous metals sold as a mix and would decrease the amount of Al, Cu and Ag sold as "pure" together with the initial investment required. In this case, the required equipment is shown in Table 8.14.

***Table 8.14**: Scenario II – ADR alternative case required equipment*

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	1
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	2
Shaking table	1.5	14,100	1
Additional screen	20	100,000	1
Conveyor	15	25,000	10

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.15. From these cash flows, the resulting NPV is £3,749,498.49 with a IRR of 72%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £2,469,475.97 which would be entirely recovered in 1.23 years.

***Table 8.15**: Scenario II – ADR alternative case cash flows*

Year	0	1	2	3	4
$CAPEX$	£ (2,469,475.97)				
Revenues		£ 2,884,823.39	£ 2,870,580.32	£ 2,821,621.25	£ 2,842,094.17
Variable costs		(478,645.06)	(478,645.06)	(478,645.06)	(478,645.06)
Depreciation		(352,888.12)	(604,774.66)	(431,911.35)	(308,437.55)
EBIT		2,053,290.21	1,787,160.59	1,911,064.84	2,055,011.56
Taxes		(410,658.04)	(357,432.12)	(382,212.97)	(411,002.31)
Net Income		1,642,632.17	1,429,738.47	1,528,851.87	1,644,009.25
Depreciation		352,888.12	604,774.66	431,911.35	308,437.55
Total cash flow	£ (2,469,475.97)	£ 1,995,520.28	£ 2,034,503.14	£ 1,960,763.22	£ 1,952,446.80
Cumulative cash flows	£ (2,469,475.97)	£ (473,955.68)	£ 1,560,547.45	£ 3,521,310.67	£ 5,473,757.46

5.2.3. Optimal case

Cumulative cash flows lines can be seen in Figure 8.14 and Table 8.16 shows a summary of the economic results for both cases. It can be seen that even if the initial investment required in the alternative case is lower than in the base case, revenues are higher due to the heavy non-ferrous metal recovered in the 0-2 mm fraction and thus the NPV of the base case is also higher. Accordingly, the growth rate of the base case is £2,063,013.83 per year and for the alternative case is £1,973,340.62 per year. Then, the base case would be considered as the optimal case for this scenario.

***Table 8.16**: Scenario II – ADR economic results summary*

	Base case	Alternative case
CAPEX	£2,573,653.03	£2,469,475.97
NPV	£ 3,887,018.49	£3,749,498.49
IRR	71%	72%
PBP	1.24 years	1.23 years

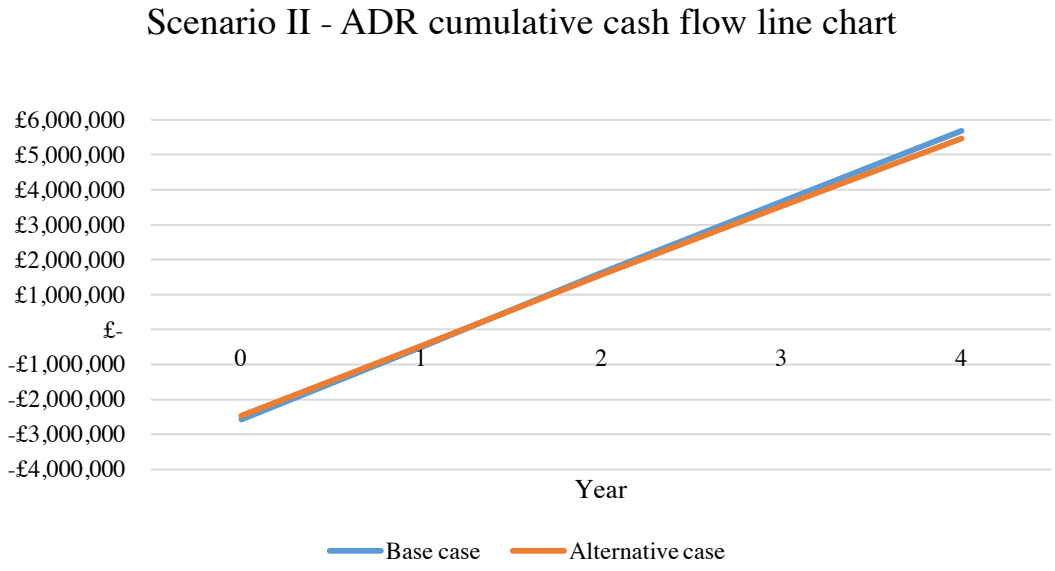

***Figure 8.14**: Scenario II - ADR cumulative cash flow line chart*

5.3. Scenario II – Wet separation

5.3.1. Base case

As explained in Chapter 6, the IBA treatment process proposed on the base case of Scenario II – Wet separation would require the equipment summarized in Table 8.17.

***Table 8.17**: Scenario II – wet separation base case required equipment*

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	1
Magnetic wet drum separator	3	20,000	2
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	3
Shaking table	1.5	14,100	1
Jig	7.5	8,334	1
Hydro-cyclone	-	1,355	1
Kinetic Gravity Separator	15	200,000	1
Conveyor	15	25,000	14

As mentioned in Chapter 6, this wet process would require a constant addition of process water. In total, 174.86 L per ton of IBA would be required.

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.18. From these cash flows, the resulting NPV is £3,664,051.89 with a IRR of 56%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £3,319,911.16 which would be entirely recovered in 1.48 years.

Since this case is already the optimized configuration for the wet separation process [MUCH10], no alternative case was considered and the base case would be the one taken into account in the comparison.

Table 8.18: Scenario II –wet separation base case cash flows

Year	0	1	2	3	4
CAPEX	£ (3,319,911.16)				
Revenues		£ 3,126,878.14	£ 3.118,179.06	£ 3,105,614.94	£ 3,094,983.34
Variable costs		(465,481.75)	(465,481.75)	(465,481.75)	(465,481.75)
Depreciation		(474,415.31)	(813,046.24)	(373,102.28)	(414,656.90)
EBIT		2,186,981.08	1,839,651.06	2,059,480.73	2,214,844.68
Taxes		(437,396.22)	(367,930.21)	(411,896.15)	(442,968.94)
Net Income		1,749,584.87	1,471,720.85	1,647,584,58	1,771,875.75
Depreciation		474,415.31	813,046.24	373,102.28	414,656.90
Total cash flow	£ (3,319,911.16)	£ 2,224,000.17	£ 2,284,767.09	£ 2,228,237.04	£ 2,186,532.65
Cumulative cash flows	£ (3,319,911.16)	£ (1,095,910.99)	£ 1,188,856.10	£ 3,417,093.15	£ 5,603,625.80

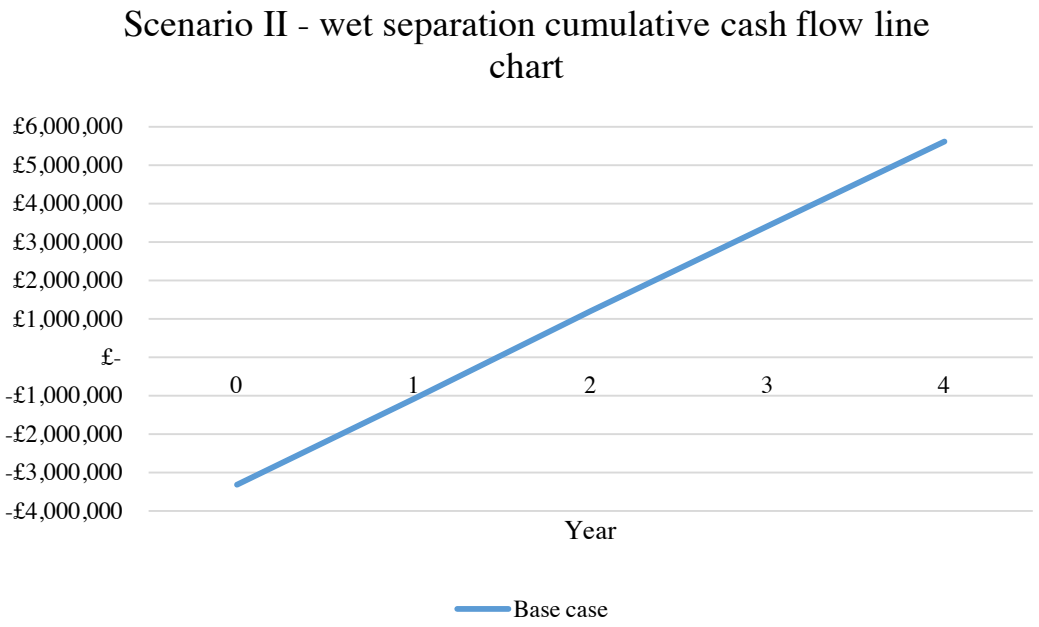

***Figure 8.15**: Scenario II - wet separation cumulative cash flow line chart*

5.4. Scenario III

5.4.1. Base case

As explained in Chapter 7, the IBA treatment process proposed on the base case of Scenario III would require the equipment summarized in Table 8.19.

***Table 8.19**: Scenario III base case required equipment*

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	3
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	4
Shaking table	1.5	14,100	1
Conveyor	15	25,000	12

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.20. From these cash flows, the resulting NPV is £7,388,917.18 with a IRR of 100%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £3,158,483.34 which would be entirely recovered in 0.94 years.

Table 8.20: Scenario III base case cash flows

Year	0	1	2	3	4
$CAPEX$	£ (3,158,483.34)				
Revenues		£ 4,548,390.64	£ 4,533,799.18	£ 4,519,207.71	£ 4,504,616.25
Variable costs		(449,949.71)	(449,949.71)	(449,949.71)	(449,949.71)
Depreciation		(451,347.27)	(773,512.57)	(552,418.74)	(394,494.57)
EBIT		3,647,093.66	3,310,336.90	3,516,839.27	3,660,171.97
Taxes		(729,418.73)	(662,067.38)	(703,367.85)	(732,034.39)
Net Income		2,917,674.93	2,648,269.52	2,813,471.41	2,928,137.58
Depreciation		451,347.27	773,512.57	552,418.74	394,494.57
Total cash flow	£ (3,158,483.34)	£ 3,369,022.20	£ 3,421,782.09	£ 3,365,890.15	£ 3,322,632.15
Cumulative cash flows	£ (3,158,483.34)	£ 210,538.85	£ 3,632,320.94	£ 6,998,211.09	£ 10,320,843.24

5.4.2. Alternative case

In the base case, the 0-6 mm fraction would pass through two in series magnetic separators and two in series eddy current separators, which is proven to raise efficiency. An alternative configuration, where those two in series separation equipment in each case would be switched for just one. Equipment requirements for this case are shown in Table 8.21.

***Table 8.21**: Scenario III alternative case required equipment*

Equipment	Power [KW]	Price per unit [£]	Units
Crusher	90	152,750	1
Screen < 40 mm	20	100,000	1
Main screen	20	100,000	1
Magnetic drum separator	3	20,000	2
Suspended magnetic separator	1.5	4,500	1
Drum ECS	10	85,000	3
Shaking table	1.5	14,100	1
Conveyor	15	25,000	12

According to this data and what is explained in previous sections in this chapter, project cash flows in Table 8.22. From these cash flows, the resulting NPV is £7,301,843.18 with a IRR of 107%, which is higher than the required return of 10.62% and thus the project is economically attractive. The initial investment would be £2,878,723.97 which would be entirely recovered in 0.89 years.

Table 8.22: Scenario III alternative case cash flows

Year	0	1	2	3	4
CAPEX	£ (2,878,723.97)				
Revenues		£ 4,373,886.63	£ 3.118,179.06	£ 3,105,614.94	£ 3,094,983.34
Variable costs		(410,520.28)	(410,520.28)	(410,520.28)	(410,520.28)
Depreciation		(411,369.66)	(704,999.50)	(503,488.82)	(359,552.62)
EBIT		3,551,996.69	3,244,204.74	3,431,553.31	3,561,327.41
Taxes		(710,399.34)	(648,840.95)	(686,310.66)	(712,265.48)
Net Income		2,841,597.36	2,595,363.79	2,745,242.65	2,849,061.93
Depreciation		411,369.66	704,999.50	503,488.82	359,552.62
Total cash flow	£ (2,878,723.97)	£ 3.252,967.01	£ 3,300,363.29	£ 3,248,731.47	£ 3,208,614.55
Cumulative cash flows	£ (2,878,723.97)	£ 374,243.04	£ 3,674,606.34	£ 6,923,337.81	£ 10,131,952.36

5.4.3. Optimal case

Cumulative cash flows lines can be seen in Figure 8.16 and Table 8.23 show a summary of the economic results for both cases. It can be seen that even if the initial investment required in the alternative case is lower than in the base case, revenues are higher due to the metal recovered in the 0-6 mm fraction and thus the NPV of the base case is also higher. Accordingly, the growth rate of the base case is £3,369,831.65 per year and for the alternative case is £3,252,669.08 per year. Then, the base case would be considered as the optimal case for this scenario.

***Table 8..23**: Scenario III economic results summary*

	Base case	Alternative case
CAPEX	£3,158,483.34	£2,878,723.97
NPV	£7,388,917.18	£7,301,843.18
IRR	100%	107%
PBP	0.94 years	0.89 years

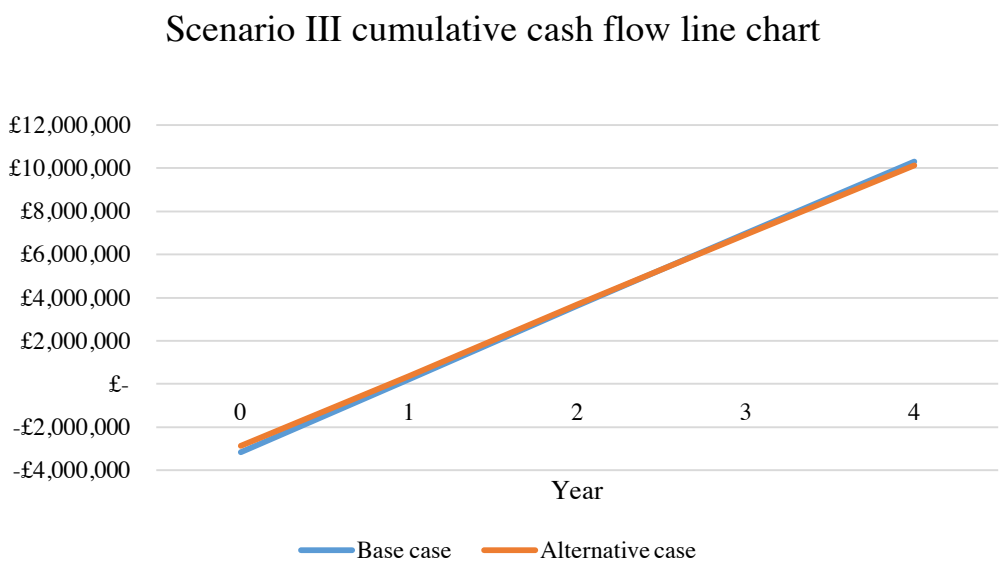

***Figure 8.16**: Scenario III cumulative cash flow line chart*

5.5. Comparison

Table 8.23 summarizes the economic results for the optimal case in each scenario and Figure 8.17 shows their cumulative cash flow lines.

Table 8.24: *Economic analysis summary*

Scenario	I	II - ADR	II - Wet sep	III
CAPEX	£1,924,344.84	£2,573,653.03	£3,319,911.16	£3,158,483.34
NPV	£3,447,747.16	£3,887,018.49	£3,664,051.89	£7,388,917.18
IRR	81%	71%	56%	100 %
PBP	1.12 years	1.24 years	1.48 years	0.94 years
Growth rate	1,704,913.97 £/y	2,050,538.27 £/y	2,230,884.24 £/y	3,369,831.65 £/y

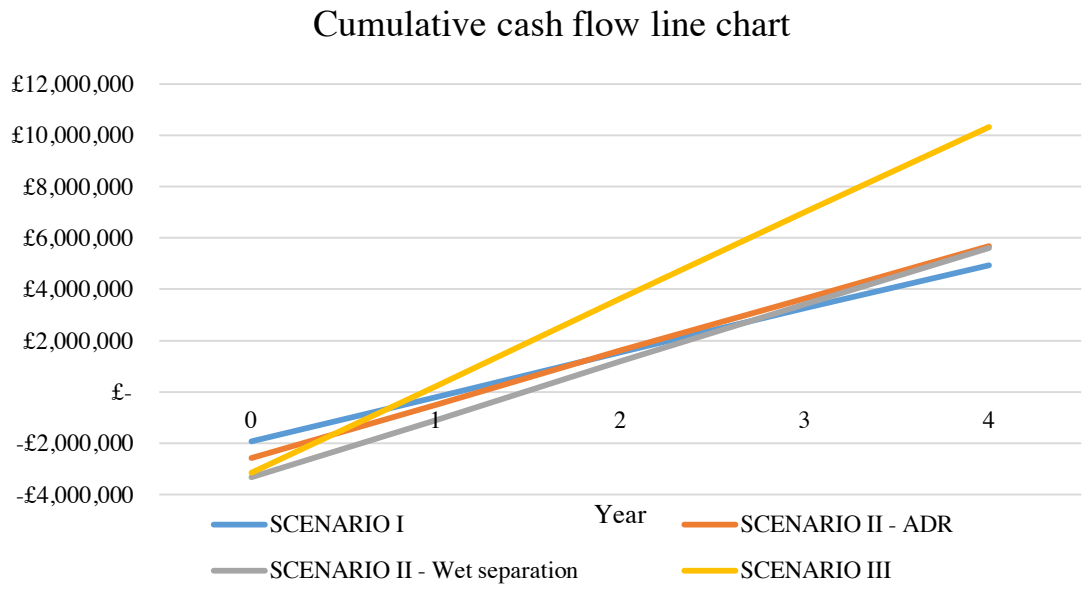

Figure 8.17*: Cumulative cash flow line chart*

As it can be seen in the previous table and chart, Scenario III based on dry IBA discharge would be much more profitable than the other cases. This result was expected as due to dry status of the IBA in all stages of the process, which reduces investments in special treatments due to moisture and maximizes the possibilities of recovery, but it has to be taken into account that this scenario is based on a new installation and not the one currently installed at Greatmoor EfW.

Based on the current installation, the most profitable option among the ones proposed would be the ADR technology, which was technically analyzed in Chapter 6, followed closely by the wet separation process installed at AEB Amsterdam, explained also in Chapter 6. Nevertheless, due to its higher growth rate, the latter would be more profitable if a longer project was

considered. The process based on conventional treatments resulted to be the least profitable option for a 4-year project life.

6. Sensibility analysis

Sensibility analysis has been performed to estimate the sensibility of the project results to changes in a parameter. It allows to get information about which variables are important depending on its percentage participation in revenues or costs and their range of possible values [BUST11].

This analysis allows to determinate the direction of change in the NPV with some limitations:

- The sensibility analysis does not represent the possible range of values or the probability of each range.
- In some cases, the direction of changes is obvious, but it helps to quantify those changes.
- An analysis based on changes in a single variable is not realistic since some variables are correlated.

Taken those limitations into account, the sensibility analysis performed in this thesis is used to get an idea of which variables affect the most the NPV of each process proposed. The variables considered are operating costs (variable costs), investment costs (CAPEX) and benefits (revenues).

In this direction, changes in NPV was calculated for an increase of 10% in each variable. Figure 8.18 shows a column chart representing the percentage change in the NPV of each scenario to this change in each variable.

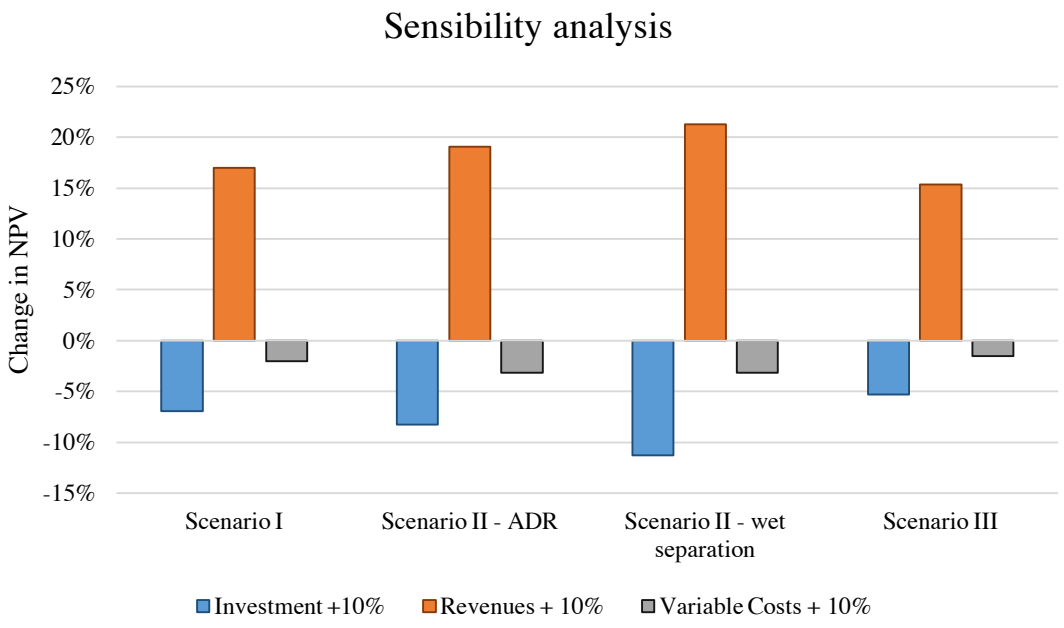

***Figure 8.18**: Percentage changes in NPV to a 10% increase*

From this column chart it can be inferred that the most explanatory variable in the NPV of the proposed processes is the value of revenues. This variable includes the amount of material

recovered and the prices at which these materials would be sold. A 10% increase in this variable would affect the NPV in the amounts shown in Table 8.25.

***Table 8.25**: Changes in NPV to a 10% increase in revenues*

	Current NPV	Revenues + 10%	Change
Scenario I	£3,447,747.16	£4,032,825.31	17%
Scenario II - ADR	£3,887,018.49	£4,628,691.03	19%
Scenario II – wet sep	£3,664,051.89	£4,442,938.85	21%
Scenario III	£7,388,917.18	£8,522,011.08	15%

As mentioned, the values of revenues depend on the amount of material recovered and the market prices of this materials. As explained in section 3.1.1 of this chapter, those prices were estimated based on time series analysis and predictions were made for the following years. Since these values are likely to change according to the uncertainty of the estimations, an optimistic/pessimistic scenario analysis has been made to quantify the increase/decrease in the value of the NPVs that these "extreme" cases would incur. Table 8.26 shows the percentage changes material prices in the optimistic (best) and pessimistic (worst) scenarios based on the confidence intervals calculated for each price[11]. Figure 8.19 show the directions of change in NPV for those particular scenarios.

***Table 8.26**: Changes in material prices in the optimistic (+) and pessimistic (-) scenarios*

	Al [£/ton]	Cu [£/ton]	Ag [£/ton]	Light Fe [£/ton]
2017	1,420.84 ± 6%	3,457.43 ± 8%	312,639.47 ± 10%	51.24 ± 31%
2018	1,435.36 ± 6%	3,442.15 ± 8%	290,201.50 ± 10%	49.71 ± 32%
2019	1,449.88 ± 6%	3,426.87 ± 8%	267,763.54 ± 11%	48.18 ± 33%
2020	1,464.41 ± 6%	3,411.59 ± 8%	245,325.57 ± 12%	46.64 ± 35%
2021	1,478.93 ± 6%	3,396.31 ± 8%	222,887.60 ± 13%	45.11 ± 36%

[11] See tables 8.2, 8.3, 8.4 and 8.5.

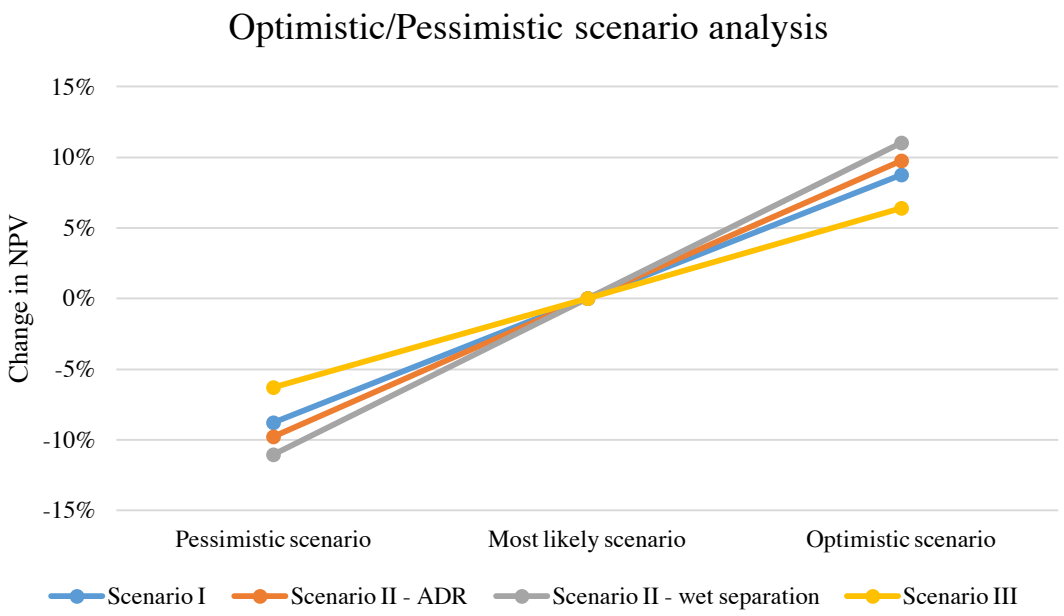

***Figure 8.19**: Percentage changes in NPV in the optimistic and pessimistic scenarios*

Then, to prove if these changes in the values for the NPV in the optimistic and pessimistic scenarios would affect selection of most profitable process, these values are shown in Table 8.27.

***Table 8.27**: NPV in the optimistic and pessimistic scenarios*

	Optimistic scenario	**Pessimistic scenario**
Scenario I	£3,749,835.44	£3,145,658.87
Scenario II – ADR	£4,266,950.66	£3,507,086.33
Scenario II – wet sep	£4,068,029.25	£3,260,074.53
Scenario III	£7,863,463.81	£6,924,370.55

Note that in figures 8.18 and 8.19 and also in Table 8.25, percentage values are only useful for quantitative comparison in scenarios I and II since the NPV of Scenario III is of a different order. Nevertheless, they are useful of qualitative comparison and conclusions in all cases.

As happens in the most likely scenario, the most profitable process would be the dry extraction based process explained in Scenario III (Chapter 7) followed by the ADR process (Chapter 6), the wet separation process (Chapter 6) and finally the conventional process (Chapter 5) in both the optimistic and pessimistic scenarios, meaning that for the project life selected changes in the material prices would not affect the selection of the most profitable process.

Chapter 9

Conclusions

The installation of a metal recovery plant would have a significantly positive impact in Greatmoor EfW and in other plants of similar characteristics. The profitability of this technology resides in the suitability of the IBA produced, the efficiency of the process and the metal market situation and it has been proven in several installations around Europe.

According to the objectives set at the beginning of this thesis, a study of the technical and economic feasibility of metal separation for Greatmoor EfW IBA has been done from where several conclusions have been obtained:

- The IBA produced on site has an important amount of metals that could be recovered by a metal recovery plant. The quantity of ferrous, non-ferrous and precious metals contained in the IBA is strongly related to the nature and origin of the MSW thermally treated which, due to the similar lifestyle and development status of all the countries of Western Europe, makes the IBA composition able to be considered similar to that produced in similar EfW plants.
- From the three scenarios studied it has been proven Scenario III, the only one based on dry discharge, as the most profitable by a wide margin, being the cases exposed in Scenario I and II quite similar in economic terms. This confirms the theory exposed in the first chapters that a critical factor for a high-grade metal recovery is the moisture content. In a new plant, a dry discharge system should be considered since it would increase substantially the benefits, both economic and operational, of a potential metal recovery plant. Revenues would raise due to the increase in the amount of material recovered and also lower the CAPEX as no special treatments due to the moisture content would be required. In operating terms, the weight and volume of material to be transported/conveyed would be reduced and there would be no need of additional water treatments, but a dust control system would be required. This latter would normally be provided by the contractor.
- For the specific situation of Greatmoor EfW, which counts with a wet discharge system, the best option would be the INASCHO's ADR solution explained in Scenario II for the project-life considered, which makes unnecessary to add water and consequently an additional water treatment plant. Nevertheless, if a longer project-life was considered, the wet separation plant also analyzed in Scenario II would be more profitable but would include the need to consider further operating factors, those including the water supply

and treatment systems. In addition, as it is based on non-conventional equipment, it might be difficult to acquire.

- The sensibility analysis concludes that the most influential variables affecting to the NPV of the project are those related to the revenues. A 10% change in those revenues would cause up to a 21% change in the NPV of the project in the case of the wet separation process, meaning that even if there are fluctuations in the IBA composition the project would still be profitable, fulfilling the condition of transferability marked at the beginning of this thesis. The wet separation process is the one that would be affected the most by a change in the value of revenues, caused by the fact that this is the one with a higher rate of recovery from the wet discharge scenarios (the NPV of those processes are of the same order, so they can be compared in those terms), which supports its importance in the final result. In all the cases exposed in the economic analysis of the different scenarios, it can be inferred that even a small raise in the efficiency of the system would justify the extra investment that it would require. At the same time, the fluctuations in price of the metals is a critical factor which can be seen in the higher economic results for Scenario III. In that case, the percentage of Al, Cu and Ag removed as "pure" is significantly higher than in the other scenarios, being those the most valuable metals which supports the importance of both factors.
- The grade of purity of each metal that is intended to be sold separately is an important factor that is not possible to predict without experimental tests. This factor would directly affect at which price those metal would be sold to purchasers, meaning that the predicted values for the metal prices are indicative and thus the quantitative results obtained in this thesis are not strictly adjusted to reality, but it would not affect the qualitative result since a change in those values would affect evenly to all scenarios.

In further studies, any process chosen and intended to be installed would require a complete planning study in terms of layout design, land requirements (civil calculations), maintenance and operating procedures, protocols and risk assessments, among others. There are also several factors that cannot be set until the commissioning stage and would depend on how the IBA is presented. These factors have been mentioned throughout the extension of this thesis and include conveyor, drum separators and belt speeds, distance from the suspended magnet to the conveying belt, etc.

The IBAA taken as a residue in this thesis has the potential of being used in the building industry. After removing most of its metal content, its mechanical and environmental characteristics would be improved making it more suitable for this task. Nevertheless, its composition and leaching values would have to be analyzed together with its mechanical properties to ensure its suitability and that it meets the industry specifications.

Eduardo Quero Ruz

Buckinghamshire (UK), June 2016

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Appendix A

Characterization of IBA

A.1 Hazardous assessment

A.1.1 Persistent Organic Pollutants Limits

***Table A.1**: Concentration limits for the classification of wastes as hazardous due to the presence of POPs*

Substance	CAS No.	EU No.	Concentration limit
Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF)			15 µg/kg(1)
DDT (1,1,1-trichloro-2,2-bis (4-chlorophenyl)ethane)	50-29-3	200-024-3	50 mg/kg
Chlordane	57-74-9	200-349-0	50 mg/kg
Hexachlorocyclohexanes, including lindane	58-89-9 319-84-6 319-85-7 608-73-1	210-168-9 200-401-2 206-270-8 206-271-3	50 mg/kg
Dieldrin	60-57-1	200-484-5	50 mg/kg
Endrin	72-20-8	200-775-7	50 mg/kg
Heptachlor	76-44-8	200-962-3	50 mg/kg
Hexachlorobenzene	118-74-1	200-273-9	50 mg/kg
Chlordecone	143-50-0	205-601-3	50 mg/kg
Aldrin	309-00-2	206-215-8	50 mg/kg
Pentachlorobenzene	608-93-5	210-172-5	50 mg/kg
Polychlorinated Biphenyls (PCB)	1336-36-3 and others	215-648-1	50 mg/kg(2)
Mirex	2385-85-5	219-196-6	50 mg/kg
Toxaphene	8001-35-2	232-283-3	50 mg/kg
Hexabromobiphenyl	36355-01-8	252-994-2	50 mg/kg
(1) The limit is calculated as PCDD and PCDF according to toxic equivalency factors (TEFs) in Table C16.2. (2) Where applicable, the calculation method laid down in European standards EN 12766-1 and EN 12766-2 shall be applied.			

***Table A.2**: Toxic equivalency factors (TEFs) for polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/PCDF)*

PCDD	TEF	PCDD	TEF	PCDF	TEF
2,3,7,8-TeCDD	1	1,2,3,6,7,8-HxCDF	0.1	2,3,7,8-TeCDF	0.1
1,2,3,7,8-PeCDD	1	1,2,3,7,8,9-HxCDF	0.1	1,2,3,7,8-PeCDF	0.03
1,2,3,4,7,8-HxCDD	0.1	2,3,4,6,7,8-HxCDF	0.1	2,3,4,7,8-PeCDF	0.3
1,2,3,6,7,8-HxCDD	0.1	1,2,3,4,6,7,8-HpCDF	0.01	1,2,3,4,7,8-HxCDF	0.1
1,2,3,7,8,9-HxCDD	0.1	1,2,3,4,7,8,9-HpCDF	0.01		
1,2,3,4,6,7,8-HpCDD	0.01	OCDF	0.0003		
OCDD	0.0003				

The waste is hazardous if:

$$\Sigma[C_i \times TEF_i] > 15\ \mu g/kg$$

Where

- C_i is the concentration of an individual PCDD or PCDF, and
- TEF_i is the toxic equivalency factor for an individual PCDD or PCDF
- Σ adds the values for each individual PCDD and PCDF present together.

A1.2 Hazard properties

***Table A.3**: Hazard properties*

HAZARDOUS PROPERTIES	
HP1	Explosive: substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene.
HP2	Oxidizing: substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
HP3-A	Highly flammable: • liquid substances and preparations having a flash point below 21°C (including extremely flammable liquids), or • substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or • solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or be consumed after removal of the source of ignition, or • gaseous substances and preparations which are flammable in air at normal pressure, or • substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.
HP3-B	Flammable: liquid substances and preparations having a flash point equal to or greater than 21ºC and less that or equal to 55ºC.
HP4	Irritant: non-corrosive substances and preparations which, through immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation.
HP5	Harmful: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks.

HP6	Toxic: substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death.
HP7	Carcinogenic: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence.
HP8	Corrosive: substances and preparations which may destroy living tissue on contact.
HP9	Infectious: substances and preparations containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms.
HP10	Toxic for reproduction: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce non-hereditary congenital malformations or increase their incidence.
HP11	Mutagenic: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defects or increase their incidence.
HP12	Waste which releases toxic or very toxic gases in contact with water, air or an acid.
HP13	Sensitizing: substances and preparations which, if they are inhaled or if they penetrate the skin, are capable of eliciting a reaction of hypersensitisation such that on further exposure to the substance or preparation, characteristic adverse effects are produced.
HP14	Ecotoxic: waste which presents or may present immediate or delayed risks for one or more sectors of the environment.
HP15	Production of hazardous substance after disposal: Waste capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics above.

***Table A.4**: Greatmoor EfW IBA hazardous assessment results*

Hazard property	Parameter	Value	Limit
HP4/HP8	pH	12.70	-
	Alkali reserve	1.06 NaOH g/100g	-
	Irritancy[1]	12.79	13.02 (HP4)
	Corrosivity	12.79	14.50 (HP8)
HP5	Lead compounds	814 mg/kg	10,000 mg/kg
	Potassium dichromate	1.25 mg/kg	1,000 mg/kg
	Sodium dichromate	1.25 mg/kg	1,000 mg/kg
HP6	Chromium (VI) trioxide	1.15 mg/kg	1,000 mg/kg
	Cobalt oxide	33.9 mg/kg	10,000 mg/kg
	Copper hydroxide	885 mg/kg	1,000 mg/kg
	Iron arsenate	13.5 mg/kg	1,000 mg/kg
	Magnesium chromate	1.62 mg/kg	1,000 mg/kg
	Nickel hydroxide	91.5 mg/kg	10,000 mg/kg
	Potassium dichromate	1.25 mg/kg	1,000 mg/kg
	Sodium dichromate	1.25 mg/kg	1,000 mg/kg
	Strontium chromate	415 mg/kg	10,000 mg/kg
HP7	Barium chromate	2.92 mg/kg	1,000 mg/kg
	Calcium chromate	1.80 mg/kg	1,000 mg/kg
	Chromium (VI) compounds	0.60 mg/kg	1,000 mg/kg
	Chromium (VI) trioxide	1.15 mg/kg	1,000 mg/kg
	Iron arsenate	13.5 mg/kg	1,000 mg/kg
	Nickel hydroxide	91.5 mg/kg	1,000 mg/kg
	Potassium dichromate	1.25 mg/kg	1,000 mg/kg
	Sodium dichromate	1.25 mg/kg	1,000 mg/kg
	PCDD/PCDF (Total ITEQ)	1.25 ng/kg	1,000 mg/kg
NP10	Lead compounds	814 mg/kg	3,000 mg/kg
	Potassium dichromate	1.25 mg/kg	3,000 mg/kg
	Sodium dichromate	1.25 mg/kg	3,000 mg/kg
HP11	Chromium (VI) trioxide	1.15 mg/kg	1,000 mg/kg
	Magnesium chromate	1.62 mg/kg	1,000 mg/kg
	Potassium dichromate	1.25 mg/kg	1,000 mg/kg
	Sodium dichromate	1.25 mg/kg	1,000 mg/kg
	Strontium chromate	2.35 mg/kg	1,000 mg/kg
HP13	Calcium chromate	1.80	100,000 mg/kg
	Iron arsenate	13.5	100,000 mg/kg

[1] pH + 1/12th alkali reserve

***Table A.5**: Number of exceedances in hazardous assessments*

H4/8	0	**H10**	0
H5	0	**H11**	0
H6	0	**H13**	0
H7	0	**H14 (sum > 2500)**	0

A.2 Elemental composition

Elemental composition values are referred to the total amount of IBA arriving at the analysis facility once the oversized material > 300 mm have been removed. This amount will be taken into consideration for the average value and it is explained below.

***Table A.6a**: Elemental composition*

Element	Unit	1	2	3	4	5	6
Aluminum	mg/kg	23601.00	21252.50	23948.21	25785.64	21720.86	22587.68
Antimony	mg/kg	40.30	46.85	39.25	36.13	34.24	31.83
Arsenic	mg/kg	6.05	4.26	4.13	7.03	5.20	4.97
Barium	mg/kg	471.00	346.34	548.03	593.68	505.22	490.93
Beryllium	mg/kg	0.40	0.35	0.33	0.45	0.51	0.44
Boron	mg/kg	69.90	79.84	80.72	67.49	84.04	77.60
Cadmium	mg/kg	7.19	16.73	5.69	196.03	5.36	3.25
Calcium	mg/kg	101107.00	74036.64	90571.64	92474.18	82360.91	83804.93
Chromium	mg/kg	71.30	86.99	74.26	83.57	64.16	67.48
Cobalt	mg/kg	24.10	26.55	30.16	52.54	24.95	19.56
Copper	mg/kg	2652.00	2414.28	3100.21	3156.62	2872.96	2186.39
Iron	mg/kg	22227.00	31581.22	28916.33	43127.34	22297.04	26655.19
Lead	mg/kg	487.00	962.74	666.10	1030.53	813.82	595.10
Lithium	mg/kg	15.10	15.90	14.23	24.31	15.32	30.44
Magnesium	mg/kg	7758.00	5636.16	7143.84	7806.37	7242.39	6996.59
Manganese	mg/kg	644.00	1141.26	783.24	1917.93	808.85	1184.06
Mercury	mg/kg	0.75	0.78	0.73	0.82	0.87	0.87
Molybdenum	mg/kg	6.53	8.41	5.30	5.76	5.14	4.47
Nickel	mg/kg	61.50	92.94	75.79	198.41	57.92	77.13
Phosphorus	mg/kg	5312.00	4924.21	5076.67	4100.71	3786.15	3725.28
Potassium	mg/kg	2431.00	2317.23	2414.13	2885.82	2588.03	2560.88
Selenium	mg/kg	0.75	0.78	0.73	0.82	0.87	0.87
Silver	mg/kg	7.11	4.77	3.19	24.52	5.06	3.90

Sodium	mg/kg	7262.00	4655.72	7798.48	7548.96	7404.98	8061.86
Strontium	mg/kg	178.00	188.93	169.29	193.13	178.69	177.18
Thallium	mg/kg	0.75	0.78	0.73	0.82	0.87	0.87
Tin	mg/kg	105.00	199.84	103.49	183.01	102.70	139.91
Titanium	mg/kg	1971.00	1715.08	2016.55	2208.82	-	1980.26
Vanadium	mg/kg	34.40	35.18	35.88	44.32	40.64	39.42
Zinc	mg/kg	2465.00	2843.59	2731.13	3809.07	2134.20	2220.22

***Table A.6b**: Elemental composition*

Element	**Unit**	**7**	**8**	**9**	**10**	**11**	**12**
Aluminum	mg/kg	20764.74	23064.36	26104.23	21603.17	24593.00	24320.39
Antimony	mg/kg	30.81	30.92	53.27	35.67	54.40	54.40
Arsenic	mg/kg	4.53	5.12	5.23	4.33	6.00	5.36
Barium	mg/kg	512.52	518.25	533.59	544.69	534.00	542.53
Beryllium	mg/kg	0.42	0.39	0.44	0.41	0.42	0.41
Boron	mg/kg	79.07	79.21	75.38	75.50	54.60	63.84
Cadmium	mg/kg	11.31	10.07	5.14	2.68	10.80	9.97
Calcium	mg/kg	70010.36	72401.14	82614.50	79257.15	92469.00	92282.35
Chromium	mg/kg	84.11	114.00	70.04	86.33	61.90	60.23
Cobalt	mg/kg	28.37	70.79	28.27	26.60	30.50	25.76
Copper	mg/kg	2601.53	2533.64	2758.71	1665.61	1648.00	1594.34
Iron	mg/kg	44568.43	62160.97	36221.56	50651	26838.00	19260.39
Lead	mg/kg	493.36	899.37	555.06	817.79	826.00	929.58
Lithium	mg/kg	16.93	23.38	15.66	17.11	18.70	17.66
Magnesium	mg/kg	6806.90	6234.50	7350.12	6803.80	7939.00	7884.86
Manganese	mg/kg	1453.94	1764.03	732.00	653.56	560.00	538.49
Mercury	mg/kg	0.90	0.88	0.85	0.88	0.77	0.74
Molybdenum	mg/kg	4.69	6.61	4.22	10.87	4.05	5.29
Nickel	mg/kg	82.35	214.16	96.46	77.69	50.70	59.23

Phosphorus	mg/kg	3405.09	3534.46	5303.48	3837.98	5280.00	5524.78
Potassium	mg/kg	2521.26	2556.04	2672.21	2666.27	3181.00	3248.80
Selenium	mg/kg	0.90	0.88	0.85	0.88	0.77	0.74
Silver	mg/kg	18.03	4.39	2.51	3.01	2.85	6.17
Sodium	mg/kg	7111.62	8504.93	7750.95	8359.38	7847.00	8174.35
Strontium	mg/kg	166.69	173.60	203.81	192.02	186.00	176.93
Thallium	mg/kg	0.90	0.95	0.85	0.88	0.77	0.74
Tin	mg/kg	97.72	113.76	148.83	101.35	111.00	93.84
Titanium	mg/kg	2016.68	2063.23	2021.15	2087.24	1754.00	1820.65
Vanadium	mg/kg	40.15	34.64	39.20	35.49	47.10	43.10
Zinc	mg/kg	2851.36	3025.65	2234.31	1890.48	2297.00	2220.59

***Table A.6c**: Elemental composition*

Element	**Unit**	**14**	**15**	**16**	**17**	**18**	**19**
Aluminum	mg/kg	19849.94	23083.33	18693.78	19757.57	23856.17	17551.22
Antimony	mg/kg	37.97	35.78	36.91	42.25	48.93	31.63
Arsenic	mg/kg	4.53	4.91	4.54	4.81	4.33	4.27
Barium	mg/kg	587.37	571.69	561.12	613.76	647.26	542.02
Beryllium	mg/kg	0.39	0.43	0.38	0.40	0.46	0.40
Boron	mg/kg	82.24	59.85	169.11	104.29	89.23	89.08
Cadmium	mg/kg	9.49	9.05	9.76	3.78	8.08	7.17
Calcium	mg/kg	88804.38	84157.25	77632.93	85219.30	118428.11	77155.56
Chromium	mg/kg	88.08	73.13	96.40	117.58	81.32	97.13
Cobalt	mg/kg	35.20	44.38	27.09	36.51	31.20	62.59
Copper	mg/kg	2875.32	1752.22	4286.69	2515.56	2367.88	2573.88
Iron	mg/kg	50920.08	33733.38	53741.77	60642.61	31367.08	60848.78
Lead	mg/kg	886.52	699.55	756.21	937.57	1171.32	909.89
Lithium	mg/kg	17.73	18.26	15.20	15.84	18.00	20.36
Magnesium	mg/kg	7048.90	7619.26	6274.95	6802.21	8820.71	6106.12

Manganese	mg/kg	1032.38	546.46	713.76	1175.02	502.30	3841.84
Mercury	mg/kg	0.84	0.78	0.84	0.90	0.75	0.84
Molybdenum	mg/kg	5.16	5.64	5.80	6.81	5.83	6.07
Nickel	mg/kg	81.56	83.60	69.26	209.48	68.83	119.51
Phosphorus	mg/kg	3851.48	4902.83	3685.41	3675.90	6122.65	3311.44
Potassium	mg/kg	2480.29	2970.88	2104.10	2396.51	3043.93	2361.41
Selenium	mg/kg	0.84	0.78	0.84	0.90	0.75	1.40
Silver	mg/kg	9.62	6.74	3.12	6.10	3.95	3.22
Sodium	mg/kg	7762.22	7440.23	7603.26	7620.89	8691.10	7566.07
Strontium	mg/kg	228.58	160.70	175.28	204.18	203.09	177.64
Thallium	mg/kg	0.84	0.78	0.84	0.90	0.75	0.93
Tin	mg/kg	233.52	148.44	101.74	131.61	112.29	126.04
Titanium	mg/kg	2221.25	1840.32	1890.72	2102.15	1896.49	2183.85
Vanadium	mg/kg	39.35	43.70	34.58	36.17	46.29	30.15
Zinc	mg/kg	2563.10	2384.46	2039.32	2531.87	2380.84	3186.23

***Table A.6d**: Elemental composition*

Element	**Unit**	**20**	**21**	**22**	**23**	**24**	**Average**	**Average***
Aluminum	mg/kg	18393.50	19804.58	21479.25	18393.50	19757.57	22450.57	21791.62
Antimony	mg/kg	42.26	41.86	53.62	42.26	42.25	40.57	39.38
Arsenic	mg/kg	8.05	4.75	4.85	8.05	4.81	5.15	5.00
Barium	mg/kg	577.07	572.52	610.08	577.07	613.76	526.58	511.12
Beryllium	mg/kg	0.38	0.41	0.41	0.38	0.40	0.44	0.42
Boron	mg/kg	106.38	101.22	77.86	106.38	104.29	81.05	78.67
Cadmium	mg/kg	8.49	5.03	7.69	8.49	3.78	19.07	18.51
Calcium	mg/kg	89235.77	89475.55	102955.99	89235.77	85219.30	83841.02	81380.17
Chromium	mg/kg	83.33	114.62	86.21	83.33	117.58	80.33	77.97
Cobalt	mg/kg	34.03	42.92	32.55	34.03	36.51	34.11	33.11
Copper	mg/kg	1651.92	2382.45	2238.90	1651.92	2515.56	2487.34	2414.33

Iron	mg/kg	41127.37	61774.66	44019.82	41127.37	60642.61	37805.62	36695.97
Lead	mg/kg	1137.45	808.06	1469.97	1137.45	937.57	755.06	732.90
Lithium	mg/kg	16.72	23.67	17.91	16.72	15.84	18.08	17.55
Magnesium	mg/kg	7073.60	7074.77	7604.01	7073.60	6802.21	7058.52	6851.35
Manganese	mg/kg	607.20	1144.57	652.17	607.20	1175.02	955.74	927.69
Mercury	mg/kg	0.84	0.88	0.79	0.84	0.90	0.80	0.78
Molybdenum	mg/kg	6.25	6.79	5.39	6.25	6.81	6.04	5.86
Nickel	mg/kg	65.01	95.03	74.26	65.01	209.48	97.41	94.55
Phosphorus	mg/kg	3424.50	2590.03	5463.31	3424.50	3675.90	4388.17	4259.37
Potassium	mg/kg	2353.06	2403.19	2570.29	2353.06	2396.51	2626.77	2549.67
Selenium	mg/kg	0.83	0.88	0.79	0.83	0.90	0.80	0.78
Silver	mg/kg	8.59	3.83	4.39	8.59	6.10	6.69	6.50
Sodium	mg/kg	6690.41	7666.60	7871.15	6690.41	7620.89	7546.17	7324.68
Strontium	mg/kg	189.17	195.97	202.59	189.17	204.18	189.54	183.98
Thallium	mg/kg	0.84	0.88	0.79	0.84	0.90	0.78	0.76
Tin	mg/kg	106.84	229.87	121.87	106.84	131.61	130.73	126.89
Titanium	mg/kg	1982.01	2098.50	2104.61	1982.01	2102.15	1956.39	1898.97
Vanadium	mg/kg	36.36	35.57	35.90	36.36	36.17	39.09	37.95
Zinc	mg/kg	2333.33	2474.97	2505.31	2333.33	2531.87	2467.90	2395.46

The column titled Average* corresponds to the average concentration of each element taking into account the amount of oversized material > 300 mm removed on site prior analysis. This amount of material corresponds to 2.94% of mass of IBA. The correction has been made following the procedure below.

$$[Average^*] = [Average] \cdot \frac{100 - [\%\ oversized\ metals\ removed]}{100}$$

Appendix B

Equipment details

B.1 Metso C96 Jaw Crusher

Budget Quotation / Technical Specification Quote Ref.:**CSE312263**
Customer: FCC Environment Date:12/05/2016

Item 1 – Metso C96 Jaw Crusher

Nordberg C Series Jaw crushers are well known for reliability and high performance.
C Jaws are based on a revolutionary modular and non-welded main frame construction for extremely good fatigue strength.
All C Series Jaws are engineered to crush hard feed materials and they are successfully applied in different mining, quarrying, contracting and recycling applications just to mention a few.
C Series Jaws are easy to install and they can be equipped with various options to meet any application requirements.

MAIN UNIT

Frequency	50 Hz
Main voltage	400V
Cavity	Standard
Jaw die configuration	Single piece jaw dies
Setting adjustment	Active setting control
Ambient temperature	Normal
Support brackets	Standard
Protection plate for pitman	Included
Protection plate - front frame	Included

AUTOMATION

Automation system	IC1000
Crusher setting measurement	Included

DRIVE EQUIPMENT

Drive side	Right
Groove type	SPB
Motor base	Integral w/o support bearings
Guards	Included
Motor pulley	Included
V-Belts	Included

MOTOR

Motor supplier	Metso
Motor type	Squirrel gage
Motor power	90 KW
Motor speed	1,500 1/min
Motor shaft diameter	75 mm
Motor shaft height	280 mm

FINISHING

Colour	Metso beige
Safety labels	ISO
Transportation	Built complete

DOCUMENTATION

Lang. for electronic manual	English
Electronic spare part book	Included

Net Price.....**CIF- UK site**.....**£ 152,750.00**

Metso (UK) Ltd.
Parkfield Road, Rugby, Warwickshire CV21 1QJ
Telephone: 01788 532100 FAX: 01788 547883

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Figure B.1: Metso C96 Jaw Crusher quotation

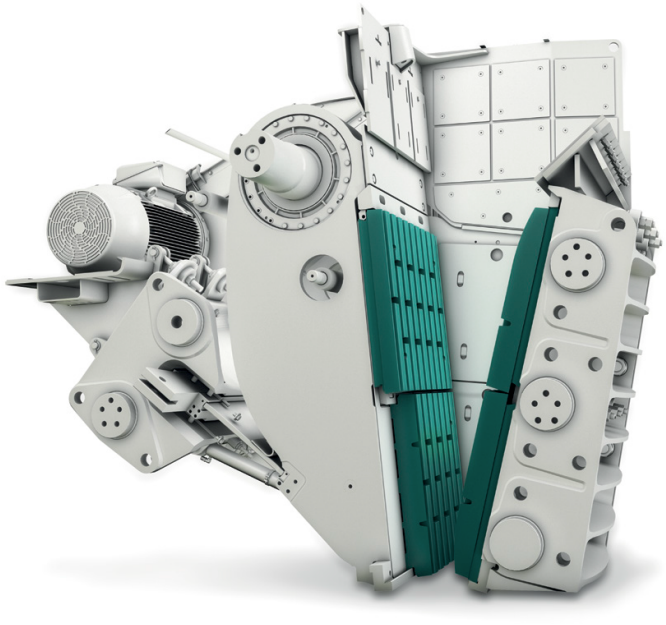

***Figure B.2**: Metso C96 Jaw Crusher*

B.2 Magnapower overband magnet OIP 3380 E

MAGNAPOWER
magnetic processing technology

Overband Magnet Application Details

Application Ref	A	B			
Separation of:	Tramp metal				
From:	incinerator bottom ash				
Throughput (weight):	22	12			tonnes / hour
Density:	1.2	1.2			tonnes / M^3
Maximum product size:	40	40			mm
Average product size estimated for calculations:	30	30			mm
Customer's product belt width:	600	600			mm
Customer's product belt speed:	1.0	1.0			M/s
Proportion of non-ferrous metal:	5	5			%
Proportion of ferrous metal:	10	10			%
Separator type requested or recommended:	Overband				
Burden depth	(or calculated below)				mm
Overband magnet position	Inline belt				
Overband Magnet operating gap:	250	250			mm
Magnet width:	600	600			mm
Magnet Length:	1100	1100			mm
Magnetic Force at operating gap:	8,500	8500			gauss sqd/cm

Magnapower overband Calculations using the above information					
Throughput (volume):	18.3	25.0			M^3 / hour
Burden depth @ 75% belt width coverage	11.3	15.4			mm
Magnet working gap	250	250			mm

Application Reference			
Item No.	Part No	Description	Unit Price (GBP)
1.0	OIP 3380 E	Overband magnet (INLINE)	£6,700.00
		Suitable for belt width up to 800mm and working gap of 250mm	
		Total	£6,700.00

Magnet Working Gap
The magnet working gap referred to above is our recommendation typically based on at least 100mm above your burden depth, trough height or lump size (whichever is the greatest). If we have not estimated this correctly, then please let us know so we can revise this proposal accordingly.

This price is ex-works UK and subject to VAT if applicable.
Additional terms are shown below.

Lead Time
Approximately 6 working weeks from the date of a signed contract, completed lay-out, and receipt of prepayment, whichever is latest? If an alternative lead time is required, then please let us know and we will do our utmost to accommodate your requirements.

Currency
Prices quoted are fixed in Pounds Sterling GBP.

Magnapower Equipment Ltd, 28 Harris Business Park, Hanbury Road, Bromsgrove, Worcestershire. B60 4DJ. UK
TEL:+44(0) 1527 557 092 **FAX:**+44(0) 1527 557 019 **email:** info@magnapower.co.uk **web:** www.magnapower.co.uk
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Figure B.3: Magnapower overband magnet OIP 3380 E quotation

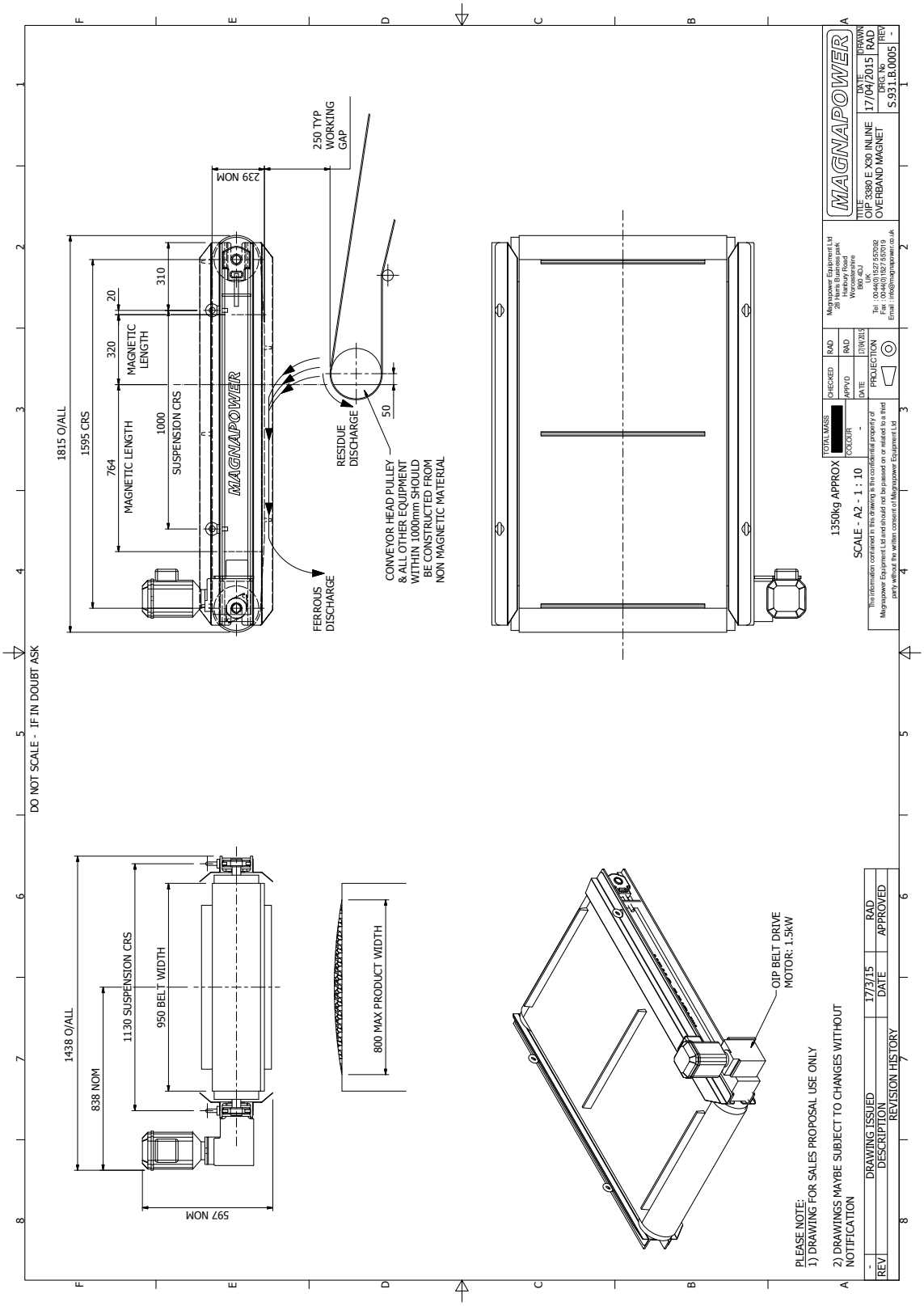

***Figure B.4**: Magnapower overband magnet OIP 3380 E plan*

B3. Holman Wilfley Holman 3000 shaking table

Holman-Wilfley

FCC Environment UK

Our Ref: E154.05.16
Date: 18.05.16

Pricing

Model Holman 3000, Gravity Table

Complete with Deck (black rubber covered), Holman drive, motor drive assembly and undercarriage assembly, for installation on level sound flooring:
Standard Electrics 380/415V 50Hz 3phase
Refer Drawing: GA W698 Right hand

Unit Price Ex-works UK	**GB£ 14,100.00**
Product Launder set (3 x 80mm NB outlets)	**GB£ 1,340.00**
Packing /Delivery (fully assembled) UK address	**GB£ 480.00**

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***Figure B.5**: Holman Wilfley Holman 3000 shaking table quotation*

Holman-Wilfley

Technical Specification of Equipment.

Holman mechanical drive gearbox
Deck attached to tilt frame, with 20 off carrier straps. Main tilt frame mounted on tilt shaft supports and supported by base steel frame for installation onto level floor. Drive imparted by Holman gearbox flywheel via V-belt motor drive.

- **Adjustable Deck Tilt (by Handwheel)**
- **Adjustable Machine Stroke (by Handwheel)**
- **Adjustable Wash water (By Valve)**

General Details

Serial Number: -	
Equipment Model: -	Holman 3000
Number of Units: -	ONE
Maximum capacity	~850kg/hour (feed size dependent)
Design	Feed size <3mm (inc. ash)
Equipment Packing Details: -	Part assembled ~1100kgs Net (gross 1295kg)
Description of Drawings Supplied: -	W698 GA

Electrical Details

Motor Manufacturer: -	To be advised
Serial Number: -	
Kilowatts: -	1.5
Supply Voltage: -	380-415V, 3 phase, 50Hz
Speed (rpm): -	1125
Number of Poles: -	6
Frame Size: -	100L
IP Rating: -	56
Motor Pulley	100 mm dia. (2 grooved)

All Motors comply with European CE Regulations.

Mounting Details

Mounting Description: -
Steel support frame for level floor bolting.

Mechanical Details

Reference Head Motion Details Drawing No: -	
Stroke Length Operating Range, mm: -	Nominal 8 - 16 mm
Steel Specification: -	British Section RSC Channel 80 x 80 x 6mm RSA
Timber Deck:	
Topcoat Colour	20D45 (Sapphire Blue)
Main steels	Galvanised BSEN1461
Bolt Specification: -	8.8 High tensile Zinc plated

Figure B.6: Holman Wilfley Holman 3000 shaking table information 1

Holman-Wilfley

Lubrication Details

Head Motion Oil Specification: -	Shell Omerta/Mobilgear 630 or equivalent [SAE 20W/50 Motor Engine oil is also suitable].
Tools Details (if applicable)	1 off Stroke Adjusting Spanner

Tools provided: -

Drive Details

Drive Pulley Type: -	4 Groove SPA 100
Drive Belt Specification: -	SPA 1450
Flywheel Specification: -	355mm
Head Motion Drive Shaft Speed, rpm: -	270 – 280 Fixed

Table Deck Details

Dimensions of Deck (mm): -	1085 (Conc. Edge), 2646 (Tail. edge)
Weight of Deck (kgs): -	160 (Without any attachments)
Deck Material Description: -	WPB Plywood
Deck Cover Description: -	Black 5mm rubber
Deck Riffle Material: -	LDPE
Deck Riffle Pattern: -	Std recycling
Feed Box Details: -	Standard fibreglass, open discharge
Wash Water Pipe Details: -	1.5” galvanised pipe, 5mm holes at 40mm centres.

Discharge Launder Details (price option)

THREE PORT (80mmNB) Standard GRP, with free standing galvanised supports

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Figure B.7: Holman Wilfley Holman 3000 shaking table information 2

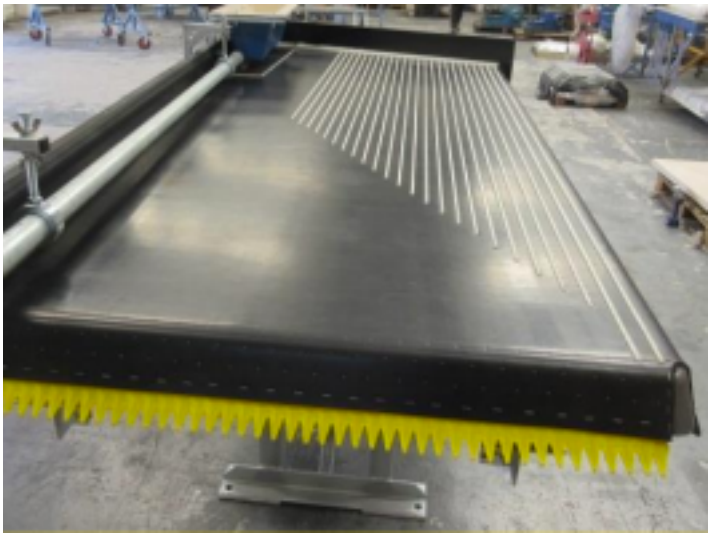


***Figure B.8**: Holman Wilfley Holman 3000*

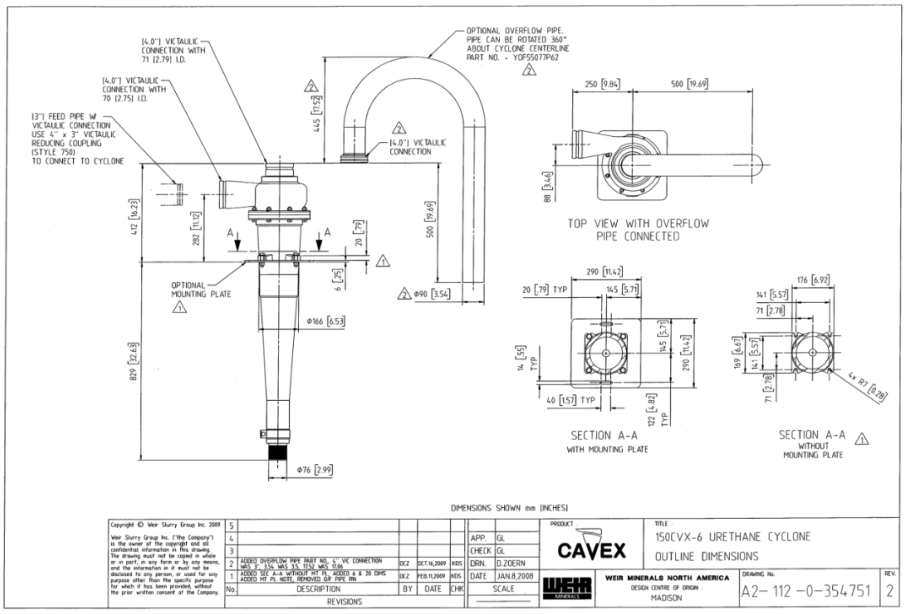
B4. Weir Minerals CAVEX® Hydrocyclone 150CVX6

Bid Equipment

Cyclone
One (1) CAVEX Model (150-06P CVX) Cyclone with a 40mm Solid Polyurethane Vortex Finder and 20mm Spigot Liner. Includes Overflow Pipe and Spiral Contoured Inlet Head Liner for low turbulence and longer wear life.

Price for one (1)
Cyclone……$1,965.00

Figure B.9: Weir Minerals CAVEX® Hydrocyclone 150CVX6 quotation



Warman International **CAVEX®**

CAVEX Flow Curve	Model : 150CVX6	Ref : 150V6-41

Feed Chamber Liner		Vortex Finder	
Part No.	**Diameter**	**Part No.**	**Diameter**
06035CVX41	41 mm	06080CVX40	40 mm
		06080CVX50	50 mm
		06080CVX60	60 mm

Figure B.10: Weir Minerals CAVEX® Hydrocyclone 150CVX6 information

B5. Well-Tech jig concentrator JT4-2

SPECIFICATIONS FOR JIG CONCENTRATOR				
Model	JT0.57-1	JT2-2	JT4-2	JT5-2
Feeding size(mm)	<6	<10	<25	<25
Amount make up water(m^3/t)	1-2	2-4	4-8	9-6
Capacity(t/h)	1.5-3	5-10	8-20	12-25
Power(Kw)	1.5	3	7.5	7.5
Dimensions(mm)	1550*780*1530	3225*1550*2050	4240*1990*2750	3600*2000*3600
Weight(Kg)	610	1640	3100	4500

***Figure B.11**: Well-Tech jig concentrator details*

B6. Magaldi ECOBELT

Magaldi Power S.p.A.
Via Irno, 219 | 84135 Salerno, Italy
Tel. +39 089 489 111 | Fax +39 089 274 431

2.9 Technical Data

All design data are summarized in the table below:

Handled Material	**Dry slag (bottom ash)**
Material Bulk Density for Volume calculation	**1˙000 ÷ 1˙400 kg/m^3**
Material Moisture Content	**Dry**
Max particle size	**300mm**
Material Inlet Temperature	**500°C max as solid state**
Material Abrasiveness	**Very abrasive**
Pressure inside Conveyors	**Conveyors will be connected to a point at negative pressure (TBD)**
Average / Max Material Production	**8.56t/h (design capacity)**
Required Function	**Limiting air, passing into the conveyor**
Ambient Temperature	**5 ÷ 50 °C**
Power Supply	**3 x 400 Vac, 50 Hz (drive IP65)**

2.10 List of Electrical Motors

	ELECTRICAL MOTORS	Number of drives in operation	Preliminary Installed Power (*) [kW]
	Magaldi ECOBELT® WA conveyor	1	1 x 3
	Magaldi Spill Chain	1	1 x 1,5
		TOTAL	**4,5**

(*) *The installed power values will be confirmed during the final engineering stage.*

Figure B.12: Magaldi ECOBELT technical information

Magaldi Power S.p.A.
Via Irno, 219 | 84135 Salerno, Italy
Tel. +39 089 489 111 | Fax +39 089 274 431

3 COMMERCIAL TERMS

3.1 Introduction

The prices given in this quotation are based on the scope of supply as defined in par. 2.2, with the exclusions as defined in par. 2.3.

3.2 Budget Quotation (+/- 10%) for the ECOBELT® WA Conveyors project

Budget Price for the Magaldi ECOBELT® WA conveyor (belt pans in aisi304L), to handle bottom ash at Greatmoor Energy WtE Plant in UK as per the scope of supply defined in par. 2.2 with the exclusions defined in par. 2.3, is:

299˙000,-- Euro
(Two Hundred and Ninety-nine Thousand Euro/00)

3.3 Price Adjustment

Any changes in design criteria and/or in scope of supply may imply a price adjustment.

3.4 Taxes, Duties, Levies

The prices indicated in this offer are indicated in Euro currency and are to be considered net of any current or future taxes including but not limited to VAT, duties, levies, interest payments, movement of goods, personnel or corporate income taxes or other charges (no matter what type).

3.5 Terms of Delivery

The delivery of the equipment under this Proposal will be done, as an option, EXW Buccino (SA) - Italy **20 weeks** after receipt of purchase order, down-payment and clarification of technical details. All trade terms provided in this Proposal shall be interpreted in accordance with the year 2010 version of INCOTERMS, as published by the International Chamber of Commerce, Paris France.

3.6 Validity of Proposal

This proposal is valid for three months from the date of its issuance (*see cover page*).

Figure B.13: Magaldi ECOBELT quotation

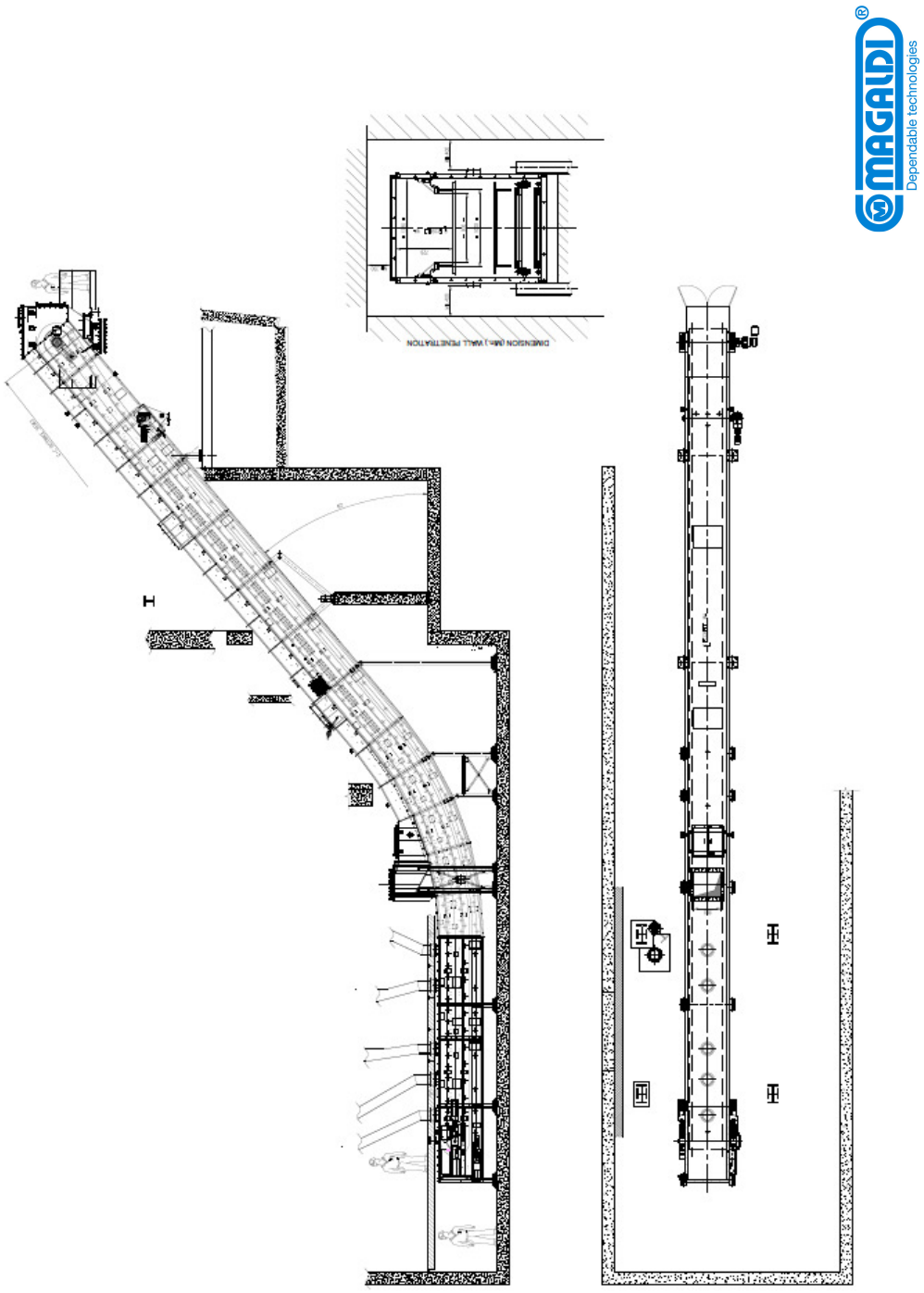


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Figure B.14: Magaldi ECOBELT plan

WTE & BIOMASS

Client: A Swiss CHP Plant
Project: Slag handling retrofit

Start-up date: July 2015

EQUIPMENT DATA:	
Superbelt® type:	ED4.NX.1006.206/S
Centre distance:	30.363 mm
Width:	1000 mm
Inclination:	40 degrees
Installed power:	3 kW

PROCESS DATA:	
Material:	Waste ash
Capacity:	900 kg/h
Temperature:	500 °C

Project Description:

In October 2014, a Swiss engineering customer awarded Magaldi the installation of the patented **Magaldi Ecobelt® WA** (Waste Ash) conveyor for an Incinerator located close to Zurich - Switzerland. The **Magaldi Ecobelt® WA** is actually under erection and it is a retrofit of the existing wet Apron conveyor.
The hot slag falls from the existing combustion grate that has five hoppers in a row (for grate throughput) and one discharge chute for the waste slag at its end. Everything is connected with the **Magaldi Ecobelt® WA** conveyor by means of chutes, which cools and conveys the hot slag in a complete dry mode to the downstream equipment.
The **Magaldi Ecobelt® WA** is 40 degrees inclined and 30 meters long. The belt is equipped with cleats to avoid the material to roll back. The amount of cooling air flowing into the furnace is limited by means of suitably designed skirtboards of the steel belt conveyor and special flaps hinged to the conveyor covers, that allow the slag passage while preventing uncontrolled air backflow to the furnace.
A scraper conveyor removes the fine residuals, generated by the turbulence of the loading and discharge chutes, from the bottom of the **Magaldi Ecobelt® WA** casing. Usually the Magaldi Spill-chain conveyor is operating temporized for short periods due to small quantity of material to be conveyed. The dry material conveyed with our **Magaldi Ecobelt® WA** is then processed in a metal recovery Plant to separate valuable metals such as iron, aluminum, copper, gold, silver, etc., improving the separation efficiency and metal quality.

BENEFITS:

- Zero water usage.
- No dust or gas dispersion to the environment.
- No risks of sudden failures thanks to the multilink Superbelt® design.
- Flexible layout arrangement, including inclined ramps for material lifting.
- Possibility to recover ferrous and non-ferrous metals from dry bottom ash, allowing access to small particles (< 5 mm).
- Boiler efficiency improvement due to recovery of ash enthalpy in the form of sensible heat.

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Figure B15: Magaldi ECOBELT experience

Appendix C

Metal prices forecast modeling

C1. Aluminum

C1.1. Historical data

***Table C1**: Aluminum price historical data*

ALUMINUM PRICE HISTORICAL DATA					
Year	**US$/ton**	**£/ton**	**Year**	**US$/ton**	**£/ton**
1980	1,430.66	993.51	1999	1,554.48	1,079.50
1981	1,130.88	785.33	2000	1,565.14	1,086.90
1982	987.40	685.69	2001	1,344.63	933.77
1983	1,549.30	1,075.90	2002	1,375.07	954.91
1984	1,095.20	760.56	2003	1,554.90	1,079.79
1985	1,039.20	721.67	2004	1,849.18	1,284.15
1986	1,133.48	787.14	2005	2,247.45	1,560.73
1987	1,823.93	1,266.62	2006	2,813.63	1,953.91
1988	2,502.65	1,737.95	2007	2,381.69	1,653.95
1989	1,633.26	1,134.21	2008	1,490.43	1,035.02
1990	1,522.44	1,057.25	2009	2,180.10	1,513.96
1991	1,097.55	762.19	2010	2,350.67	1,632.41
1992	1,207.10	838.26	2011	2,022.25	1,404.34
1993	1,094.30	759.93	2012	2,086.76	1,449.14
1994	1,878.31	1,304.38	2013	1,739.81	1,208.20

1995	1,656.74	1,150.51	2014	1,909.46	1,326.01
1996	1,500.29	1,041.87	2015	1,497.20	1,039.72
1997	1,530.51	1,062.85	2016	1,531.01	1,063.20
1998	1,249.06	867.40			

C1.2. Moving Means with Linear Trend

***Table C2**: Aluminum price moving means*

MOVING MEANS					
Year	**t**	**MM**	**Year**	**t**	**MM**
1980	1	-	1999	20	1,011.27
1981	2	821.51	2000	21	1,033.39
1982	3	848.98	2001	22	991.86
1983	4	840.72	2002	23	989.49
1984	5	852.71	2003	24	1,106.28
1985	6	756.45	2004	25	1,308.22
1986	7	925.14	2005	26	1,599.60
1987	8	1,263.90	2006	27	1,722.86
1988	9	1,379.59	2007	28	1,547.63
1989	10	1,309.80	2008	29	1,400.98
1990	11	984.55	2009	30	1,393.80
1991	12	885.90	2010	31	1,516.90
1992	13	786.79	2011	32	1,495.30
1993	14	967.53	2012	33	1,353.89
1994	15	1,071.61	2013	34	1,327.78
1995	16	1,165.59	2014	35	1,191.31
1996	17	1,085.08	2015	36	1,142.98
1997	18	990.71	2016	37	-
1998	19	1,003.25			

***Table C3**: Regression line data*

$\overline{MM}$	1,144.95
$Cov(MM, t)$	1,701.32
$Var(t)$	117.17
$\bar{t}$	19

***Table C4**: Regression line points (predictions)*

REGRESSION LINE					
t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$	t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1	883.58	12,084.72	22	1,188.51	64,894.57
2	898.10	12,717.20	23	1,203.04	61,566.41
3	912.62	51,497.23	24	1,217.56	18,979.03
4	927.15	22,128.87	25	1,232.08	2,711.93
5	941.67	32,800.84	26	1,246.60	98,678.91
6	956.19	54,999.37	27	1,261.12	479,960.74
7	970.71	33,697.13	28	1,275.64	143,120.80
8	985.23	79,180.80	29	1,290.16	65,095.40
9	999.75	544,944.57	30	1,304.68	43,797.68
10	1,014.27	14,385.60	31	1,319.20	98,100.37
11	1,028.79	810.04	32	1,333.72	4,987.15
12	1,043.31	79,029.54	33	1,348.24	10,180.37
13	1,057.83	48,209.27	34	1,362.76	23,888.86
14	1,072.35	97,606.25	35	1,377.28	2,628.44
15	1,086.87	47,310.97	36	1,391.80	123,960.67
16	1,101.39	2,412.99	37	1,406.32	117,732.62
17	1,115.91	5,482.54	38	1,420.84	
18	1,130.43	4,566.87	39	1,435.36	
19	1,144.95	77,034.30	40	1,449.88	
20	1,159.47	6,395.82	41	1,464.41	

21	1,173.99	7,584.95	42	1,478.93

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 70{,}139.56$$

C1.3. Double Exponential Smoothing $\alpha = 0.1$

***Table C5**: Double Exponential Smoothing*

DOUBLE EXPONENTIAL SMOOTHING						
Year	$Z(t)$	$Y(t)$	$b0_t$	$b1_t$	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1980	993.51	993.51	993.51	0.00	993.51	0.00
1981	972.70	991.43	953.96	-2.08	993.51	43,339.14
1982	944.00	986.69	901.30	-4.74	951.88	70,853.57
1983	957.19	983.74	930.63	-2.95	896.56	32,164.08
1984	937.52	979.12	895.93	-4.62	927.68	27,932.04
1985	915.94	972.80	859.08	-6.32	891.31	28,778.32
1986	903.06	965.82	840.29	-6.97	852.76	4,305.94
1987	939.41	963.18	915.64	-2.64	833.32	187,750.05
1988	1,019.27	968.79	1,069.74	5.61	913.00	680,540.05
1989	1,030.76	974.99	1,086.53	6.20	1,075.35	3,464.13
1990	1,033.41	980.83	1,085.99	5.84	1,092.73	1,258.92
1991	1,006.29	983.38	1,029.20	2.55	1,091.83	108,665.47
1992	989.49	983.99	994.98	0.61	1,031.75	37,435.02
1993	966.53	982.24	950.82	-1.75	995.59	55,537.57
1994	1,000.32	984.05	1,016.58	1.81	949.07	126,244.64
1995	1,015.34	987.18	1,043.49	3.13	1,018.39	17,457.03
1996	1,017.99	990.26	1,045.72	3.08	1,046.62	22.59
1997	1,022.48	993.48	1,051.47	3.22	1,048.80	197.54
1998	1,006.97	994.83	1,019.11	1.35	1,054.69	35,076.96
1999	1,014.22	996.77	1,031.67	1.94	1,020.46	3,486.30
2000	1,021.49	999.24	1,043.74	2.47	1,033.61	2,839.82

2001	1,012.72	1,000.59	1,024.85	1.35	1,046.21	12,642.57
2002	1,006.94	1,001.22	1,012.65	0.63	1,026.19	5,081.48
2003	1,014.22	1,002.52	1,025.92	1.30	1,013.29	4,423.13
2004	1,041.22	1,006.39	1,076.04	3.87	1,027.22	66,013.84
2005	1,093.17	1,015.07	1,171.26	8.68	1,079.91	231,189.56
2006	1,179.24	1,031.49	1,327.00	16.42	1,179.94	599,027.61
2007	1,226.71	1,051.01	1,402.41	19.52	1,343.41	96,434.61
2008	1,207.54	1,066.66	1,348.42	15.65	1,421.94	149,704.23
2009	1,238.18	1,083.81	1,392.55	17.15	1,364.08	22,464.60
2010	1,277.61	1,103.19	1,452.02	19.38	1,409.71	49,596.89
2011	1,290.28	1,121.90	1,458.66	18.71	1,471.40	4,496.88
2012	1,306.17	1,140.33	1,472.00	18.43	1,477.37	796.80
2013	1,296.37	1,155.93	1,436.81	15.60	1,490.43	79,652.76
2014	1,299.33	1,170.27	1,428.39	14.34	1,452.41	15,976.05
2015	1,273.37	1,180.58	1,366.16	10.31	1,442.74	162,419.36
2016	1,252.36	1,187.76	1,316.95	7.18	1,376.47	98,138.86
2017					1,324.13	
2018					1,331.31	
2019					1,338.48	
2020					1,345.66	
2021					1,352.84	

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 82{,}848.88$$

C1.4. Holt method $\alpha = 0.8, \beta = 0.2$

Table C6: Holt method

HOLT METHOD				
Year	L_t	b_t	$\hat{y}_{t+h,t}$	$(y_t - \hat{y}_t)^2$
1980	993.51	-208.18	993.51	0.00
1981	785.33	-208.18	785.33	0.00
1982	663.99	-190.81	577.15	11,781.29
1983	955.36	-94.38	473.17	363,284.12
1984	780.64	-110.44	860.98	10,085.00
1985	711.37	-102.21	670.20	2,649.28
1986	751.54	-73.73	609.16	31,675.43
1987	1,148.86	20.48	677.81	346,694.48
1988	1,624.23	111.45	1,169.33	323,327.53
1989	1,254.50	15.22	1,735.68	361,771.21
1990	1,099.74	-18.78	1,269.72	45,144.45
1991	825.94	-69.78	1,080.97	101,620.98
1992	821.84	-56.65	756.16	6,740.68
1993	760.98	-57.49	765.20	27.75
1994	1,184.20	38.65	703.50	361,063.71
1995	1,164.98	27.08	1,222.86	5,233.75
1996	1,071.91	3.05	1,192.06	22,558.05
1997	1,065.27	1.11	1,074.95	146.42
1998	907.20	-30.73	1,066.39	39,594.26
1999	1,038.89	1.76	876.47	41,219.66
2000	1,077.65	9.16	1,040.65	2,139.01
2001	964.38	-15.33	1,086.81	23,421.40
2002	953.74	-14.39	949.05	34.33
2003	1,051.70	8.08	939.35	19,724.61
2004	1,239.28	43.98	1,059.78	50,341.67

2005	1,505.24	88.37	1,283.26	76,989.98
2006	1,881.85	146.02	1,593.61	129,815.93
2007	1,728.74	86.20	2,027.87	139,817.10
2008	1,191.00	-38.59	1,814.93	608,260.05
2009	1,441.65	19.26	1,152.41	130,715.23
2010	1,598.11	46.70	1,460.91	29,413.41
2011	1,452.43	8.22	1,644.81	57,824.11
2012	1,451.44	6.38	1,460.66	132.66
2013	1,258.13	-33.56	1,457.82	62,310.77
2014	1,305.72	-17.33	1,224.57	10,291.58
2015	1,089.46	-57.12	1,288.40	61,839.04
2016	1,057.03	-52.18	1,032.34	952.33
2017			1,004.85	
2018			952.67	
2019			900.50	
2020			848.32	
2021			796.14	

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 94{,}017.33$$

C1.5. Error analysis

Table C7: Error analysis

ERROR ANALYSIS			
		$y_t - \hat{y}_t$	
Year	**DES**	**MMLT**	**Holt**
1980	0.00	109.93	0.00
1981	-208.18	-112.77	0.00
1982	-266.18	-226.93	108.54
1983	179.34	148.76	602.73

1984	-167.13	-181.11	-100.42
1985	-169.64	-234.52	51.47
1986	-65.62	-183.57	177.98
1987	433.30	281.39	588.81
1988	824.95	738.20	568.62
1989	58.86	119.94	-601.47
1990	-35.48	28.46	-212.47
1991	-329.64	-281.12	-318.78
1992	-193.48	-219.57	82.10
1993	-235.66	-312.42	-5.27
1994	355.31	217.51	600.89
1995	132.13	49.12	-72.34
1996	-4.75	-74.04	-150.19
1997	14.06	-67.58	-12.10
1998	-187.29	-277.55	-198.98
1999	59.04	-79.97	203.03
2000	53.29	-87.09	46.25
2001	-112.44	-254.74	-153.04
2002	-71.28	-248.13	5.86
2003	66.51	-137.76	140.44
2004	256.93	52.08	224.37
2005	480.82	314.13	277.47
2006	773.97	692.79	360.30
2007	310.54	378.31	-373.92
2008	-386.92	-255.14	-779.91
2009	149.88	209.28	361.55
2010	222.70	313.21	171.50
2011	-67.06	70.62	-240.47
2012	-28.23	100.90	-11.52

2013	-282.23	-154.56	-249.62
2014	-126.40	-51.27	101.45
2015	-403.01	-352.08	-248.67
2016	-313.27	-343.12	30.86
St. Dev.	287.18	264.71	305.49
Z (95%)	1.96	1.96	1.96
Margin	±92.54	±85.29	±98.43

C2. Copper

C2.1. Historical data

***Table C8**: Copper price historical data*

COPPER PRICE HISTORICAL DATA					
Year	**US$/ton**	**£/ton**	**Year**	**US$/ton**	**£/ton**
1980	1,879.00	1,304.86	1999	1,764.75	1,225.52
1981	1,655.30	1,149.51	2000	1,850.55	1,285.10
1982	1,473.20	1,023.06	2001	1,471.74	1,022.04
1983	1,415.20	982.78	2002	1,595.68	1,108.11
1984	1,321.10	917.43	2003	2,201.29	1,528.67
1985	1,390.90	965.90	2004	3,145.45	2,184.34
1986	1,335.60	927.50	2005	4,576.78	3,178.32
1987	2,868.90	1,992.29	2006	6,675.10	4,635.49
1988	3,498.91	2,429.80	2007	6,587.67	4,574.77
1989	2,418.60	1,679.58	2008	3,071.98	2,133.32
1990	2,485.38	1,725.96	2009	6,981.71	4,848.41
1991	2,223.14	1,543.85	2010	9,147.26	6,352.26
1992	2,206.82	1,532.51	2011	7,565.48	5,253.81
1993	1,724.19	1,197.35	2012	7,966.49	5,532.28
1994	2,985.30	2,073.13	2013	7,214.90	5,010.35

1995	2,926.26	2,032.13	2014	6,446.45	4,476.70
1996	2,268.08	1,575.06	2015	4,638.83	3,221.41
1997	1,762.33	1,223.84	2016	4,983.80	3,460.97
1998	1,473.57	1,023.31			

C2.2. Moving Means with Linear Trend

***Table C9**: Copper price moving means*

MOVING MEANS					
Year	**t**	**MM**	**Year**	**t**	**MM**
1980	1	-	1999	20	1,177.98
1981	2	1,159.14	2000	21	1,177.56
1982	3	1,051.78	2001	22	1,138.42
1983	4	974.42	2002	23	1,219.61
1984	5	955.37	2003	24	1,607.04
1985	6	936.94	2004	25	2,297.11
1986	7	1,295.23	2005	26	3,332.72
1987	8	1,783.20	2006	27	4,129.53
1988	9	2,033.89	2007	28	3,781.19
1989	10	1,945.11	2008	29	3,852.17
1990	11	1,649.80	2009	30	4,444.66
1991	12	1,600.77	2010	31	5,484.83
1992	13	1,424.57	2011	32	5,712.78
1993	14	1,601.00	2012	33	5,265.48
1994	15	1,767.53	2013	34	5,006.44
1995	16	1,893.44	2014	35	4,236.15
1996	17	1,610.34	2015	36	3,719.69
1997	18	1,274.07	2016	37	-
1998	19	1,157.56			

Table C10: Regression line data

$\overline{MM}$	2,391.36
$Cov(MM, t)$	12,098.69
$Var(t)$	117,17
$\bar{t}$	19

***Table C11**: Regression line points (predictions)*

REGRESSION LINE					
t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$	t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1	532.67	596,281.93	22	2,701.14	2,819,370.26
2	635.93	263,769.72	23	2,804.40	2,877,396.90
3	739.19	80,580.06	24	2,907.66	1,901,605.71
4	842.45	19,691.93	25	3,010.92	683,236.29
5	945.71	799.75	26	3,114.18	4,113.62
6	1,048.97	6,900.32	27	3,217.44	2,010,847.78
7	1,152.23	50,504.24	28	3,320.70	1,572,686.10
8	1,255.49	542,873.71	29	3,423.96	1,665,762.24
9	1,358.75	1,147,139.61	30	3,527.22	1,745,531.41
10	1,462.01	47,336.80	31	3,630.48	7,408,082.16
11	1,565.27	25,819.56	32	3,733.75	2,310,583.45
12	1,668.53	15,546.85	33	3,837.01	2,873,970.76
13	1,771.79	57,255.34	34	3,940.27	1,145,073.16
14	1,875.06	459,278.86	35	4,043.53	187,640.17
15	1,978.32	8,988.77	36	4,146.79	856,323.86
16	2,081.58	2,445.44	37	4,250.05	622,640.52
17	2,184.84	371,833.37	38	4,353.31	
18	2,288.10	1,132,643.48	39	4,456.57	
19	2,391.36	1,871,548.68	40	4,559.83	
20	2,494.62	1,610,609.19	41	4,663.09	

21	2,597.88	1,723,378.20	42	4,766.35

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 1{,}100{,}542.98$$

C2.3. Double Exponential Smoothing $\alpha = 0.4$

***Table C12**: Double Exponential Smoothing*

DOUBLE EXPONENTIAL SMOOTHING						
Year	$Z(t)$	$Y(t)$	$b0_t$	$b1_t$	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1980	1,304.86	1,304.86	1,304.86	0.00	1,304.86	0.00
1981	1,242.72	1,280.01	1,205.44	-24.86	1,304.86	24,132.76
1982	1,154.86	1,229.95	1,079.77	-50.06	1,180.58	24,815.00
1983	1,086.02	1,172.38	999.67	-57.57	1,029.71	2,202.22
1984	1,018.59	1,110.86	926.31	-61.52	942.10	608.75
1985	997.51	1,065.52	929.50	-45.34	864.80	10,222.45
1986	969.51	1,027.12	911.90	-38.41	884.17	1,877.88
1987	1,378.62	1,167.72	1,589.52	140.60	873.49	1,251,708.26
1988	1,799.09	1,420.27	2,177.92	252.55	1,730.13	489,541.00
1989	1,751.29	1,552.68	1,949.90	132.41	2,430.47	563,825.14
1990	1,741.16	1,628.07	1,854.24	75.39	2,082.31	126,986.15
1991	1,662.23	1,641.73	1,682.73	13.67	1,929.64	148,833.66
1992	1,610.35	1,629.18	1,591.51	-12.56	1,696.40	26,857.76
1993	1,445.15	1,555.57	1,334.73	-73.61	1,578.96	145,620.22
1994	1,696.34	1,611.88	1,780.80	56.31	1,261.12	659,353.68
1995	1,830.65	1,699.39	1,961.92	87.51	1,837.11	38,030.11
1996	1,728.41	1,711.00	1,745.83	11.61	2,049.43	225,032.46
1997	1,526.58	1,637.23	1,415.94	-73.77	1,757.44	284,730.66
1998	1,325.28	1,512.45	1,138.10	-124.78	1,342.17	101,671.12
1999	1,285.37	1,421.62	1,149.13	-90.83	1,013.32	45,029.59
2000	1,285.27	1,367.08	1,203.45	-54.54	1,058.30	51,441.14

2001	1,179.98	1,292.24	1,067.72	-74.84	1,148.91	16,096.20
2002	1,151.23	1,235.83	1,066.63	-56.40	992.87	13,279.49
2003	1,302.21	1,262.38	1,342.03	26.55	1,010.22	268,790.99
2004	1,655.06	1,419.45	1,890.67	157.07	1,368.58	665,463.79
2005	2,264.36	1,757.42	2,771.31	337.96	2,047.74	1,278,215.35
2006	3,212.81	2,339.58	4,086.05	582.16	3,109.27	2,329,323.88
2007	3,757.60	2,906.78	4,608.41	567.21	4,668.21	8,730.42
2008	3,107.89	2,987.22	3,228.55	80.44	5,175.62	9,255,568.37
2009	3,804.10	3,313.97	4,294.22	326.75	3,308.99	2,369,823.18
2010	4,823.36	3,917.73	5,729.00	603.76	4,620.97	2,997,393.65
2011	4,995.54	4,348.85	5,642.23	431.12	6,332.75	1,164,126.36
2012	5,210.24	4,693.41	5,727.07	344.55	6,073.35	292,752.55
2013	5,130.28	4,868.16	5,392.41	174.75	6,071.62	1,126,304.92
2014	4,868.85	4,868.43	4,869.27	0.28	5,567.16	1,189,091.44
2015	4,209.87	4,605.01	3,814.74	-263.42	4,869.54	2,716,340.47
2016	3,910.31	4,327.13	3,493.49	-277.88	3,551.31	8,161.50
2017					3,215.62	
2018					2,937.74	
2019					2,659.86	
2020					2,381.98	
2021					2,104.10	

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 808{,}702.23$$

C2.4. Holt method $\alpha = 0.8, \beta = 0.1$

Table C13: Holt method

HOLT METHOD				
Year	L_t	b_t	$\hat{y}_{t+h,t}$	$(y_t - \hat{y}_t)^2$
1980	1,304.86	-155.35	1,304.86	0.00
1981	1,149.51	-155.35	1,149.51	0.00
1982	1,017.28	-153.04	994.17	834.57
1983	959.07	-143.55	864.24	14,050.81
1984	897.05	-135.40	815.52	10,386.30
1985	925.05	-119.06	761.65	41,720.12
1986	903.20	-109.34	805.99	14,764.19
1987	1,752.61	-13.46	793.86	1,436,240.19
1988	2,291.67	41.79	1,739.14	477,008.41
1989	1,810.36	-10.52	2,333.46	427,548.32
1990	1,740.73	-16.43	1,799.84	5,457.92
1991	1,579.94	-30.87	1,724.30	32,563.93
1992	1,535.83	-32.19	1,549.07	274.10
1993	1,258.61	-56.69	1,503.63	93,806.34
1994	1,898.88	13.00	1,201.91	759,007.17
1995	2,008.08	22.62	1,911.88	14,457.71
1996	1,666.18	-13.83	2,030.70	207,610.04
1997	1,309.54	-48.11	1,652.35	183,623.75
1998	1,070.94	-67.16	1,261.43	56,700.68
1999	1,181.17	-49.42	1,003.78	49,171.05
2000	1,254.43	-37.15	1,131.75	23,517.37
2001	1,061.09	-52.77	1,217.28	38,118.17
2002	1,088.15	-44.79	1,008.32	9,958.80
2003	1,431.61	-5.96	1,043.36	235,525.66
2004	2,032.60	54.73	1,425.65	575,614.24

2005	2,960.12	142.01	2,087.33	1,190,250.62
2006	4,328.82	264.68	3,102.13	2,351,172.69
2007	4,578.52	263.18	4,593.49	350.56
2008	2,674.99	46.51	4,841.70	7,335,305.60
2009	4,423.03	216.66	2,721.51	4,523,721.36
2010	6,009.75	353.67	4,639.69	2,932,902.68
2011	5,475.73	264.90	6,363.42	1,231,240.46
2012	5,573.95	248.23	5,740.63	43,406.88
2013	5,172.71	183.29	5,822.19	659,081.70
2014	4,652.56	112.94	5,356.00	773,166.35
2015	3,530.23	-10.59	4,765.50	2,384,222.51
2016	3,472.71	-15.28	3,519.64	3,442.17
2017			3,457.43	
2018			3,442.15	
2019			3,426.87	
2020			3,411.59	
2021			3,396.31	

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 760{,}438.47$$

C2.5. Error analysis

***Table C14**: Error analysis*

ERROR ANALYSIS			
		$y_t - \hat{y}_t$	
Year	**DES**	**MMLT**	**Holt**
1980	0.00	772.19	0.00
1981	-155.35	513.59	0.00
1982	-157.53	283.87	28.89
1983	-46.93	140.33	118.54

1984	-24.67	-28.28	101.91
1985	101.11	-83.07	204.26
1986	43.33	-224.73	121.51
1987	1,118.80	736.80	1,198.43
1988	699.67	1,071.05	690.66
1989	-750.88	217.57	-653.87
1990	-356.35	160.68	-73.88
1991	-385.79	-124.69	-180.45
1992	-163.88	-239.28	-16.56
1993	-381.60	-677.70	-306.28
1994	812.01	94.81	871.21
1995	195.01	-49.45	120.24
1996	-474.38	-609.78	-455.64
1997	-533.60	-1,064.26	-428.51
1998	-318.86	-1,368.05	-238.12
1999	212.20	-1,269.10	221.75
2000	226.81	-1,312.78	153.35
2001	-126.87	-1,679.10	-195.24
2002	115.24	-1,696.29	99.79
2003	518.45	-1,378.99	485.31
2004	815.76	-826.58	758.69
2005	1,130.58	64.14	1,090.99
2006	1,526.21	1,418.04	1,533.35
2007	-93.44	1,254.07	-18.72
2008	-3,042.30	-1,290.64	-2,708.38
2009	1,539.42	1,321.19	2,126.90
2010	1,731.30	2,721.78	1,712.57
2011	-1,078.95	1,520.06	-1,109.61
2012	-541.07	1,695.28	-208.34

2013	-1,061.28	1,070.08	-811.84
2014	-1,090.45	433.17	-879.30
2015	-1,648.13	-925.38	-1,544.09
2016	-90.34	-789.08	-58.67
St. Dev.	898.05	1,049.06	870.75
Z (95%)	1.96	1.96	1.96
Margin	±289.37	±338.03	±280.57

C3. Silver

C3.1. Historical data

***Table C15**: Silver price historical data*

SILVER PRICE HISTORICAL DATA					
Year	**US$/ozt**	**£/ton**	**Year**	**US$/ozt**	**£/ton**
1980	16.46	367,498.08	1999	5.16	115,138.98
1981	8.45	188,616.27	2000	4.64	103,596.06
1982	10.57	235,993.60	2001	4.37	97,567.84
1983	9.15	204,178.00	2002	4.63	103,395.11
1984	6.64	148,160.22	2003	5.63	125,654.87
1985	5.85	130,656.06	2004	7.09	158,184.93
1986	5.35	119,448.04	2005	8.63	192,612.75
1987	6.81	152,089.73	2006	13.28	296,499.06
1988	6.12	136,728.93	2007	14.30	319,272.33
1989	5.57	124,337.59	2008	10.29	229,742.11
1990	4.08	90,981.45	2009	17.64	393,843.63
1991	3.94	88,034.32	2010	29.32	654,619.90
1992	3.73	83,167.09	2011	30.30	676,500.10
1993	4.97	111,008.53	2012	31.87	711,553.08
1994	4.78	106,721.80	2013	19.67	439,166.90

1995	5.18	115,585.51	2014	16.30	363,925.80
1996	4.83	107,748.83	2015	14.13	315,476.78
1997	5.84	130,321.16	2016	15.46	345,171.34
1998	4.88	108,909.82			

C3.2. Moving Means with Linear Trend

***Table C16**: Silver price moving means*

MOVING MEANS					
Year	**t**	**MM**	**Year**	**t**	**MM**
1980	1	-	1999	20	109,214.95
1981	2	264,035.98	2000	21	105,434.29
1982	3	209,595.96	2001	22	101,519.67
1983	4	196,110.61	2002	23	108,872.61
1984	5	160,998.09	2003	24	129,078.30
1985	6	132,754.77	2004	25	158,817.52
1986	7	134,064.61	2005	26	215,765.58
1987	8	136,088.90	2006	27	269,461.38
1988	9	137,718.75	2007	28	281,837.83
1989	10	117,349.33	2008	29	314,286.02
1990	11	101,117.79	2009	30	426,068.55
1991	12	87,394.29	2010	31	574,987.88
1992	13	94,069.98	2011	32	680,891.03
1993	14	100,299.14	2012	33	609,073.36
1994	15	111,105.28	2013	34	504,881.93
1995	16	110,018.71	2014	35	372,856.49
1996	17	117,885.17	2015	36	341,524.64
1997	18	115,659.94	2016	37	-
1998	19	118,123.32			

Table C17: Regression line data

$\overline{MM}$	221,398.93
$Cov(MM, t)$	1,039,964.27
$Var(t)$	117,17
$\bar{t}$	19

***Table C18**: Regression line points (predictions)*

REGRESSION LINE					
t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$	t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1	61,632.02	93,554,046,145.31	22	248,026.75	22,637,884,987.65
2	70,507.96	13,949,572,823.28	23	256,902.69	23,564,575,955.46
3	79,383.90	24,526,599,392.43	24	265,778.63	19,634,668,126.58
4	88,259.84	13,437,021,054.79	25	274,654.57	13,565,178,263.58
5	97,135.78	2,603,493,957.91	26	283,530.51	8,266,038,698.92
6	106,011.72	607,343,685.02	27	292,406.45	16,749,419.91
7	114,887.66	20,797,089.67	28	301,282.39	323,637,819.81
8	123,763.60	802,369,702.79	29	310,158.33	6,466,767,619.33
9	132,639.54	16,723,167.23	30	319,034.27	5,596,439,713.75
10	141,515.47	295,079,607.27	31	327,910.21	106,739,224,052.01
11	150,391.41	3,529,543,918.93	32	336,786.15	115,405,571,568.26
12	159,267.35	5,074,145,090.37	33	345,662.09	133,876,217,646.97
13	168,143.29	7,220,954,888.92	34	354,538.03	7,162,045,840.93
14	177,019.23	4,357,412,737.65	35	363,413.97	261,970.75
15	185,895.17	6,268,423,268.85	36	372,289.91	3,227,731,320.02
16	194,771.11	6,270,359,284.49	37	381,165.85	1,295,604,533.89
17	203,647.05	9,196,469,430.20	38	390,041.79	
18	212,522.99	6,757,141,487.97	39	398,917.73	
19	221,398.93	12,653,800,656.46	40	407,793.67	
20	230,274.87	13,256,274,052.74	41	416,669.61	

21	239,150.81	18,375,091,913.07	42	425,545.55

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 19{,}204{,}088{,}132.25$$

C3.3. Double Exponential Smoothing $\alpha = 0.7$

Table C19: Double Exponential Smoothing

DOUBLE EXPONENTIAL SMOOTHING						
Year	$Z(t)$	$Y(t)$	$b0_t$	$b1_t$	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1980	367,498.08	367,498.08	367,498.08	0.00	367,498.08	0.00
1981	242,280.81	279,845.99	204,715.63	-87,652.09	367,498.08	31,998,701,849.50
1982	237,879.76	250,469.63	225,289.90	-29,376.36	117,063.54	14,144,358,676.06
1983	214,288.53	225,142.86	203,434.20	-25,326.77	195,913.54	68,301,375.77
1984	167,998.71	185,141.96	150,855.47	-40,000.90	178,107.43	896,835,289.37
1985	141,858.86	154,843.79	128,873.93	-30,298.17	110,854.57	392,099,123.05
1986	126,171.28	134,773.03	117,569.53	-20,070.75	98,575.75	435,652,243.84
1987	144,314.19	141,451.85	147,176.54	6,678.81	97,498.78	2,980,171,365.62
1988	139,004.51	139,738.71	138,270.31	-1,713.13	153,855.35	293,314,286.54
1989	128,737.67	132,037.98	125,437.36	-7,700.73	136,557.18	149,318,175.72
1990	102,308.32	111,227.22	93,389.42	-20,810.77	117,736.63	715,839,460.68
1991	92,316.52	97,989.73	86,643.31	-13237.49	72,578.65	238,877,770.12
1992	85,911.92	89,535.26	82,288.58	-8,454.47	73,405.82	95,282,377.24
1993	103,479.55	99,296.26	107,662.83	9,761.00	73,834.11	1,381,937,468.65
1994	105,749.12	103,813.27	107,684.98	4,517.00	117,423.83	114,533,569.57
1995	112,634.60	109,988.20	115,281.00	6,174.93	112,201.98	11,448,264.09
1996	109,214.56	109,446.65	108,982.47	-541.55	121,455.93	187,884,546.06
1997	123,989.18	119,626.42	128,351.94	10,179.77	108,440.92	478,744,815.05
1998	113,433.63	115,291.46	111,575.79	-4,334.96	138,531.71	877,456,277.30
1999	114,627.37	114,826.60	114,428.15	-464.86	107,240.83	62,380,691.21
2000	106,905.45	109,281.80	104,529.11	-5,544.80	113,963.28	107,479,356.35

2001	100,369.12	103,042.92	97,695.32	-6,238.87	98,984.30	2,006,371.04
2002	102,487.32	102,654.00	102,320.63	-388.92	91,456.45	142,531,807.22
2003	118,704.60	113,889.42	123,519.79	11,235.42	101,931.71	562,788,353.80
2004	146,340.83	136,605.41	156,076.25	22,715.98	134,755.21	548,951,538.53
2005	178,731.18	166,093.44	191,368.91	29,488.04	178,792.24	191,006,690.80
2006	261,168.69	232,646.12	289,691.27	66,552.67	220,856.94	5,721,729,095.44
2007	301,841.24	281,082.70	322,599.77	48,436.58	356,243.94	1,366,900,069.69
2008	251,371.85	260,285.11	242,458.60	-20,797.59	371,036.35	19,964,062,176.71
2009	351,102.09	323,857.00	378,347.19	63,571.89	221,661.00	29,646,855,815.93
2010	563,564.56	491,652.29	635,476.83	167,795.29	441,919.08	45,241,640,105.58
2011	642,619.44	597,329.30	687,909.59	105,677.00	803,272.12	16,071,144,724.72
2012	690,872.99	662,809.88	718,936.10	65,480.58	793,586.59	6,729,496,924.24
2013	514,678.73	559,118.07	470,239.38	-103,691.81	784,416.68	119,197,411,389.07
2014	409,151.68	454,141.60	364,161.76	-104,976.48	366,547.57	6,873,692.85
2015	343,579.25	376,747.95	310,410.55	-77,393.64	259,185.28	3,168,732,964.44
2016	344,693.71	354,309.99	335,077.44	-22,437.97	233,016.90	12,578,617,492.79
2017					312,639.47	
2018					290,201.50	
2019					267,763.54	
2020					245,325.57	
2021					222,887.60	

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 8{,}561{,}388{,}275.53$$

C3.4. Holt method $\alpha = 0.9, \beta = 0.4$

***Table C20**: Holt method*

HOLT METHOD				
Year	L_t	b_t	$\hat{y}_{t+h,t}$	$(y_t - \hat{y}_t)^2$
1980	367,498.08	-178,881.81	367,498.08	0.00
1981	188,616.27	-178,881.81	188,616.27	0.00
1982	213,367.69	-97,428.52	9,734.46	51,193,200,130.48
1983	195,354.12	-65,662.54	115,939.17	7,786,091,717.83
1984	146,313.36	-59,013.83	129,691.58	341,090,677.79
1985	126,320.41	-43,405.48	87,299.53	1,879,788,723.14
1986	115,794.73	-30,253.56	82,914.93	1,334,667,979.86
1987	145,434.87	-6,296.08	85,541.17	4,428,710,386.26
1988	136,969.92	-7,163.63	139,138.79	5,807,432.69
1989	124,884.46	-9,132.36	129,806.29	29,906,650.22
1990	93,458.52	-18,049.79	115,752.10	613,585,352.06
1991	86,771.76	-13,504.58	75,408.72	159,405,764.51
1992	82,177.10	-9,940.61	73,267.18	98,008,215.68
1993	107,131.33	4,017.32	72,236.49	1,503,271,222.13
1994	107,164.48	2,423.66	111,148.65	19,597,030.59
1995	114,985.78	4,582.71	109,588.14	35,968,469.88
1996	108,930.79	327.63	119,568.49	139,704,316.65
1997	128,214.89	7,910.22	109,258.43	443,638,613.07
1998	111,631.35	-1,887.29	136,125.10	740,671,673.21
1999	114,599.49	54.88	109,744.06	29,105,121.22
2000	104,701.89	-3,926.11	114,654.37	122,286,342.72
2001	97,888.63	-5,080.97	100,775.78	10,290,887.44
2002	102,336.37	-1,269.49	92,807.66	112,094,136.91
2003	123,196.07	7,582.19	101,066.88	604,569,069.60
2004	155,444.26	17,448.59	130,778.26	751,125,191.96

2005	190,640.76	24,547.75	172,892.85	388,874,643.96
2006	288,368.00	53,819.55	215,188.52	6611,403,791.58
2007	321,563.85	45,570.07	342,187.55	525,107,478.61
2008	243,481.29	-3,890.98	367,133.92	18,876,507,290.69
2009	378,418.29	51,640.21	239,590.31	23,794,083,961.86
2010	632,163.76	132,482.31	430,058.51	50,427,821,350.99
2011	685,314.70	100,749.76	764,646.08	7,769,712,586.12
2012	719,004.22	73,925.67	786,064.47	5,551,946,586.05
2013	474,543.20	-53,429.01	792,929.88	125,148,249,051.63
2014	369,644.64	-74,016.83	421,114.19	3,270,511,945.06
2015	313,491.88	-66,871.20	295,627.81	393,981,737.06
2016	335,316.27	-31,392.96	246,620.68	9,712,231,709.57
2017			303,923.31	
2018			272,530.35	
2019			241,137.39	
2020			209,744.42	
2021			178,351.46	

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 8{,}779{,}811{,}276.73$$

C3.5. Error analysis

***Table C21**: Error analysis*

ERROR ANALYSIS			
	$y_t - \hat{y}_t$		
Year	**DES**	**MMLT**	**Holt**
1980	0.00	305,866.06	0.00
1981	-178,881.81	118,108.31	0.00
1982	118,930.06	156,609.70	226,259.14
1983	8,264.46	115,918.17	88,238.83

1984	-29,947.21	51,024.44	18,468.64
1985	19,801.49	24,644.34	43,356.53
1986	20,872.28	4,560.38	36,533.11
1987	54,590.95	28,326.13	66,548.56
1988	-17,126.42	4,089.40	-2,409.86
1989	-12,219.58	-17,177.88	-5,468.70
1990	-26,755.18	-59,409.96	-24,770.66
1991	15,455.67	-71,233.03	12,625.60
1992	9,761.27	-84,976.20	9,899.91
1993	37,174.42	-66,010.70	38,772.04
1994	-10,702.04	-79,173.37	-4,426.85
1995	3,383.53	-79,185.60	5,997.37
1996	-13,707.10	-95,898.22	-11,819.66
1997	21,880.24	-82,201.83	21,062.73
1998	-29,621.89	-112,489.11	-27,215.28
1999	7,898.14	-115,135.89	5,394.92
2000	-10,367.23	-135,554.76	-11,058.32
2001	-1,416.46	-150,458.91	-3,207.94
2002	11,938.67	-153,507.58	10,587.45
2003	23,723.16	-140,123.76	24,587.99
2004	23,429.71	-116,469.65	27,406.66
2005	13,820.52	-90,917.76	19,719.90
2006	75,642.11	4,092.61	81,310.54
2007	-36,971.61	17,989.94	-22,915.22
2008	-141,294.24	-80,416.21	-137,391.80
2009	172,182.62	74,809.36	154,253.31
2010	212,700.82	326,709.69	224,561.40
2011	-126,772.02	339,713.96	-88,145.97
2012	-82,033.51	365,890.99	-74,511.39

2013	-345,249.78	84,628.87	-353,762.98
2014	-2,621.77	511.83	-57,188.39
2015	56,291.50	-56,813.13	19,848.97
2016	112,154.44	-35,994.51	98,550.66
St. Dev.	92,519.49	138,472.99	93,044.11
Z (95%)	1.96	1.96	1.96
Margin	±29,811.82	±44,619.05	±29,980.86

C4. Light Iron scrap

C4.1. Historical data

***Table C22**: Light Iron scrap price historical data*

LIGHT IRON SCRAP PRICE HISTORICAL DATA	
Year	**£/ton**
2000	5.00
2001	3.00
2002	15.00
2003	21.00
2004	29.00
2005	25.00
2006	55.00
2007	34.00
2008	45.00
2009	80.00
2010	169.00
2011	145.00
2012	125.00
2013	130.00
2014	85.00

2015	30.00
2016	55.00

C4.2. Moving Means with Linear Trend

***Table C23**: Light Iron scrap moving means*

MOVING MEANS		
Year	**t**	**MM**
2000	1	-
2001	2	7.67
2002	3	13.00
2003	4	21.67
2004	5	25.00
2005	6	26.33
2006	7	38.00
2007	8	44.67
2008	9	53.00
2009	10	98.00
2010	11	131.33
2011	12	146.33
2012	13	133.33
2013	14	113.33
2014	15	81.67
2015	16	56.67
2016	17	-

***Table C24**: Regression line data*

$\overline{MM}$	66.67
$Cov(MM, t)$	147.78
$Var(t)$	25.50
$\bar{t}$	9

***Table C25**: Regression line points (predictions)*

REGRESSION LINE		
t	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
1	20.31	234.24
2	26.10	533.62
3	31.90	285.46
4	37.69	278.58
5	43.49	209.84
6	49.28	589.57
7	55.08	0.01
8	60.87	722.08
9	66.67	469.44
10	72.46	56.82
11	78.26	8234.28
12	84.05	3714.62
13	89.85	1235.70
14	95.64	1180.42
15	101.44	270.20
16	107.23	5964.95
17	113.03	3367.29
18	118.82	
19	124.62	

20	130.41
21	136.21
22	142.00

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 1608.65$$

C4.3. Double Exponential Smoothing $\alpha = 0.6$

***Table C26**: Double Exponential Smoothing*

DOUBLE EXPONENTIAL SMOOTHING						
Year	$Z(t)$	$Y(t)$	$b0_t$	$b1_t$	$\hat{y}_t$	$(y_t - \hat{y}_t)^2$
2000	5.00	5.00	5.00	0.00	5.00	0.00
2001	3.80	4.28	3.32	-0.72	5.00	4.00
2002	10.52	8.02	13.02	3.74	2.60	153.76
2003	16.81	13.29	20.32	5.27	16.76	17.98
2004	24.12	19.79	28.45	6.50	25.59	11.61
2005	24.65	22.71	26.59	2.91	34.95	99.04
2006	42.86	34.80	50.92	12.09	29.51	649.90
2007	37.54	36.45	38.64	1.65	63.01	841.76
2008	42.02	39.79	44.25	3.34	40.29	22.19
2009	64.81	54.80	74.81	15.01	47.59	1050.44
2010	127.32	98.31	156.33	43.51	89.83	6268.64
2011	137.93	122.08	153.78	23.77	199.85	3008.07
2012	130.17	126.94	133.41	4.85	177.54	2760.94
2013	130.07	128.82	131.32	1.88	138.26	68.23
2014	103.03	113.34	92.71	-15.47	133.20	2323.35
2015	59.21	80.86	37.56	-32.48	77.24	2231.55
2016	56.68	66.36	47.01	-14.51	5.08	2492.08
2017					32.51	
2018					18.00	

2019	3.49
2020	-11.02
2021	-25.53

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 1294.33$$

C4.4. Holt method $\alpha = 0.9, \beta = 0.1$

***Table C27**: Holt method*

HOLT METHOD				
Year	L_t	b_t	$\hat{y}_{t+h,t}$	$(y_t - \hat{y}_t)^2$
2000	5.00	-2.00	5.00	0.00
2001	3.00	-2.00	3.00	0.00
2002	13.60	-0.74	1.00	196.00
2003	20.19	-0.01	12.86	66.26
2004	28.12	0.79	20.18	77.82
2005	25.39	0.44	28.90	15.24
2006	52.08	3.06	25.83	851.15
2007	36.11	1.16	55.14	447.04
2008	44.23	1.85	37.27	59.72
2009	76.61	4.91	46.08	1150.52
2010	160.25	12.78	81.51	7653.76
2011	147.80	10.26	173.03	785.75
2012	128.31	7.28	158.06	1092.98
2013	130.56	6.78	135.59	31.22
2014	90.23	2.07	137.34	2739.22
2015	36.23	-3.54	92.30	3881.56
2016	52.77	-1.53	32.69	497.67
2017			51.24	
2018			49.71	

2019	48.18
2020	46.64
2021	45.11

$$Mean\ Square\ Error = \frac{\sum_1^n (y_t - \hat{y}_t)^2}{n} = 1149.76$$

C4.5. Error analysis

***Table C28**: Error analysis*

ERROR ANALYSIS			
		$y_t - \hat{y}_t$	
Year	**DES**	**MMLT**	**Holt**
2000	0.00	-15.31	0.00
2001	-2.00	-23.10	0.00
2002	12.40	-16.90	14.00
2003	4.24	-16.69	8.14
2004	3.41	-14.49	8.82
2005	-9.95	-24.28	-3.90
2006	25.49	-0.08	29.17
2007	-29.01	-26.87	-21.14
2008	4.71	-21.67	7.73
2009	32.41	7.54	33.92
2010	79.17	90.74	87.49
2011	-54.85	60.95	-28.03
2012	-52.54	35.15	-33.06
2013	-8.26	34.36	-5.59
2014	-48.20	-16.44	-52.34
2015	-47.24	-77.23	-62.30
2016	49.92	-58.03	22.31
St. Dev.	35.90	39.81	33.91

Z (95%)	1.96	1.96	1.96
Margin	±17.07	±18.93	±16.12