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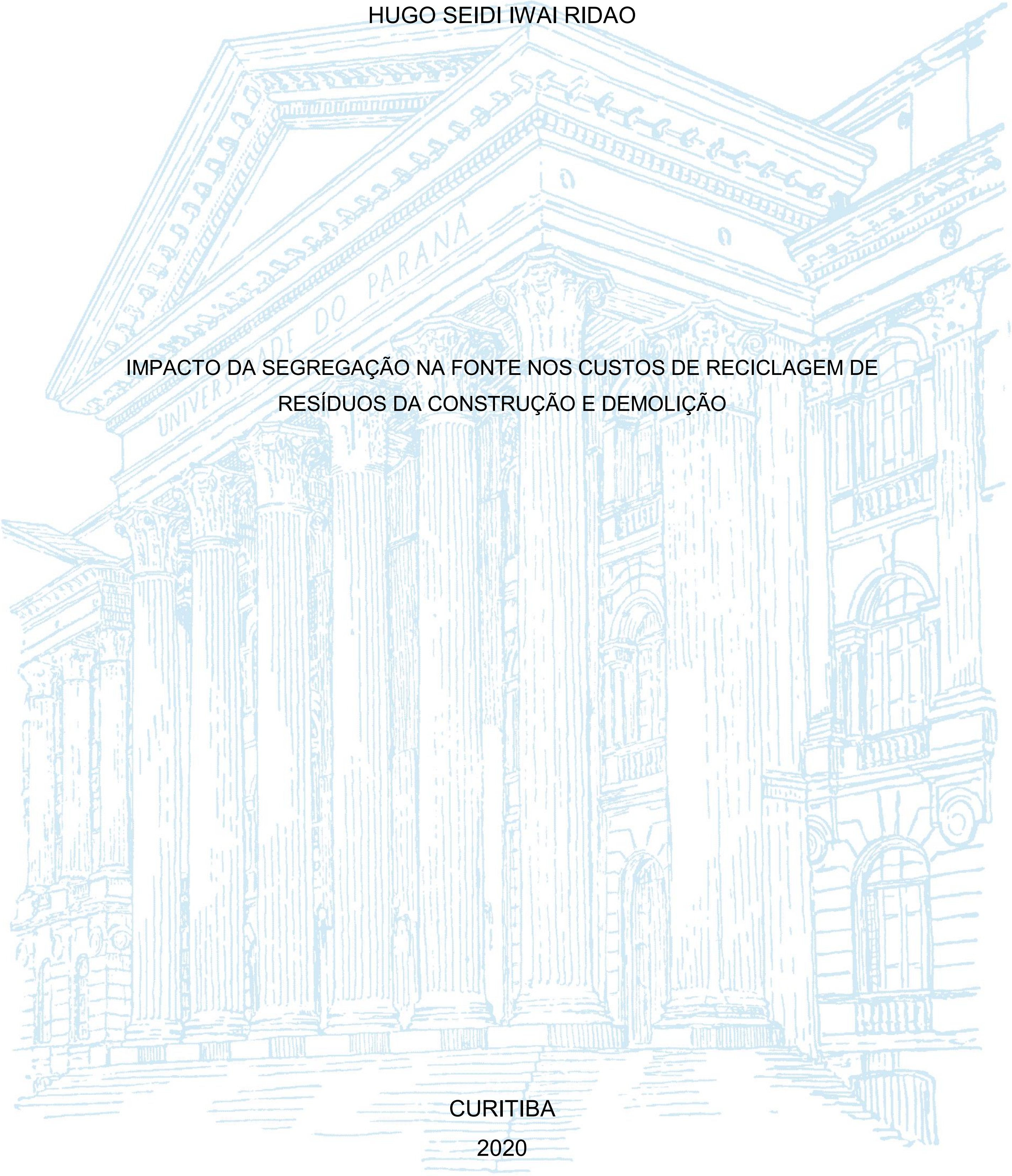
HUGO SEIDI IWAI RIDAO



IMPACTO DA SEGREGAÇÃO NA FONTE NOS CUSTOS DE RECICLAGEM DE RESÍDUOS DA CONSTRUÇÃO E DEMOLIÇÃO

CURITIBA
2020

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Dissertação apresentada como requisito parcial à obtenção do grau de Mestre em Meio Ambiente Urbano e Industrial, no curso de Pós-Graduação em Meio Ambiente Urbano e Industrial, Setor de Tecnologia, da Universidade Federal do Paraná (UFPR) em convênio com o Serviço Nacional de Aprendizagem Industrial do Paraná (SENAI-PR) e a *Stuttgart Universität* (USTUTT).

Orientador: Prof^(a). Dr^(a). Elaine V. Takeshita
Coorientadora: Prof. Dr. Klaus Fischer

Dissertation presented to the faculty of Federal University of Paraná, as a partial requirement to obtain the Master's Degree in Urban and Industrial Environment which is a cooperation between the Federal University of Paraná, University of Stuttgart and the National System of Industrial Learning of Paraná.

Advisor: Prof. Dr. Elaine V. Takeshita
Co-Advisor: Prof. Dr. Klaus Fischer

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Assinatura Eletrônica
31/08/2020 12:27:03.0
ELAINE VOSNIAK TAKESHITA
Presidente da Banca Examinadora (UNIVERSIDADE FEDERAL DO PARANÁ)

Assinatura Eletrônica
28/08/2020 17:09:19.0
ARISLETE DANTAS DE AQUINO
Avaliador Interno (UNIVERSIDADE FEDERAL DO PARANÁ)

Assinatura Eletrônica
31/08/2020 16:43:16.0
DANIELA NEUFFER
Avaliador Interno (UNIVERSIDADE DE STUTTGART)

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RESUMO

O Resíduo de Construção e Demolição (CDW) perfaz um dos maiores fluxos de materiais do mundo. Se não bem administrado, o CDW pode causar grandes problemas em áreas urbanas, ocupando e esgotando os recursos já limitados de aterros sanitários ou mesmo sendo despejados em áreas suburbanas, riachos próximos, estradas e outros lugares inapropriados, causando uma série de impactos sociais, econômicos e ambientais. Por outro lado, se devidamente gerido, pode ser praticamente reciclado ou recuperado em sua totalidade, substituindo quantidades equivalentes de materiais primários e o uso de recursos naturais, bem como, os impactos relacionados para produzi-los. Considerando que a contaminação cruzada e a mistura de materiais são frequentemente observadas em canteiros de obras e demolição, é essencial que cada componente do CDW seja segregado na fonte. Com isso, a reciclabilidade do material é garantida, permitindo que sejam utilizados processos de reciclagem mais simples e que sejam obtidos produtos reciclados de maior qualidade. O presente estudo investiga a influência do nível de contaminação do CDW nos aspectos técnicos e econômicos da reciclagem. Foram estabelecidos, pré-projetados e simulados múltiplos cenários de instalações de reciclagem de modo a tratar três diferentes níveis de contaminação do CDW, cada qual representando diferentes graus de segregação na fonte. Considerando condições específicas no Brasil, mais precisamente na região metropolitana de Curitiba, todos os custos relacionados para o tratamento dos materiais de entrada foram estimados, entre eles, investimentos de implantação, despesas de operação, bem como, receitas de comercialização de produtos. Com base nisso, foi realizada uma análise de fluxo de caixa e foram calculados os valores da taxa de recebimento do CDW necessários para fornecer uma rentabilidade mínima ao investimento. Os resultados demonstram que a segregação na fonte é essencial para o desenvolvimento da reciclagem de CDW. Em termos de economia, o custo para tratar materiais contaminados é de 2 a 4 vezes maior do que para materiais segregados, atribuídos principalmente ao aumento dos custos com pessoal, à disposição de resíduos e à compra de equipamentos adicionais. Em termos de condições de mercado, a segregação na fonte é o método mais aconselhável para garantir a produção de agregados reciclados de alta qualidade e certificáveis, essenciais para reduzir a diferença entre os preços dos produtos reciclados e os naturais. Além disso, também são investigadas outras variáveis que influenciam a viabilidade econômica de uma usina de reciclagem. Por exemplo, afirmando o princípio do ganho de escala e eficiência energética do sistema, as taxas de recebimento do CDW são reduzidas em até 44% ao dobrar a capacidade da usina. Além disso, o custo do frete pode ser comparável ou até mesmo superar as taxas de portão do CDW cobradas na fábrica, revelando que a reciclagem é mais atraente em áreas densamente povoadas, onde a oferta e a demanda podem ser garantidas com distâncias de transporte mais curtas. Felizmente, é o caso da região metropolitana de Curitiba, uma área densamente povoada como muitas outras no Brasil.

Palhavras-chave: resíduos. construção civil. reciclagem. meio ambiente. gestão.

ABSTRACT

Construction and Demolition Waste (CDW) is one of the largest flows of waste in the world. If not well managed CDW may constitute one of the greatest problems in urban areas, ending up occupying and depleting the already limited landfill resources or even dumped in suburban areas, nearby creeks, roads and other inappropriate places, causing a series of social, economic and environmental impacts. On the other hand, if properly managed it can be virtually entirely recycled or recovered, displacing equivalent quantities of primary materials and the usage of natural resources, as well as, the related impacts to produce them. As general mixing and cross-contamination is frequently observed in construction and demolition sites, it is essential that each component of the CDW is segregated at the source. By doing so, the recyclability of the material is guaranteed, allowing simpler recycling processes to be used and higher quality recycled products to be obtained. The present study investigates the influence of the CDW's contamination level on technical and economical aspects of recycling. Several recycling facilities scenarios have been pre-designed and simulated in order to treat three CDW`s levels of contamination, each of them representing different degrees of segregation at source. Considering specific conditions in Brazil, more precisely in the metropolitan region of Curitiba, all related costs to treat the incoming materials are estimated, including, initial investments to set up the plant, replacement costs, annual capital and operation expenses, as well as, revenues from products commercialization. Based on that, a cash flow analysis was carried out and the CDW's gate fee values required to provide a minimum profitability to the investment was calculated. The results demonstrate that segregation at source is essential to the development of CDW recycling. In terms of economy, the cost to treat contaminated materials are 2 to 4 times greater than for segregated materials, much attributed to the increase of staff costs, residues disposal and purchase of additional equipment. In terms of market conditions, segregation at source is the most advisable method to ensure the production of high-quality and certifiable recycled aggregates, which is essential to reduce the gap between prices for recycled and natural products. Furthermore, other variables which influence the economical feasibility of a recycling plant are also investigated. For instance, supporting the principle of gain of scale and energy efficiency of the system, the CDW's gate fees are reduced up to 44% by doubling the capacity of the plant. Moreover, freight cost can be comparable or even surpass the CDW's gate fees charged at the plant, revealing that recycling is most attractive in densely populated areas, where the supply and demand can be guaranteed with shorter transportation distances. Fortunately, this is the case of the metropolitan region of Curitiba, a highly densely populated area like many others in Brazil.

Key-words: construction and demolition waste. recovering. environment. recycling process. waste management.

KURZFASSUNG

Bauschutt stellt eine der größten Abfallmengen in der Welt dar. Wird dieser nicht angemessen entsorgt, kann es zu großen Problemen in städtischen Gebieten kommen. Die Deponieressourcen sind bereits begrenzt und drohen zu erschöpfen, was sich selbst in den Vorstädten abzeichnet. Der Bauschutt wird an nahe gelegenen Bächen, Straßen und anderen unangemessenen Orten deponiert, was zu einer Reihe von sozialen, wirtschaftlichen und vor allem ökologischen Problemen führt. Er kann jedoch bei ordnungsgemäßer Bewirtschaftung praktisch vollständig recycelt oder zurückgewonnen werden. Dadurch können äquivalente Mengen an Ausgangsmaterialien eingespart werden und die Verwendung natürlicher Ressourcen sowie die damit verbundenen positiven Auswirkungen auf deren Herstellung nehmen zu. Da es auf Baustellen und bei Gebäudeabrissen häufig zu Vermischungen der verschiedenen Materialien kommt, ist es wichtig, dass bereits vor Ort der Bauschutt in die einzelnen Bestandteile getrennt wird. Dadurch wird die Wiederverwertbarkeit des Materials gesteigert, da einfachere Recyclingprozesse angewendet werden und schlussendlich qualitativ hochwertigere Werkstoffe wiedergewonnen werden können. Die vorliegende Studie untersucht den Einfluss des Kontaminationsgrads des Bauschutts auf technische und wirtschaftliche Aspekte des Recyclingprozesses. Basierend auf drei verschiedenen Kontaminationsgraden, wurden vorab verschiedene Recyclingszenarien entworfen und simuliert. Unter Berücksichtigung spezifischer Bedingungen in der Metropolregion Curitiba in Brasilien, wurden die mit der Weiterverarbeitung des angelieferten Bauschutts verbundenen Kosten geschätzt. Dazu gehören anfängliche Investitionskosten für die Errichtung der Anlage, die Kosten für den Austausch von Betriebsmitteln, jährliche Kapital- und Betriebskosten, sowie Einnahmen aus dem Verkauf der Produkte. Auf dieser Grundlage wurde eine Cashflow-Analyse durchgeführt und die anfallenden Entsorgungskosten des Bauschutts berechnet, die erforderlich sind um eine Mindestrentabilität der Investition zu erzielen.

Die Ergebnisse zeigen, dass die Trennung vor Ort von wesentlicher Bedeutung für die Entwicklung des Recyclings von Bauschutt ist. Aus wirtschaftlicher Sicht sind die Kosten für die Behandlung verunreinigter Materialien ungefähr 2 bis 4 mal höher als für die reinen Materialien, was in erster Linie auf die Erhöhung der Personalkosten, die Lagerung von Rückständen und den Kauf zusätzlicher Ausrüstung zurückzuführen ist. In Bezug auf die Marktbedingungen stellt die Trennung vor Ort die sinnvollste Methode dar, um die Herstellung hochwertiger, zertifizierbarer und recyclingpflichtiger Zuschlagstoffe sicherzustellen. Dies ist unerlässlich, um die Preisspanne zwischen recycelten und natürlichen Produkten zu verringern. Darüber hinaus werden auch andere Möglichkeiten untersucht, um die Wirtschaftlichkeit einer Recyclinganlage beeinflussen. Mithilfe des Skaleneffektes und verbesserter Energieeffizienz des Systems werden beispielsweise die Gate-Gebühren des Bauschutts durch die Verdopplung der Anlagenkapazität um bis zu 44 % gesenkt. Darüber hinaus können die Frachtkosten einen mit den in der Anlage erhobenen Gate-Gebühren des Bauschutts vergleichbaren Wert annehmen oder diesen sogar übertreffen. Dies zeigt, dass das Recycling in dicht besiedelten Gebieten am attraktivsten ist, da Angebot und Nachfrage mit kürzeren Transportstrecken gewährleistet werden können. In der Metropolregion Curitiba, einem von vielen dicht besiedelten Gebieten in Brasilien, ist dies glücklicherweise der Fall

Schlüsselwörter: abfallwirtschaft. bauschutt. recyclingprozesses. umwelt. recyclinganlage

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LIST OF ABBREVIATIONS

€	Euros
°C	Degree Celsius
ABNT	Brazilian Association of Technical Standards
CCTV	Closed Circuit Television
CDRA	Construction and Demolition Recycled Aggregate
CDW	Construction and Demolition Waste
CONAMA	The National Environment Council
h	hour
HBCD	Hexabromocyclododecane
HDI	Human Development Index
HDPE	Polyethylen
HSI	Horizontal Shaft Impactor
IRR	Internal Rate of Return
k€	Kilo Euros
kg	Kilogramm
km	Kilometers
kt	Kilotonnes
kW	KiloWatts
kWh	Kilowatt hour
l	litre
LCC	Life Cycle Costing
LDPE	Low-density polyethylene
LoW	European List of Waste
m^2	Square metre
m^3	Cubic meters
MDF	Medium-density Fiberboard
mm	Millimeters
MRA	Mixed Recycled Aggregate
MWh	Megawatt hour
OPEX	Operational Expenditures
PBDEs	Polybrominateddiphenyl Ethers
PCB	Polychlorierte Biphenyle
PET	Polyethylene Terephthalate
PP	Polypropylen
PVC	Polyvinyl Chloride
R$	Real
RA	Recycled Aggregates
RCA	Recycled Concrete Aggregate
RDF	Refuse Derived Fuel
t	Tonnes
UK	United Kingdom

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1 INTRODUCTION

1.1 Background

Construction and Demolition Waste (CDW) is one of the largest flows of waste in the world. It is estimated that more than 10 billion tons of CDW are generated each year all over the world Wang et al. (2019). The amount of CDW produced and its relative share in the total waste generated vary considerably among countries. Although, these values are very dependent on interpretations (e.g. some countries include soil, stones and dredging soil in CDW waste statistics, while others do not) and commonly estimated based on secondary data (e.g. human development index - HDI, financial value of building permits), they review the importance of CDW and reflect, in some degree, different economic structures. As result of rapid urbanization and large-scale construction sites, China is the world biggest producer of CDW. It is estimated that 2.36 billion tons are generated annually Zheng et al. (2017), amounting for 30% to 40% of the total amount of waste generated Huang et al. (2018) in the country. In European Union, the construction sector has the highest contribution within all economic activities with 36.4% of the total waste generated, corresponding to 923.5 million tonnes per year. At individual member states level, this share can be as high as 73.9% in Austria, 69.9% in the Netherland, 69.4% in France and 55.1% in Germany, for example EUROSTAT (2019). In Brazil, even though no official data is available, it is estimated that around 70 million tons are generated each year. This amount is based on the generation rate of 500 kg/year per capita (correlated to the HDI)Contreras et al. (2016).

CDW arises from activities such as the construction of buildings and civil infrastructure, total or partial demolition, road construction and maintenance EUROPEAN COMMISSION (2019). If not well managed CDW may constitute one of the greatest problems in urban areas. One issue is related to the enormous quantity of CDW produced, which ends up predominantly occupying and depleting the already limited landfill resources Marzouk; Azab (2014) or even dumped in urban/suburban areas, nearby creeks, roads and other inappropriate places Seror; Portnov (2018)Yuan (2017). Another problem is related to the characteristics of the CDW. Even though most of the CDW are inert materials, buildings may have been constructed (or contaminated) with materials with hazardous characteristics, such as asbestos, brominated flame retardants (e.g. hexabromocyclododecane -HBCD and polybrominated diphenyl ethers -PBDEs), some solvents and adhesives, and heavy metals (e.g. As, Pb, Hg, Cr, Cd, Cu, and Zn), which may cause soil and water contamination Yu et al. (2018)Li et al. (2016)Duan et al. (2016).

In line with the principle of circular economy, recovery/recycling is one of the most advisable solutions to mitigate the impacts of CDW on environment Ghisellini et al. (2018). High CDW recovery rates are already reported in many developed countries. In the Netherlands for example, CDW landfilling is almost non-existent with 98% of the CDW already recovered Giorgi et al. (2018). In Germany, a well-developed recycling infrastructure, with around 2870 recycling plants in operation Destatis (2019), allows a CDW recovery rate of 85% to be achieved BMU (2018). In Japan the recycling/reduction rate was high at 96.0% in 2012 MLIT (2018). However, many countries, particularly under developing countries, still lack infrastructure and regulatory conditions to recover/recycle CDW and most of the waste is simply landfilled or illegally dumped. In China, on average recycling and re-use accounts to only 5% of the total CDW generated Huang et al. (2018). In Brazil it is estimated that 21% of CDW is recycled Abrecon (2015).

In general, CDW consists of a mix of different streams including mineral materials (e.g. concrete, bricks, tiles, ceramics, mortar), wood, metals, plastic, gypsum-based waste, paper, cardboard and hazardous wastes, many of which can be recovered or recycled Deloitte (2017). Typically, a high proportion is made of “stony” materials, which are well suitable to be recycled and used as a substitute for “virgin” quarried aggregates. In that way, equivalent quantities of primary aggregates are displaced, reducing the usage of natural resources and impacts in terms of energy consumption, pollution, waste disposal and climate change Hossain et al. (2016)Coelho; Brito (2013)Coelho; De Brito (2013a). The RA are most commonly used in low-grade applications as base and sub-base material in road construction Behera et al. (2014a)Wijayasundara et al. (2018)Ossa et al. (2016), being in this case labelled as downcycling, that is to use recycled material in a less valuable application than the original purpose of the material Allwood (2014a). However, RA can also be used in higher-value applications such as concrete production. In that instance, the quality of the RA is vital to ensure a high-performing concrete in terms of compressive strength and durability. If present, impurities such as plastics, metals, mortar and wood decrease the mechanical properties of the RA Behera et al. (2014b)Butler et al. (2011)McNeil; Kang (2013).

Within the value chain, it can be said that the recycling process already starts where the waste is generated. The proper segregation at source of the CDW into mono streams ensures that different categories of waste don’t contaminate each other, guaranteeing high recycling potential and higher-value applications for the recycled materials. Whereas, relative “clean” mineral material requires only basic processes such as crushing and sieving to produce RA, totally mixed CDW requires more complex, costly and usually very labour-intensive recycling methods. In demolition activities for instance, apart from the conventional practice of total demolition that generates high contaminated CDW, selective demolition technique may be used. Also referred to as selective dismantling or deconstruction, this technique dismantles building components roughly in the reverse order as they were originally constructed. In that way, materials can be easier salvaged for reuse, recovered or recycled Guy (2000).

All in all, large quantities of CDW are produced and many countries still lack infrastructure and regulatory conditions to manage it in a more sustainable way. The waste is frequently simply landfilled, or even illegally dumped, causing a series of social, economic and environmental impacts. Likewise, without a well-developed program of segregation at source, totally mixed CDW is generated, compromising its recyclability and imposing additional obstacles to a competitive recycling program.

1.2 Problem Statement

Despite of some available studies on CDW recycling, few of them have focused on the influence of the CDW contamination level on the technical and economical aspects of the recycling process. This comprehension is well applied in most of the municipalities in Brazil, where a growing demand to increase the rate of recycling contrasts with large quantities of CDW being generated partially or totally mixed. Presumably, this is the case of the metropolitan region of Curitiba (located in south Brazil with around 3,6 million inhabitants) on which this work is based. Additionally, a more accurate economic evaluation of the recycling process is also frequently mentioned or perceived as a necessity and fundamental to tackle the issues related to the CDW sorting recycling platforms Oliveira Neto et al. (2017a) Galán; Viguri, J.R.; et al. (2019).

1.3 Objectives

1.3.1 General Objective

The main objective of this project is to investigate the costs to recycle Construction and Demolition Waste (CDW) based on different scenarios of waste segregation at source and contaminations levels.

1.3.2 Specific Objectives

- Review the current technologies and processes applied on CDW recycling facilities;
- Investigate the variables that influence the economy of CDW recycling;
- Design CDW recycling plants and develop a cost spreadsheet based on waste input scenarios;

1.4 Research Benefit

This research benefits the scientific community, constructors and any related entities on CDW by providing updated information regarding the incurred costs to process CDW at recycling facilities based on simulated scenarios of contamination levels. From that, many strategies may be better outlined to promote CDW recycling in the most advantageous form. Notably, the gate fee values calculated in the present research may support policies to ensure the economic viability of CDW recycling facilities, such as taxes on CDW being disposed off in landfills.

1.5 Methodology

The present research was based on three different approaches, as follow: review on relevant literature; data from equipment suppliers; and information acquired from operating recycling plants and interviews. The combined information was used to simulate different scenarios of recycling plants, considering the current practices and processes economically applied in the sector and the lowest global cost principle.

1.6 Report Structure

The report comprises of six chapters each serving a distinct purpose and sorting in order based on flow of research. The report is structured as follows:

- Chapter 1 - Introduction

The first chapter introduces the reader to the research topic. It contains the background and the problem statement of the research, the research`s objectives and the methodology to achieve the aims of the study.

- Chapter 2 - Literature Review

The second chapter reviews the current relevant literatures related to CDW management, focusing on the processes and the technologies applied in CDW recycling activities; on financial and economical evaluation of CDW recycling facilities and on environmental impacts.

- Chapter 3 - Scenarios Definition

This chapter evaluate the variables which influence CDW recycling activities and defines the scenarios to be simulated in the present study. The scenarios will be based on different CDW`s contamination levels, so as to represent several degrees of segregation of CDW at source.

- Chapter 4 - Plant Design and Cost Calculation

This chapter presents the results of the simulated scenarios. The plant predesign is presented, as well as, the cost calculation for each simulated scenario.

- Chapter 5 – Discussion, Conclusion and Recommendation

This chapter discuss the results and summarizes the research findings regarding CDW recycling platforms. It also gives recommendations and suggestions for further researches and explains any limitation of the present study.

2 LITERATURE REVIEW

2.1 Definition of Construction and Demolition Waste (CDW)

CDW covers a wide range of materials and generating sources. The main categories are the waste arising from construction, total or partial demolition of buildings and/or civil infrastructure; soil rocks and vegetation arising from land levelling, civil works and/or general foundations; and associated materials arising from road construction and maintenance Symonds (1999).

The composition and representative quantity of the waste generated are depended on a multitude of variables, highly influenced by regional particularities (country to country, or even by districts in the region) Pacheco-Torgal et al. (2013)Galán; Viguri, J.R.; et al. (2019). The type and availability of raw materials, construction and demolition techniques, use and age of the buildings and origin of the activity are just some examples. Due to this diversity, it is important to make use of a classification system to standardise the separation and collection of the waste, thus, facilitating the treatment process for a given type of waste.

Although there is no absolute and uniform classification, the waste is typically classified based on its composition and/or origin. For instance, in European Union the CDW is categorised in groups according to the European List of Waste (LoW) (even though each member may also define and classify CDW according to its own legislation). TABLE 1 presents a summary of the main types of CDW and their related code. The full list contains on total 38 different codes for CDW and can also be found in the ANNEX I.

TABLE 1 - CATEGORIES OF CDW BASED ON THE EUROPEAN LIST OF WASTE (LOW) CODES

(continue)

Category	LoW code	Description
Demolition Waste	17 01 01	Concrete
	17 01 02	Bricks
	17 01 03	Tiles and ceramics
	17 01 07	Mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
Road construction waste	170302	Bituminous mixtures other than those mentioned in 17 03 01

TABLE 1 - CATEGORIES OF CDW BASED ON THE EUROPEAN LIST OF WASTE (LOW) CODES

(conclusion)

Soil and Stones	17 05 04	Soil and stones other than those mentioned 17 05 03
	17 05 06	Dredging spoil other than those mentioned in 17 05 05
	17 05 08	Track ballast other than those mentioned in 17 05 07
Construction waste on gypsum-base	17 08 02	Gypsum-based construction materials other than those mentioned in 17 08 01
Construction waste	17 02 01	Wood
	17 02 02	Glass
	17 02 03	Plastic
	17 04	Metals (including their alloys)
	17 06 04	Insulation materials other than those mentioned in 17 06 01 and 17 06 03
	17 09 04	Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

SOURCE: adapted from European Commission (2000)

In Brazil, CDW is classified into four classes of residues, on which the treatment/disposal methods vary respectively, according to CONAMA n° 307 and n° 431 (TABLE 2). Class A materials must be re-used or recycled as aggregates or be sent to landfill specific for CDW. According to the norm ABNT NBR 15113, only Class A materials or inert waste can be disposed of in landfill for CDW and they must be arranged in a way that allow their use or future recycling. Other classes of materials (Class B, C and D) must be previously sorted (at the generating source, in transfer areas or in the landfill itself) and sent to an appropriate treatment or final disposal ABNT (2004a).

TABLE 2 - CLASSIFICATION OF CDW AND THEIR RESPECTIVE TREATMENT/DISPOSAL METHODS

(continue)

Classification	Treatment/disposal methods
Class A - reusable residues or residues recyclable as aggregates, such as: ceramic components (bricks, blocks, tiles, coating plates, etc.), mortar, concrete, soil, sand and stone.	must be reused or recycled as aggregates, or sent to landfill areas of civil construction, being arranged in a way that allows their use or future recycling
Class B - recyclable wastes for other purposes, such as: plastics, paper/cardboard, metals, glass, wood and others.	must be reused, recycled or sent to temporary storage areas, being arranged in a way that allow their use or future recycling.

TABLE 2 - CLASSIFICATION OF CDW AND THEIR RESPECTIVE TREATMENT/DISPOSAL METHODS

(conclusion)

Class C - residues for which no economically viable technologies or applications have been developed that allow its recycling/recovery.	must be stored, transported and destined in accordance with the specific technical standards
Class D - hazardous wastes from the construction process, such as paint, solvents, oils and others; or those contaminated or harmful to health from demolitions, renovations and repairs to radiological clinics, industrial and other facilities; as well as tiles and other objects and materials containing asbestos or other products harmful to health.	must be stored, transported, reused and disposed off in accordance with specific technical standards.

SOURCE: Adapted from CONAMA (2002) and CONAMA (2011)

Despite of CDW being categorized in classes, its different components are not as much specified and detailed in comparison with the LoW. This is reflected on TABLE 3, which shows the gravimetric composition and a great number to different components considered by various authors, making it difficult to compare results. Nevertheless, the authors' results agree that the majority of the CDW is composed of Class A materials, with mortar, ceramics and concrete among the highest shares.

Important to note the relatively small quantity of concrete in the CDW produced in Brazil. This is due to the greater predominance of waste from construction activities compared to demolition, much due to the development of numerous urban areas Pinto (1999)Lima; Cabral (2013a).

TABLE 3 - GRAVIMETRIC COMPOSITION OF CDW ACCORDING TO VARIOUS AUTHORS

(continue)

Class	Component	Neto; Schalch (2010)	Tessaro et al. (2012)	Lima; Cabral (2013b)	Bernardes et al. (2008)	OLIVEIRA et al. (2011)	Carneiro et al. (2000)	Brito Filho (1999)	Pinto (1986)	Zordan (1997)	Miranda et al. (2009)	
		São Carlos, SP	**Pelotas, RS**	**Fortaleza, CE**	**Passo Fundo, RS**	**Fortaleza, CE**	**Salvador, BA**	**Itatinga, SP**	**São Carlos, SP**	**Ribeirão Preto, SP**	**São Paulo, SP**	**Recife, PE**
Class A	Mortar	8	32	22	43,7	37,7	53	25	64	37,4	79,6	80,5
	Concrete	26		15,6	13,8	14		8	4,7	21,1		
	Polish ceramic	14	31	6,3	35,1	8	3	30	29	2,5		
	Red ceramic	19	-	14,4		12,7	12			20,8		
	White bricks		-	10,4		4,3	-					
	Stones	10	-	-	1,1	4,3	4		1,4	17,7		

TABLE 3 - GRAVIMETRIC COMPOSITION OF CDW ACCORDING TO VARIOUS AUTHORS
(conclusion)

	Sand	9	-	24,6		12,7	21	-	-	-		
	Soil		25		0,7	-		32	0,1	-		
Total Class A		86	88	93,3	94,4	93,7	93	95	99,2	99,5	79,6	80,5
Class B	Gypsum	1	1	5	2,4	2,7	-	-	-	-	9,2	-
	Wood	7	4	1,4	2,1	-	4	-	0,1	-	10,2	16,6
	Metals	2	2,5		0,3	-	-	-	-	-	0,1	2
	Plastics/PVC	1	2,2		0,6	-	-	-	-	-	0,3	0,7
	Paper/cardboard		0,3			-	-	-	-	-	0,6	0,2
	Glass	1	-		-	-	-	-	-	-	-	-
Class C	Organic matter	-	1	-	0,1	-	-	1	-	-	-	-
	Foam, leather, fabric	-	-	0,02	-	-	-	-	-	-	-	-
Class D	Paint, solvent, asbestos	-	-	0,2	-	-	-	-	-	-	-	-
	Others	2	1	-	-	3	3	4	0,6	0,5	-	-

SOURCE: it is indicated in the table itself for visualization reasons

2.2 Segregation at Source

If not well managed, general mixing and cross-contamination of materials is frequently observed in construction and demolition sites. Segregation at source is an important technique to ensure that each component is obtained separately. In doing so, CDW can be virtually entirely recycled/recovered and the costs related to the disposal of CDW in landfills are concomitantly reduced.

The avoidance of mixing of the waste on the site itself is always preferable than sorting it at the recycling plant, as later separation is more complex, more expensive and the quality of the recycled materials is invariably compromised. Especially important are those of hazardous characteristics, such as asbestos based materials, lead paints, PCB-containing Caulk, varnished materials, batteries, fluorescent tubes, lubricants, oils, grease, etc. Even non-hazardous waste may become hazardous through mixing, e.g. asbestos roof thrown onto a pile of bricks and concrete, turn the whole pile into hazardous waste Roussat et al. (2008). Gypsum-based materials content in RA are also important as it can generate hydrogen sulphide, compromising the durability and the mechanical behaviour of concrete and mortars Tovar-Rodríguez et al. (2013)Agrela et al. (2011).

For instance, TABLE 4 presents the elements of selective dismantling in demolition activities. Although this technique may take longer than conventional demolition due to its labour-intensive nature, the revenue from salvaged materials and the disposal cost avoided counterbalance these expenses. As a matter of fact, selective demolition with subsequently recycling could present overall costs 40% lower compared to total demolition and subsequently landfilling, when life cycle costing (LCC) method is considered Di Maria et al. (2018).

TABLE 4 - ELEMENTS OF SELECTIVE DEMOLITION

Activities	Materials	Comments
Selective removal of accessible materials with obvious sales value.	Valuable architectural salvage (such as fireplaces, stained glass, carved door and wall panelling, some decorative wrought iron and tiles), some sorts of roof tiles, some sealed double-glazed window and door units, some electrical fittings, some metals (such as lead off the roof and easily accessible items such as cooper pipes and wiring).	If the owners of the site do not manage this process, “informal recyclers” (i.e. thieves) may do it for them.
Selective removal of accessible materials which, if not removed, will cause the CDW to be treated as hazardous	Asbestos and other hazardous materials	This will reduce the proportion of CDW that has to go to hazardous landfill
Selective removal of materials which, if not removed, will depress the value of the remaining CDW when crushed	Other accessible wooden items, other accessible plastic items, excessive volumes of glass. Even plaster (gypsum) may be removed for this reason	This will raise the value of the CDW derived aggregates subsequently produced
Demolish the balance of the structure(s), sort into waste streams as appropriate, and treat each waste stream on- or off-site prior to recycling or final disposal	After the structure has been demolished it is normally possible to remove further steel (or possibly wooden) beams which were part of the basic structure (and therefore could not be removed previously)	

SOURCE: Symonds (1999)

From the perspective of the technologies and processes required to process CDW, three main categories of waste can be identified based on the contamination level (**Erro! Fonte de referência não encontrada.**):

- Mineral CDW: relative “clean material, which requires only basic processes to be treated, such as crushing, metal separation and sieving;
- “Mainly” mineral CDW: mineral materials with some contaminations. Additional processes are required to treat the waste, such as air separation and manual sorting;

- Totally mixed CDW: requires complex and usually very labour-intensive recycling processes.

FIGURE 1 – TYPES OF CDW

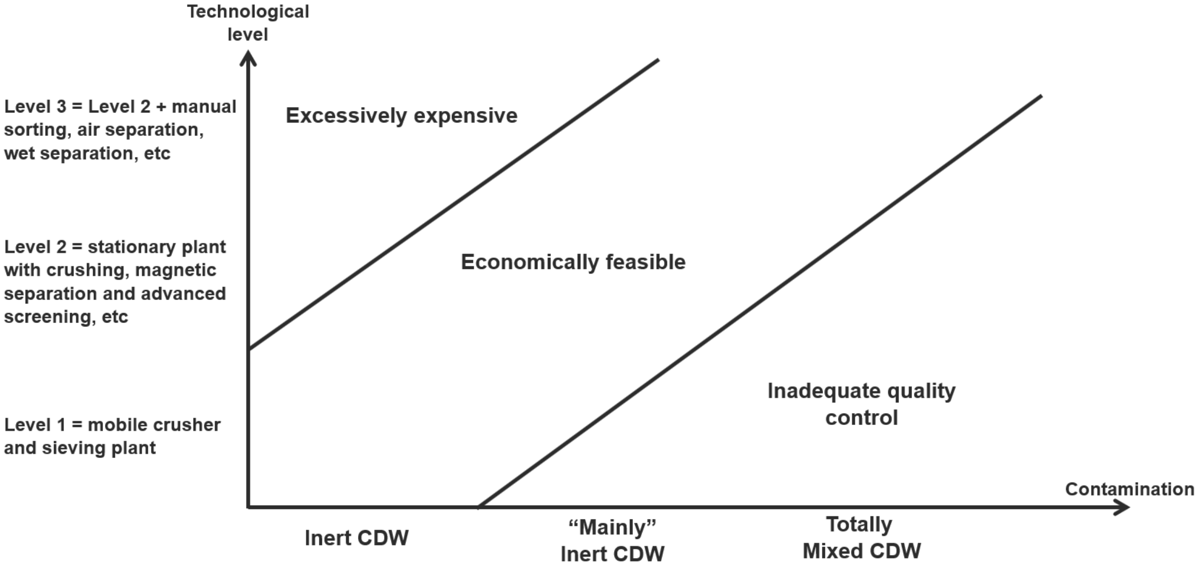
a) mineral CDW, b) "mainly" mineral CDW and c) totally mixed CDW
SOURCE: CEG (2017), Nichetti (2019) and Costa (2014)

2.3 Types of CDW Recycling Plants

A long list of techniques, processes and configurations are available to process CDW. According to the degree of complexity, CDW recycling plants may be classified into three main levels Symonds (1999), as shown in

Although, the number of processes increase from level 1 up to level 3 plants, one should not imply that level 1 plants are inferior. Such levels have to be understood as a technical and economical indicative for the feasibility of a recycling plant to a given type of waste and an envisioned quality of the products Pacheco-Torgal et al. (2013).

FIGURE 2 - EMPLOYED RECYCLING TECHNOLOGY AND CDW CHARACTERISTICS VERSUS RECYCLED PRODUCTS USE



SOURCE: Adapted from Symonds (1999)

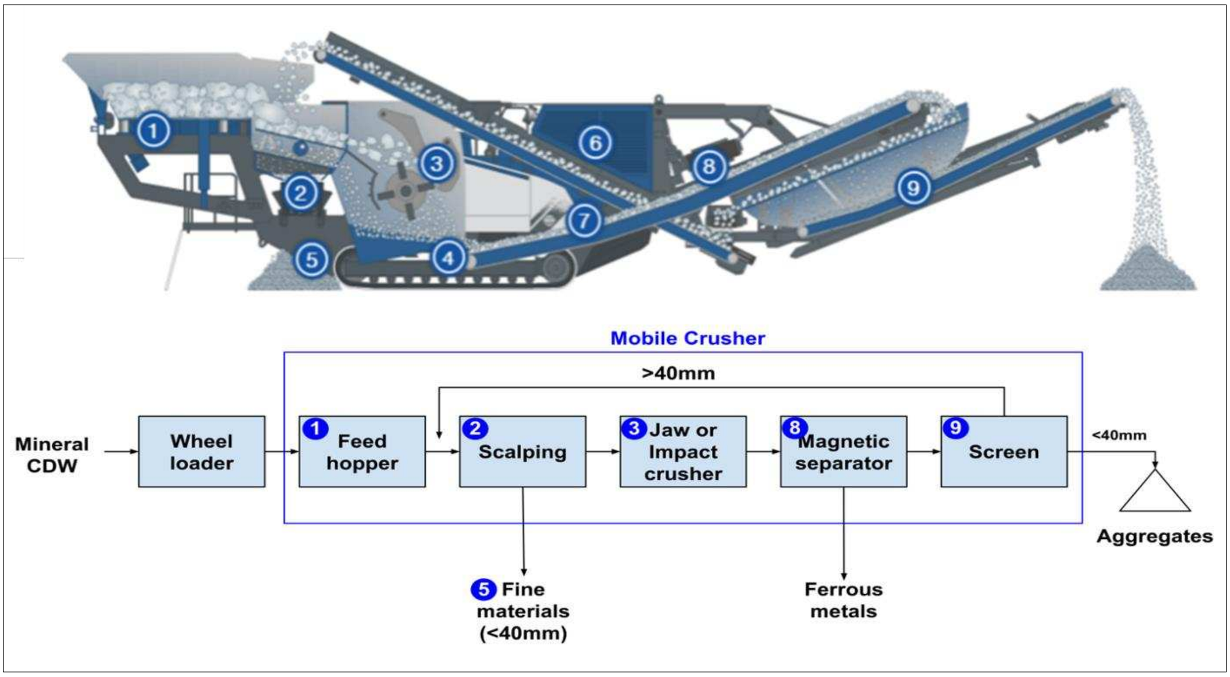
Each Level is described below, and a detailed description of each recycling process is given on Section 2.4**:**

2.3.1 Level 1 - mobile crusher and sieving plant:

Mobile recycling plants are the most basic types of facilities and have risen in popularity due to the possibility of operation directly at the worksite, instead of transferring the waste to a fixed facility. Consequently, the transport costs are greatly reduced, and the processed material can be reused directly on site, being well suitable for demolition sites generating large amount of CDW. However, avoided transport costs comes at the expense of a lower separation performance, as additional separation processes, such as air separation, wet classification systems, manual picking and advanced sieving, are easier implemented in stationary plants. Therefore, these plants are usually specific to homogeneous and relative “clean” mineral materials Pacheco-Torgal et al. (2013).

A typical mobile crusher with its main components and process flow is illustrated by FIGURE 3.

FIGURE 3 - COMPONENTS OF A TYPICAL MOBILE CRUSHER AND ITS PROCESS FLOW



SOURCE: adapted from Kleemann (2019a)

It is composed of:

1. Feed hopper: control the feed of material to ensure continuous crushing;
2. Primary screening: screen of fines of the material ensuring continuous crusher feed and avoidance of blockages in crusher;
3. Crusher: either impact or jaw crusher can be used to obtain the desired grain size.
4. Discharge chute: discharge the crushed material to the discharge belt;
5. Chassis: accessibility to all machine components for maintenance;
6. Power unit: generates the energy necessary, usually with a diesel fired motor, to power all the equipment;
7. Electrics-control: accessibility to electric control of the equipment;
8. Magnetic separator: a cross-belt electromagnet removes any ferrous-metal;
9. Classifying screening unit: usually only a single deck vibrating screen is provided, which separates the crushed material to the desired size. Working in a loop, materials with higher dimension are returned to the crusher. For more advanced screening, some units may have additional screen installed and independent mobile screens are also available.

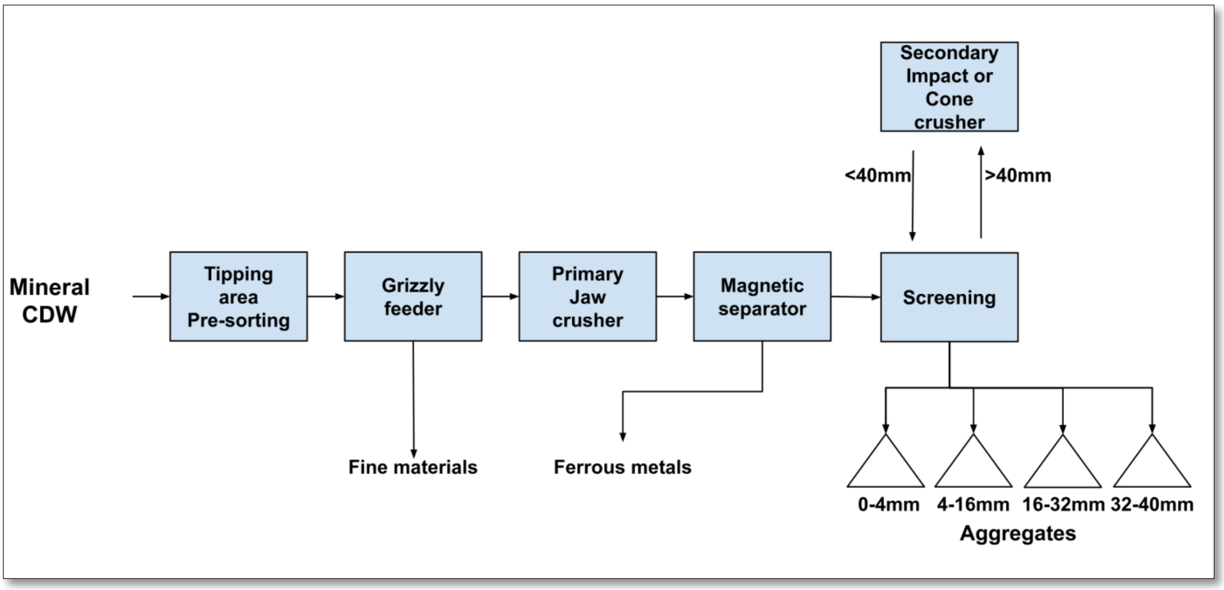
2.3.2 Level 2 - stationary plant (crushing, magnetic separation and advanced screening):

Even though transport costs are higher in stationary plants, both to bring CDW to the plant and to transport recycled materials to the construction site, the gain of scale, energy efficiency and higher quality of the recycled aggregates contribute to the economical viability of stationary plants. Gain of scale is achieved since stationary plants can receive CDW from various generation sources, leading to higher capacities compared to mobile plants. Energy efficiency is achieved considering that stationary plants are commonly connected to the grid and more efficient electric equipment can be used, compared to diesel fired motors of mobile plants. Higher quality standards of the products are most likely met in stationary plants, as additional process can be easier implemented and operational control better performed. This is quite relevant for the commercialization of recycled aggregates, as the quality of the material can be controlled, and certificates issued Pacheco-Torgal et al. (2013).

In Level 2 plants, the material is typically crushed in two or more stages, initially by a primary crusher (jaw crusher), followed by a secondary crusher (impact or cone crusher). A cross-belt electromagnetic removes ferrous-metal and the crushed material is screening into more grain sizes compared to a mobile plant. Depending on the contamination level or the envisioned use of the recycled products, an air separator and a few manual sorters may be also applied. In level 2 plants, the RA are most often used in road construction as base and sub-base material, and in some cases in concrete production.

A typical process flow of a stationary plant is illustrated by **Erro! Fonte de referência não encontrada.**.

FIGURE 4 - TYPICAL PROCESS FLOW OF A STATIONARY PLANT (LEVEL 2)



SOURCE: own elaboration

2.3.3 Level 3 - advanced stationary plant (same as level 2 + manual sorting, air separation, wet classification system):

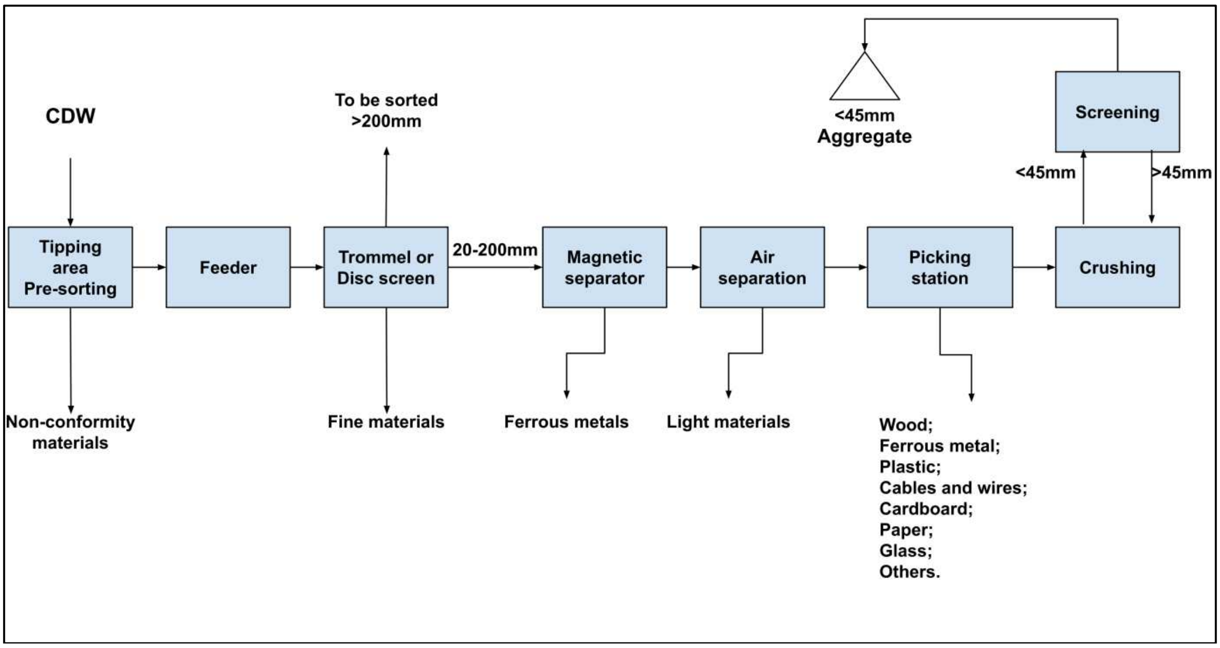
In addition to level 2 plants, level 3 plants may have manual sorting, to separate and remove contaminants; air separation to remove light materials; wet separation systems to separate both organic and lightweight materials; and other advanced processes. Therefore, this type of plant can handle all type of CDW, including totally mixed

CDW. In the last case, the recycling process can be very labour-intensive and high quality of the products are not commonly achieved, due to the high variability of the input material. However, if mineral CDW or “mainly” mineral CDW are to be treated, high quality products can be achieved by this type of plant.

A wet classification system may be unavoidable if the aggregates are to be used in concrete production, depending on the level of contamination. However, higher separating efficiencies of the system come with higher treatment costs, as this system requires additional processes related to the treatment of waste water and sludge.

A typical process flow of a stationary plant (Level 3) is illustrated by **Erro! Fonte de referência não encontrada.**.

FIGURE 5 - TYPICAL PROCESS FLOW OF A STATIONARY PLANT (LEVEL 3) RECYCLING TOTALLY MIXED CDW



SOURCE: own elaboration

2.4 CDW Recycling Processes

This section describes the most important processes often found in CDW recycling facilities and may be applied (or not) depending of the technology level of the plant.

2.4.1 CDW reception and storage

Upon arrival at the plant, all the relevant data is recorded and transmitted to central command, such as, gross weight of the truck, truck`s identification number, origin, data and time of arrival. The driver has also to inform the type of waste being transported detailing the 6-digit code from the LoW or any other waste categorisation code applied. This code is also used to set the tipping fee to be charged. Apart from that, inspectors usually work at the weighbridge to have a direct overview of the incoming waste. Any hazardous or non-conformity waste identified are rejected at the entrance. Each different type of waste must be unloaded and stored separately in individual areas or bunkers. This avoids cross contamination and unnecessary efforts to treat “clean” waste, while increases the quality of the recycled products. Well-managed single materials from trusted sources may bypass some of the processes Wrap (2009).

Good communication between the weighbridge and the personnel working in the unloading area is also crucial, as they can quickly inform the weighbridge any non-conformities found and the unloaded CDW be extra charged accordingly. In that case, photographs should be taken, and if possible, sites should operate a CCTV system, to corroborate evidences. On its way out of the plant, the empty truck is weighted again, and the net value calculated. The drivers also receive a “receipt” stating all the information which were gathered Wrap (2009).

2.4.2 Pre-sorting and bulk materials size reduction

Pre-sorting at the tipping area is vital to all subsequent processes, as problematic materials that could damage or cause blockages on equipment and those that could contaminate products are, whenever possible, removed. This may include electronic equipment, mattresses, tires, batteries, canisters, large plastic films, treated wood, gypsum-containing materials, hazardous waste, among others. This is can be done mechanically by a grab operator or manually by sorters Wrap (2009).

Large pieces of metal and wood are also separated in this stage. In the case of wood, shredders may be used to facilitate storage and transportation. Large chunks of concrete, masonry and rocks are broken by excavators equipped with hydraulic cutter/hammer. The maximum size of those blocks is given by the requirements of the crusher and the primary screen, e.g. wider materials can be processed by a jaw crusher than by an impact crusher Metso (2011).

FIGURE 6 - EXCAVATOR EQUIPPED WITH HYDRAULIC CUTTER/HAMMER

SOURCE: NPK (2019)

2.4.3 Screening and classifying

Screening is the mechanical process which stratifies particles according to size and their acceptance or rejection by a screening surface. A distinction has to be made between primary screen (or up front) and secondary screen. The first is located in the initial steps of the recycling process and usually handles larger and more contaminated materials, e.g. totally mixed CDW. Primary screening serves several purposes: soil and other fines are sieved out, the weight of material is reduced and compacted waste is loosened up. Secondary screening usually handles aggregates or materials that were already processed in the previous steps. The aim in this case is to classify the material to meet the size range required by the costumers Wrap (2009). Several types of screens are available, as follow:

2.4.3.1 Trommel/Drum screen

Trommel/Drum screen consists of a perforated cylindrical drum rotating at a certain angle. Materials smaller than the holes fall through it, while larger objects continue and exit the equipment onto a conveyor belt. They can be made of several holes' diameters fitted in series from fines to coarsest, classifying the material in additional under fractions Napier-Munn; Wills (2005).

By being vibration free, they are less noisy and less susceptible to mechanical stress, thus, lasting longer. However, they are more susceptible to plugging and blinding. Plugging is when material larger than the aperture may become stuck. Blinding is when wet materials clump up and stick to the surface of the screen. In general, trommel screen are cheaper to produce and more robust compared to vibrating screens. However, they generally have lower capacities since only part of the screen surface is used Napier-Munn; Wills (2005). In CDW recycling applications trommel screen is suitable to process mixed CDW as a primary screen Wrap (2009).

Trommel screens can be easily damaged by heavy material (e.g. large pieces of concrete, rubble and stones) when they are lifted and dropped by the rotation of the trommel. Some other objects, such as carpets and boards, can block the holes. Therefore, it is important to remove such materials whenever possible at the pre-sorting step Wrap (2009).

FIGURE 7 – EXEMPLES OF SCREENS

(a) and (b) examples of trommel screen, (c) disc screen
SOURCE: BHS (2019), EXCT (2019) and NIHOT (2018)

2.4.3.2 Disc screen

Disc screens are comprised of steel shafts to which rotating discs or stars are fitted. The shafts rotate altogether in the same direction, carrying the oversized material to the end of the screen exiting onto a conveyor belt, while allow fines to fall through the gaps between the discs. They are usually used for screening applications from 3 to 300mm. They offer high capacity, low noise levels, low space requirement Napier-Munn; Wills (2005). Disc screens are also less prompt to have problems with heavy impacts compared to trommel. However, they are typically 50% more expensive Wrap (2009).

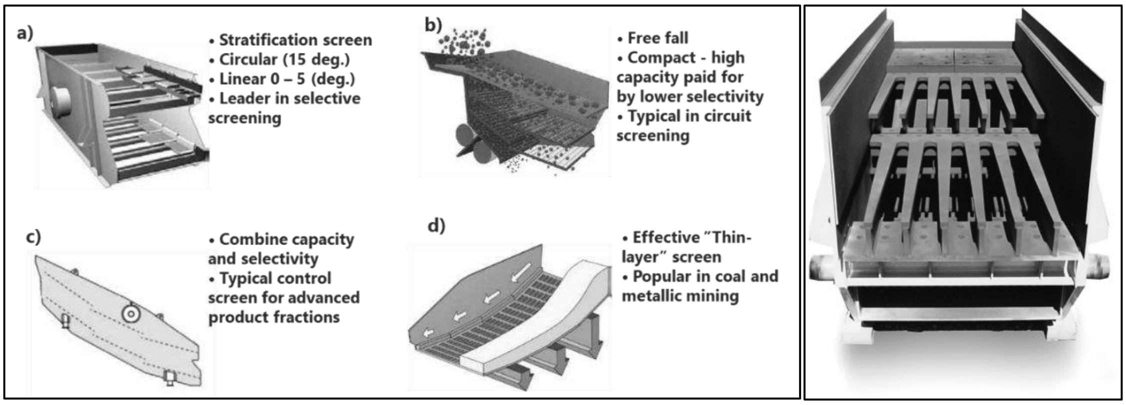
One issue related to this screen is that wire, rope, tape and plastic film can wrap around the disks jamming them up. Therefore, those materials should be removed at the tipping area. In CDW recycling application, this screen is suitable for mixed waste as primary screen.

2.4.3.3 Vibrating screens

Vibrating screens are the most important and versatile screening machines for mineral processing applications. Many types of vibrating screens are available in the market as shown by FIGURE 8, but approximately 80% used worldwide are single inclination screens Metso (2018). Vibrating screens can be manufactured with multiple screening decks. In that way, the input material is fed to the top coarse screen and the undersize material falls through to lower screen decks, therefore, producing a range of sized fraction from a single screen. In CDW applications, multiple screening decks are commonly used to better meet the aggregate size specifications.

The flow of material through the screen is guaranteed by oscillations movement, which can be vertical, circular or elliptical, induced mechanically by the rotation of unbalanced weights or flywheels attached usually to a single drive shaft Napier-Munn; Wills (2005).

FIGURE 8 – TYPES OF VIBRATING SCREENS



(a) single inclination, (b) double inclination, (c) triple inclination, (d) multiple inclination ("banana screen") and (e) grizzly screen/feeder
SOURCE: Adapted from Metso (2018) and Napier-Munn; Wills (2005)

When very coarse material has to be screened, grizzly screens are commonly applied. These screens are characterized by parallel steel bars set at a fixed distance, according to the undersize desired. They are frequently associated with a feeder and usually precede a crusher, in order to reduce the load material to be crushed Metso (2018).

2.4.4 Crushing

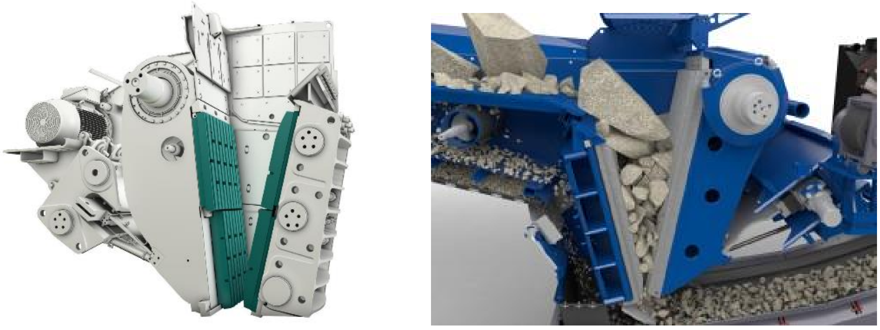
A multitude types of crushers are available in the mining industry. The material type, size, maximum nominal size, deviation in size distribution, capacity, etc., all contribute to the choice of one or another crusher. A distinction has to be made considering that crushing can be performed in one, two or even three stages (i.e., primary, secondary, tertiary) Metso (2018).

The purpose of a primary crusher is to reduce the input material to a size that can be transported in conveyors belts to the next crushing stages or other processes. The purpose of a secondary/tertiary crusher is to further crush the material into the final marketable size. Since the size of the feeding material is smaller and much of the harmful constituents have been removed, secondary crusher can be simpler constructed compared to the heavy-duty primary crushers. In CDW recycling applications the main type of crushers used are Jaw crushers, Impact crushers and Cone crushers.

2.4.4.1 Jaw Crusher

Jaw crushers are the most common type of primary crusher in CDW applications, mainly due to their reliable and easy operation, low maintenance, heavy duty construction and large input opening. The crushing process takes place between a fixed and a moving jaw. In a reciprocating motion, high pressure is created, which crushes the material into smaller pieces. The reduction ratio for this equipment is usually between 3-5. Pre-scalping, e.g. through grizzly feeders, is typically associated with jaw crusher to increase its efficiency and maximize throughput Metso (2019a).

FIGURE 9 - EXAMPLE OF JAW CRUSHER



SOURCE: Metso (2019a) and Kleemann (2019b)

Higher feed opening compared to other crusher means lower cost on breaking up large blocks. However, jaw crushers are unable to produce small size particles (closed side setting usually <40mm for recycled aggregates), when high throughput capacity is required. For that, impact or cone crushers are commonly utilized instead.

2.4.4.2 Impact Crusher

Impact crushers apply impact rather than compression to crush the material. This can be relevant, considering that pressure creates internal stresses in the broken material that can later cause cracking. On the other hand, impact causes immediate comminution with no residual stresses, particularly valuable in stone used for brick-making, building and roadmaking Youcai; Sheng (2017).

These crushers rely on “beaters” or “bars” rotating at high speed (at 250-500 rpm), which transfer some of their kinetic energy to the particles upon contact. The particles are further crushed by their collision upon an anvil, a breaker plate and between themselves. This type of crusher can deliver a high reduction ratio compared to other crushers, from 5-10. However, high reduction ratio is generally inefficient, being recommendable to process it in multiple stages of crushing Metso (2018).

When the hammer is fixed to the rotor, the crusher is referred as Horizontal Shaft Impactor (HSI). This crusher is extensively used in CDW recycling applications. The main reasons for that are: lower investment cost compared to compression type of crusher; greater reduction ratio. For many installation, especially small plants, the product`s size specification can be achieved with only one pass through the crush.

Although they have substantially lower investment cost on a size-for-size basis, their running costs are much higher, particularly with very hard materials like some reinforced concretes. In that way, they are well suitable as secondary crushers, preceded by a primary jaw crusher.

FIGURE 10 - HORIZONTAL SHAFT IMPACTOR (HSI)

SOURCE: Kleemann (2019b)

2.4.4.3 Cone Crusher

Cone Crusher breaks the material by squeezing and compressing it between a rotating cone-shaped plate and a stationary one. The material gets smaller as it moves gravitationally down through the cavity until it is discharged at the bottom of the equipment. The size reduction is determined by the closed side setting between the two crushing members at the lowest point. The reduction ratio is usually between 3-5. This crusher is best suited to be used as a secondary or tertiary crusher, as it can be inefficient if fed with a wide range of particle sizes (Marmash, 2010).

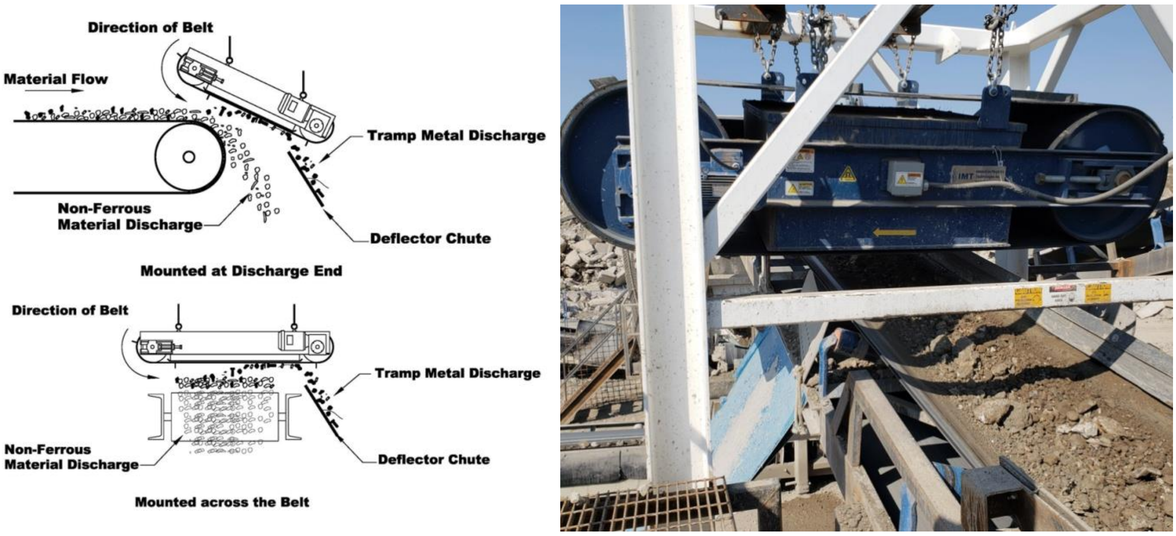
FIGURE 11 - CONE CRUSHER

SOURCE: Metso (2019b)

2.4.5 Ferrous-metal separation

Magnetic separation is a process used to separate magnetic metals, e.g. ferrous metal, from the CDW stream. The process is technically simple, of relatively low cost and helps to avoid possible damages in equipment located downstream such as crushers. Magnets used in the separator may be either permanent or electromagnetic. Unlike electromagnets, permanent magnets operate in a passive way and with minimum energy consumption, retaining metals even during power outages and fluctuations. In turn, electromagnetic separators use electrical current to generate an electromagnetic field. A common separator uses round aluminium or copper wire in an oil-filled assembly to generate a powerful electromagnetic field, which will heat the equipment up to 220 °C. Consequently, this equipment requires a heat exchanger.

FIGURE 12 - FERROUS-METAL SEPARATION



SOURCE: IMT (2019)

Within CDW recycling plants, the magnetic separator is usually suspended with a continuously running belt that strips off captured metal and discharges it off to the side or end of the conveyor. In addition, magnets are fitted as standard on wood shredders for extracting nails.

2.4.6 Manual sorting

Although machines are able to automatically separate a wide range of materials, humans are still very effective at identifying and extracting most objects from the waste flow and are of great importance in ensuring quality of the final product. In CDW recycling plants designed with a manual sorting, initial size reduction of input material is always avoided, as it would increase the effort to pick objects in the sorting cabin. However, in those highly automated plants that relies less on manual picking, crushing or shredding of input material is advisable, as separating equipment perform better with reduced size waste Wrap (2009).

Manual sorters pull off various types of materials, such as wood, non-ferrous metal (e.g. copper, aluminium, lead, tin, brass), rigid and film plastic (e.g. PET, PP, HDPE, LDPE, PVC), cables and wires, paper, cardboard, textiles and any other non-stony material. Recycling plastic, paper and cardboard is problematic as they tend to be contaminated with cement and other materials. Recycling glass is also difficult, considering that the glass must be separated in colours in order to be recycled and that the amount of glass produced in CDW is not appreciable. Therefore, it is usually crushed together with mineral materials into aggregates Wrap (2009).

Any “awkward” oversized objects missed in the pro-sorting step or non-recyclables materials are also removed (e.g. insulation foam, electronic equipment, batteries, tires, etc). Each different recovered material is dropped down into separate bays located below the sorting cabin, usually directly into a skip. Materials on which recycling is uneconomic are removed and dropped down into a “waste” chute.

FIGURE 13 - PICKING STATION FOR CDW

SOURCE: Kiverco (2019) and USA Gypsum (2019)

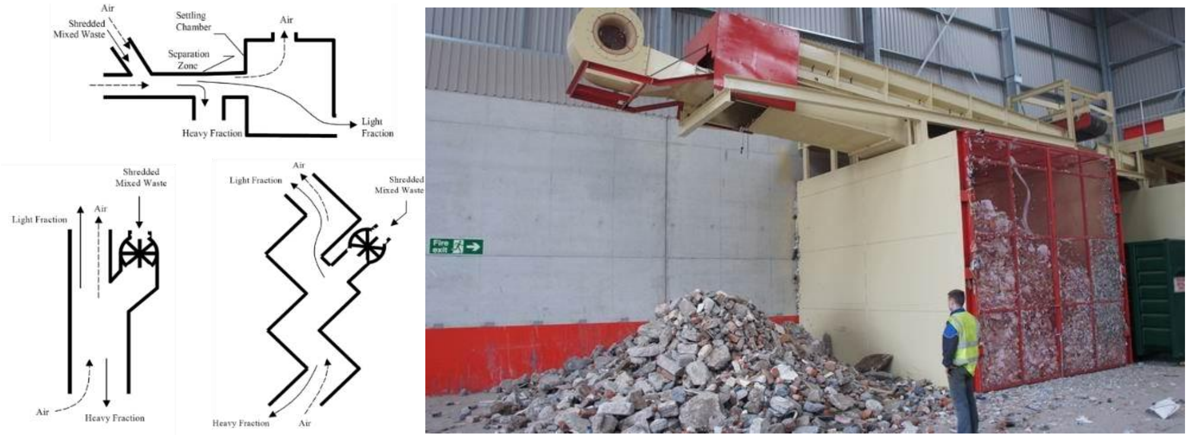
Most of the “untouched” objects would be composed of mineral materials and can be crushed into aggregates. Additionally, an air separation process, or even a wet classification system, is usually applied after the manual cabin to remove light material missed by the sorters and increase the quality of the products.

2.4.7 Air separation

Air separation is a process that separates particles based on the relative difference of their aerodynamic characteristics, being primarily function of its density, geometry and size. The process is technically simple, of relatively low cost compared to other wet methods, such as sink float systems and wet jigs. Materials such as paper, plastic, cardboard, wood, gypsum and other foreign materials often associated with demolition debris will be concentrated on the light fraction and are sellable as Refuse Derived Fuel (RDF). Depending on the velocity of the air, small size particles of sand, soil and rocks can be also dragged out to the light fraction.

Air separators can be classified into diagonals, verticals, zigzag or drum separators, according to the exhaustion column shape and patterns of the obstacles that the particles must go through (FIGURE 14(a)). The most common air separator applied in CDW recycling activities is known as air-knife (or air-sifting). The materials enter the air knife via conveyer belt, where heavy materials simply drop off onto conveyers positioned accordingly. A high velocity stream of air, through which the falling materials has to travel, redirects the lighter materials from the waste stream into a “cage”, trapping the materials.

FIGURE 14 – AIR SEPARATION SYSTEMS



(a) types of air separators, (b) air-knife separator
SOURCE: UNEP (2005) and EMS (2019)

2.4.8 Wet classification system

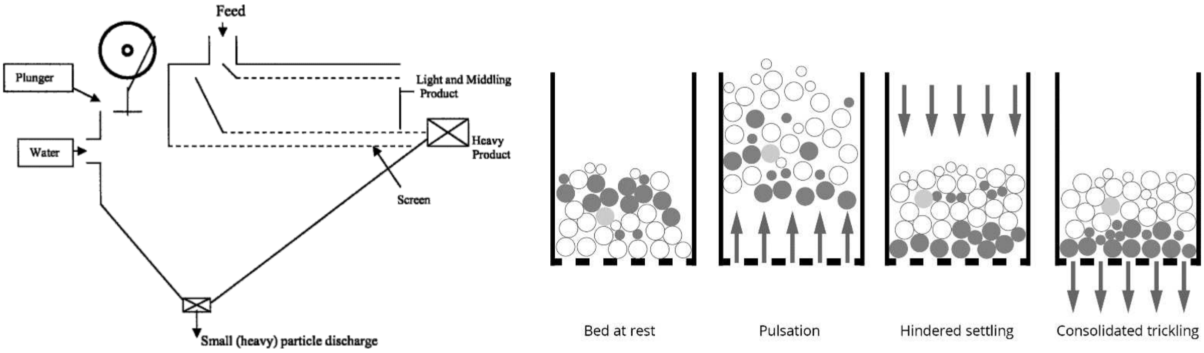
In comparison to dry separation systems, wet classification systems offers higher separation efficiencies and are able to separate both organic and lightweight materials. However, higher efficiencies come at expense of higher treatment costs, as additional processes to treat the wastewater and to dispose the sludge are required Pacheco-Torgal et al. (2013).

Several types of wet separation systems are available including sink-float tank, up-current sorters, table belts (e.g. Aquamator) and wet jigs Garbarino (2010). Although they differ on the mechanism applied, their main operating principle is the same. Water is used as a medium to separate materials based on their different specific weight.

In sink-float tanks, lightweight components such as plastics, paper, cardboards, wood, gypsum, clay, and asbestos fibres will float and then can be removed by combs or paddles moving from one end to the other of the equipment. Materials heavier than water will sink, being extracted at the bottom of the equipment.

Wet jigs, in addition, can separate minerals materials which present significant differences in specific weight. Jigging uses a pulsation of a fluid at a given frequency and amplitude to induce a separation based on differential acceleration, hindered settling and consolidated trickling UAF (2020), as illustrated by FIGURE 15. As reported by Xing (2004), wet jigging can be an effective method to separate concrete rubble and masonry rubble from each other, while washable and soluble components are removed with the slurry.

FIGURE 15 – WET SEPARATION SYSTEM



(a) schematic of a wet jigging (b) principle of operation of wet jigging
SOURCE: Ramachandra Rao (2004) and UAF (2020)

These techniques also have the advantage of leaching water-soluble chlorides and sulphates, which are accountable for attack and corrosion of the concrete and of embedded metals Xie et al. (2019)Silva et al. (2015)Lee et al. (2005).

2.4.9 Shredding

Shredders are employed to reduce the required storage area taken by recovered wood and to increase the efficiency when it is transported. The wood waste can also be separated into high quality wood or “clean wood”, e.g. wooden pallets, that have a higher price and can be converted into animal bedding, panel board or burned as biomass fuel; or into low quality wood, e.g. painted or treated wood, chipboard and MDF, that have lower price, but it can still be sold as fuel Wrap (2009).

Shredders usually have an integrated magnetic separator to remove metals such as nails and screws. Highly automated plants, which rely less on manual picking, treating unsorted CDW may apply a shredder in the beginning of the treatment process, as equipment perform better with reduced sizes. One example is shown on FIGURE 16.

FIGURE 16 – TYPES OF SHREDDERS

(a) shredder for wood waste, (b) inside a twin-shafted slow-speed shredder
SOURCE: WMW (2018) and Wrap (2009)

3 MATERIALS AND METHODS

3.1 Definition of scenarios

This section defines the scenarios of CDW recycling facilities to be simulated in the present work. They were based on four main variables which have high influence on the economical viability of a project: plant's capacity, input material, technology of the plant and source of revenues. TABLE 5 presents the summary of the scenarios and a detailed valuation of each variable is presented in the next sections.

TABLE 5 - SUMMARY OF THE SCENARIOS OF CDW RECYCLING PLATFORMS

Scenario	Capacity (kt/y) Section 3.1.3	Input material Section 3.1.1	Technology of the Plant (level) Section 3.1.2	Source of revenues (main products) Section 3.3
1	300	Mineral CDW	2	RCA, MRA, recycled sand
2	600	Mineral CDW	2	RCA, MRA, recycled sand
3	300	Totally mixed CDW (average case)	3	MRA
4	600	Totally mixed CDW (average case)	3	MRA
5	300	Totally mixed CDW (worst case)	3	MRA
6	600	Totally mixed CDW (worst case)	3	MRA

Source: own elaboration

3.1.1 Input material

As already discussed on Section 2.1, the composition of the CDW varies greatly. In order to obtain a better representation of a typical CDW in Brazil, data from several authors regarding CDW composition were considered. Using the information from TABLE 3, three scenarios of CDW were derived in order to simulate different input contamination levels: mineral CDW (segregation at source), totally mixed CDW (average case) and totally mixed CDW (worst case), according to TABLE 6.

TABLE 6 - CDW'S COMPOSITION ASSUMED IN THE PRESENT WORK

(continue)

Component(1)(2)	**Mineral CDW (Segregation at source)(3)**	**Totally mixed CDW (average case)**	**Totally mixed CDW (worst case)(4)**
Mortar	**30,3%**	**27,9%**	**24,7%**
Concrete	**17,2%**	**15,8%**	**14,0%**
Ceramic	**31,0%**	**28,5%**	**25,3%**
Stones	**5,8%**	**5,3%**	**4,7%**
Sand and Soil	**13,8%**	**12,7%**	**11,2%**
Total (Class A)	**98,0%**	**90,3%**	**80,0%**

TABLE 6 CDW'S COMPOSITION ASSUMED IN THE PRESENT WORK

(conclusion)

Gypsum	**0,5%**	**2,3%**	**4,8%**
Wood	**1,0%**	**4,6%**	**9,5%**
Paper/Cardboard	**0,1%**	**0,5%**	**1,1%**
Glass	**0,1%**	**0,3%**	**0,6%**
Plastic/PVC	**0,0%**	**0,2%**	**0,4%**
Metals	**0,0%**	**0,1%**	**0,3%**
Others	**0,3%**	**1,6%**	**3,3%**
Total (impurities)	**2,0%**	**9,7%**	**20,0%**

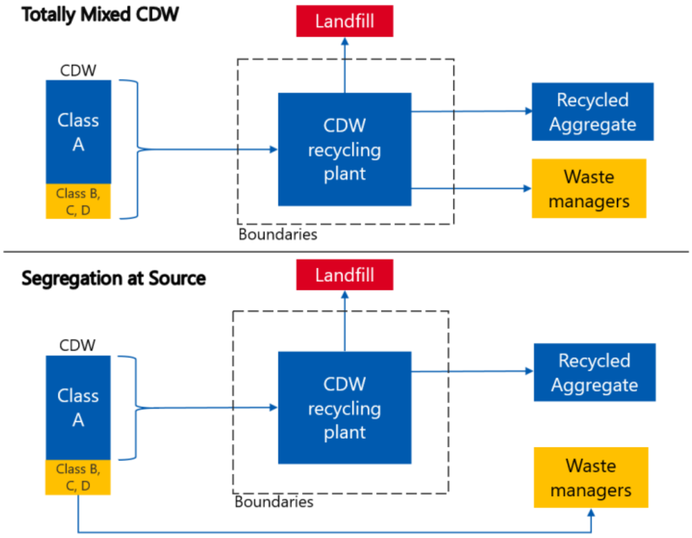
SOURCE: own elaboration

NOTE: (1) The different types ceramic materials were grouped under Ceramic. Class C and D materials were grouped under Others; (2) The composition of Class A materials and of Class B, C and D were calculated considering the authors' results on Table 2, which contain detailed information at individual components; (3) In the case of segregation at source, it was assumed that the waste delivered has 2% of contamination; (4) Based on the worst case for the total percentage of Class A materials found among the different authors`` results (work of Miranda et al. (2009));

Safe to say, the contamination levels assumed are in accordance when compared to those reported by recycling facilities in Brazil. According Bruno (2016), 46% of the CDW received by the plants presents from 0-10% of contamination, 31% from 10-20% and 16% from 20-30%.

Important to note that, for the scenarios with segregation at source, only Class A materials (with a residual contamination of 2%) were assumed to be delivered to the CDW recycling facility. Other materials (Class B, C and D) are delivered directly to other specialized destination, being out of scope of the simulations. In the case of non-segregation at source, the totality of the CDW is delivered and treated in the CDW recycling facility, according to FIGURE 17.

FIGURE 17 - BOUNDARIES CONSIDERED FOR THE SIMULATED SCENARIOS



SOURCE: own elaboration

3.1.2 Technology of the plant

Simply put, Brazil is in the early stages of development in CDW management and the technology generally applied in the sector are rather basic. This consideration is essential in order to investigate the applicability of a certain technology. As previously addressed on Section 2.3, the level of technology is given mainly by the capacity of the plant, type of the waste to be treated and the envisioned quality of the products.

Although mobile plants (Level 1) may be used to recycle CDW, the capacities assumed on Section 3.1.3 favours stationary facilities. According to Pacheco-Torgal et al. (2013), mobiles plants are typically economically applicable for capacities under 200 kt/y. In that way, Level 1 type of plant was not regarded in the present work.

For totally mixed CDW a more complex type of plant is required (Level 3). Even though, some highly automated processes may be used on Level 3 type of plants, it was considered that the separation stages would rely mainly on manual sorters. This is related to the fact that relative low labour wages are applicable to unskilled workers in Brazil.

3.1.3 Capacity of the plant

The capacity of the plant is one of the most important variables on the feasibility of recycling facilities. Gain of scale is favoured, considering that many of the fixed costs can be diluted in higher capacities facilities. However, a global economic analysis has to be performed for each case, considering that longer transport distances may overcome the benefits a concentrated processing.

In the work of Coelho; De Brito (2013b), a large recycling plant with 350 t/h of capacity (amounting to 840 kt/y), located in the metropolitan area of Lisbon was proposed. This value was calculated using a generation rate of 416 kg/person-year in Portugal, determined by Coelho; De Brito (2011), and the resident population of the area. The same authors in another published paper performed a sensitivity analysis, focusing on the investment return period. The results indicate that the capacity variation alone is responsible for reducing by half the investment return period, from 4 years for a 85 t/h facility to 2 years for a 350 t/h Coelho; De Brito (2012).

In the work of Oliveira Neto et al. (2017b) three production level of 100, 300 and 600 kt/y, corresponding to small, medium and large capacities were evaluated. According to the authors, production capacities around 100 kt/y are the most commonly found in the European continent, however, these plants were not economically feasible with the conditions simulated by the authors. Despite of being less common, capacities of 300 kt/y are found in high-populated metropolitan areas and the payback period in this case was estimated in 8 years. Levels of 600 kt/y are considered as an extreme situation but still worth to be simulated and a valid option considering that the higher the level of production, the lower the production costs. Corroborating this statement, a 5 year payback period was estimated for large capacities Oliveira Neto et al. (2017b).

As a matter of fact, even higher capacity facilities are already in operation. For instance, the Abu Dhabi CDW recycling facility has the capacity to process from 5.000 to 7.000 tones per shift Dhafra (). These values would represent from 1.500 to 2.100 kt/y, considering an 8-hours shift and 300 days/year of operation. Another example, a CDW recycling facility located in Burari, New Delhi can process 2.000 tonnes per day, representing around 600 kt/y IL&FS (2019).

Bearing in mind that Brazil has many highly populated areas, medium to large capacity plants seems to be an appropriate strategy. For instance, the 3.6 million inhabitants IBGE (2019) of the metropolitan region of Curitiba would generate around 1800 kt/y of CDW (considering a generation rate of 0,5 kg/y per inhabitant) Contreras et al. (2016). In that way, two capacities were assumed in the present work: a 300 kt/y and a 600 kt/y recycling facility.

3.1.4 Source of revenues

3.1.4.1 Products commercialization

Several categories of RA exist based on different composition, grain size distribution and contamination level, in which prices may vary accordingly. Based on the composition, RA can be classified into four main categories: recycled concrete aggregate (RCA); recycled masonry aggregate (RMA); mixed recycled aggregate (MRA), composed of a mix of recycled concrete and masonry; and construction and demolition recycled aggregate (CDRA), which contains higher levels of contaminants such as asphalt, wood, plastics, glass, etc Pedro et al. (2018).

Moreover, the RA can be distinguished according to the grain size distribution and be commercialized as coarse, fine or all-in-one aggregate. In Brazil, RCA are frequently available as recycled sand (<4,8 mm), coarse RCA (<150 mm), RCA (e.g. 4,8-9,5mm;9,5-19,5mm; 19,5-25mm; 25-39mm) and All-in-one RCA (<39 mm).

Furthermore, there are no well-defined categories based on the contamination level. Technical specifications are essentially given by the envisioned use of the RA, which must comply with certain requirements, such as: compressive strength, grain composition, contamination, water solubility, density, particle form, and heavy-metal content. The norm ABNT NBR 15116:2004 establishes the required conditions in Brazil for the use of RA from pavement to non-structural concrete applications ABNT (2004b). Up to now, it is not allowed to use RA in structural concrete, even though studies have shown satisfactorily results Angulo; De Figueiredo (2011). According to the norm, the contamination level of the material must be lower than 3% and RCA must have more than 90% of concrete and rocks in its composition.

TABLE 7 presents the unit prices for products and by-products of the CDW recycling process, as well as, the average price for natural aggregates.

TABLE 7 - CDW PRODUCTS' UNIT PRICES (NOT INCLUDING FREIGHT)

(continue)

Product	Input	Description	Uses	Price (€/t)			Source[(1)]
				Average	Min.	Max.	
Recycled sand	concrete and concrete building blocks;	Grain size: <4,8mm; Contamination level: <3%	Sealing masonry laying mortar, subfloor, soil-cement, sealing blocks and bricks.	5,4	3,3	8,9	data research
Recycled Concrete Aggregate (RCA)		Input: concrete and concrete building blocks; Grain size: All-in-one (<39mm) or size ranges: 4,8-9,5mm;9,5-19,5mm; 19,5-25mm; 25-39mm; Content of concrete and rocks: >90% Contamination level: <3%	Manufacture of non-structural concretes.	4,1	2,9	7,7	data research
Coarse Recycled Concrete Aggregate (Coarse RCA)		Input: concrete and concrete building blocks; Grain size: <150mm; Content of concrete and rocks: >90% Contamination level: <3%	Paving, drainage, earthwork	5,2	3,2	7,2	data research

TABLE 7 - CDW PRODUCTS' UNIT PRICES (NOT INCLUDING FREIGHT)

(conclusion)

Mixed Recycled Aggregate (MRA)	mix of recycled concrete and masonry;	Grain size: All-in-one (<63mm); Contamination level: <3%	Base and sub-base applications (including road construction), levelling of unpaved roads, landfills and land topographic adjustment.	3,1	0,6	6,7	data research
Natural Aggregate (graded)				7,2	-	-	CEF (2020)
Natural Aggregate (All-in-one)				7,2	-	-	CEF (2020)
Sand				8,8	-	-	CEF (2020)
Ferrous-metal			New ferrous-metal	136,3	131,9	140,8	data research
Recycled wood chips			Fuel in industrial applications	9,9	-	-	SEAB (2020)
Plastics(2)			New plastics	40,8	-	-	CONRESOL (2020)
Refused Derived Fuel (RDF)(3)			Fuel	free	-	-	data research
Uncontaminated gypsum(3)			New gypsum-based products	free	-	-	data research

NOTE:
(1) data search was carried out in the south region of Brazil;
(1) Based on prices for recycled PVC;
(2) Collected free of costs by the companies researched;

In regard to the scenario definition, it is assumed that only MRA would be produced for the totally mixed scenarios due to the highly mixed characteristics of the CDW. For segregation at source scenarios, however, the production of RCA is possible. In that way, it is assumed that 70% of the total input concrete would be used to produce concrete related products, consisting in 66% of RCA and 34% of recycled sand, according to the findings of Galán; Viguri, J. R.; et al. (2019). The remaining mineral materials are used to produce MRA (including the remaining 30% of the concrete, considering that some part of the concrete would still be mixed with masonry).

Moreover, the totally of wood was considered to be sold as wood chips, even though wood can be differentiated into high quality wood or into low quality wood (Section 2.4.6). Recycling plastic, paper and cardboard is problematic as they tend to be contaminated with cement and other materials. Therefore, it was assumed that 30% of these materials would be recycled and the rest commercialized as RDF. Recycling glass is also difficult, considering that it must be separated in colours in order to be recycled and that the amount of glass produced in CDW is not appreciable. Thus, it is usually crushed together with mineral materials into aggregates. Metals (including, ferrous-metals, steel, aluminium, copper, mixed metals) are easily recycled and a developed recycling industry is already available in Brazil. If not contaminated, gypsum is 100% recyclable. Few companies in Brazil are able to recycle gypsum-containing materials, and the sector is likely to grow in the next years.

3.1.4.2 CDW`s gate fee

Gate fees typically represent the major source of income of a CDW recycling facility and have pronounced effect on the investment return period. As simulated by Coelho; De Brito (2013b), gate fees could represent 86% of the total revenues of the plant and a 30% decrease in its value would imply in a 63% reduction in global economic balance Coelho; De Brito (2012).

Typically, gate fees are based on the type, quantity and composition of the material. The more complex and expensive is to treat that type of waste, higher will be the gate fees. For instance, the average gate fee reported by Coelho; De Brito (2013b) for mixed CDW in Portugal is 48,2 €/ton (ranging from 20 €/t to 75 €/t), while the value for source separated aggregates is 7,8 €/ton (ranging from 0 €/ton to 15 €/ton).

Fundamentally, the gate fee values at a CDW recycling plant are always comparable/related to other treatment/disposal options available. Since waste generators tend to opt for the most economical option, recycling can be very challenging in locations where landfill costs are low. For example, Li et al. (2019) report that low landfill charges in Shenzen (China) for CDW (approximately 0,79-1,32 €/ton) is one of the most impeditive factors for a development of a recycling economy. For that reason, landfill taxes (or even ban) on CDW (materials that could otherwise be recovered/recycled) is often used to ensure the profitability of recycling activities. In UK for instance, a standard landfill tax of 96.6 €/ton (£82,6/ton) represents almost 80% of the total average charging fee for non-hazardous waste (121,1€/ton) Deloitte (2015a). Moreover, a mixed CDW in Germany would be charged 148 €/ton, while mineral waste (mixture of concrete, bricks, tiles and ceramics) would be charged 15-60 €/ton, depending on its quality class Deloitte (2015b).

TABLE 8 - CDW GATE FEE/LANDFILL FEE ACCORDING TO TYPE OF RESIDUE (€/TON)

Residue	Germany (landfill)(1)	United Kingdom (landfill)(2)	Shenzen-China (landfill)(3)	Portugal (CDW recycling facilities)(4)	Brazil (landfill)(5)	Brazil (CDW recycling facilities)(6)
Mixed CDW	148,00	121,1	0,79-1,32	48,2		0,85-5,11
Mineral CDW	15-60	-		7,8	4,0	
Municipal waste					16,0	

Source:
(1) (Deloitte 2015a)
(2) (Deloitte 2015b)
(3) (J. Li et al. 2019)
(4) (Coelho and De Brito 2013)
(5) data search for the metropolitan region of Curitiba.
(6) Abrecon (2015), most common range values charged in Brazilian recycling facilities for CDW. Values adjusted by inflation in Brazil in the period of Dez/2014 to Oct/2019.

In Brazil, the average gate fees at CDW recycling facilities varies according to the region, ranging from 0,85-5,11 €/t. On average, 32% of the plants charge from 0,85-1,7 €/t, 32% from 1,7-2,55 €/t, 21% from 2,55-3,41 €/t and 15% more than 5,11 €/t Abrecon (2015).

4 RESULTS

4.1 Plant design and cost calculation

4.1.1 Process flow and mass balance

Based on the set of assumption established, a process flow and a mass balance were simulated for each of the scenarios. The main machineries were designed (or selected from equipment's suppliers) to cope with the amount of material to be processed. Important to note that even though the simulated facilities may considered to be of medium or large size, only one line of operation was assumed for all scenarios, in order to reduce investment costs

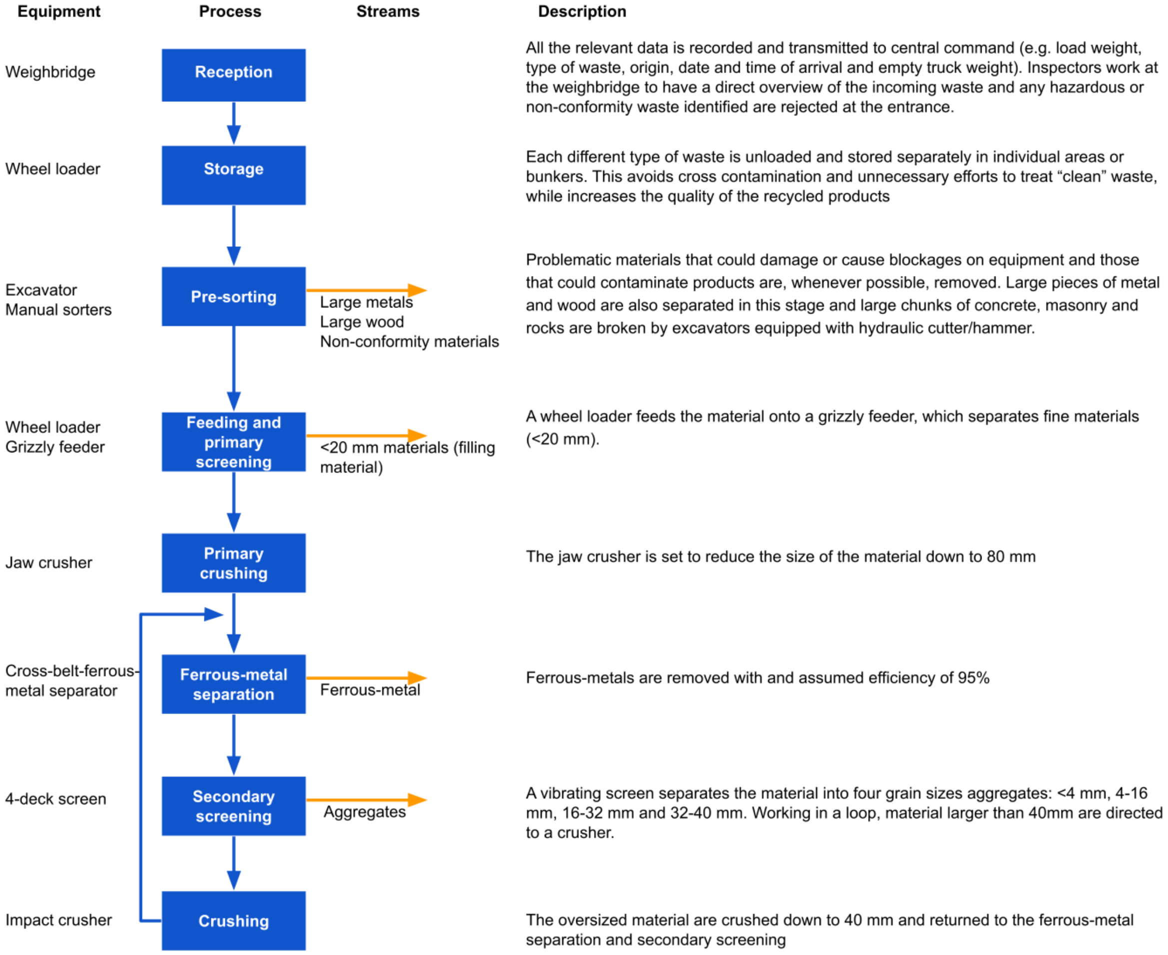
4.1.2 Segregation at Source (Scenarios 1 and 2)

Due to the low amount of contaminants of the input material, the process for Scenario 1 and Scenario 2 are relatively simple. As described in **Erro! Fonte de referência não encontrada.**, the processes consist basically in feeding, scalping of fine materials, ferrous-metal separation, crushing and screening. A detailed process flow and mass balance is provided in the ANNEX II.

Regarding the crushing process, the lowest global cost was achieved by a two-stages crushing system, in comparison with only one large impact crusher. This is due to the high amount of material to be processed and the small size of the products produced (<40 mm), favours additional crushing steps. In that way, the material is initially crushed by a primary jaw crusher and further crushed by a secondary impact crusher downstream of the process.

The secondary screening was designed to operate in a closed system. Materials larger than 40 mm are directed to and crushed by an impact crusher, returned to the process and screened yet again. By doing so, the maximum size of the aggregates can be ensured.

FIGURE 18 - DESCRIPTION OF PROCESS FLOW FOR SEGREGATION AT SOURCE SCENARIOS



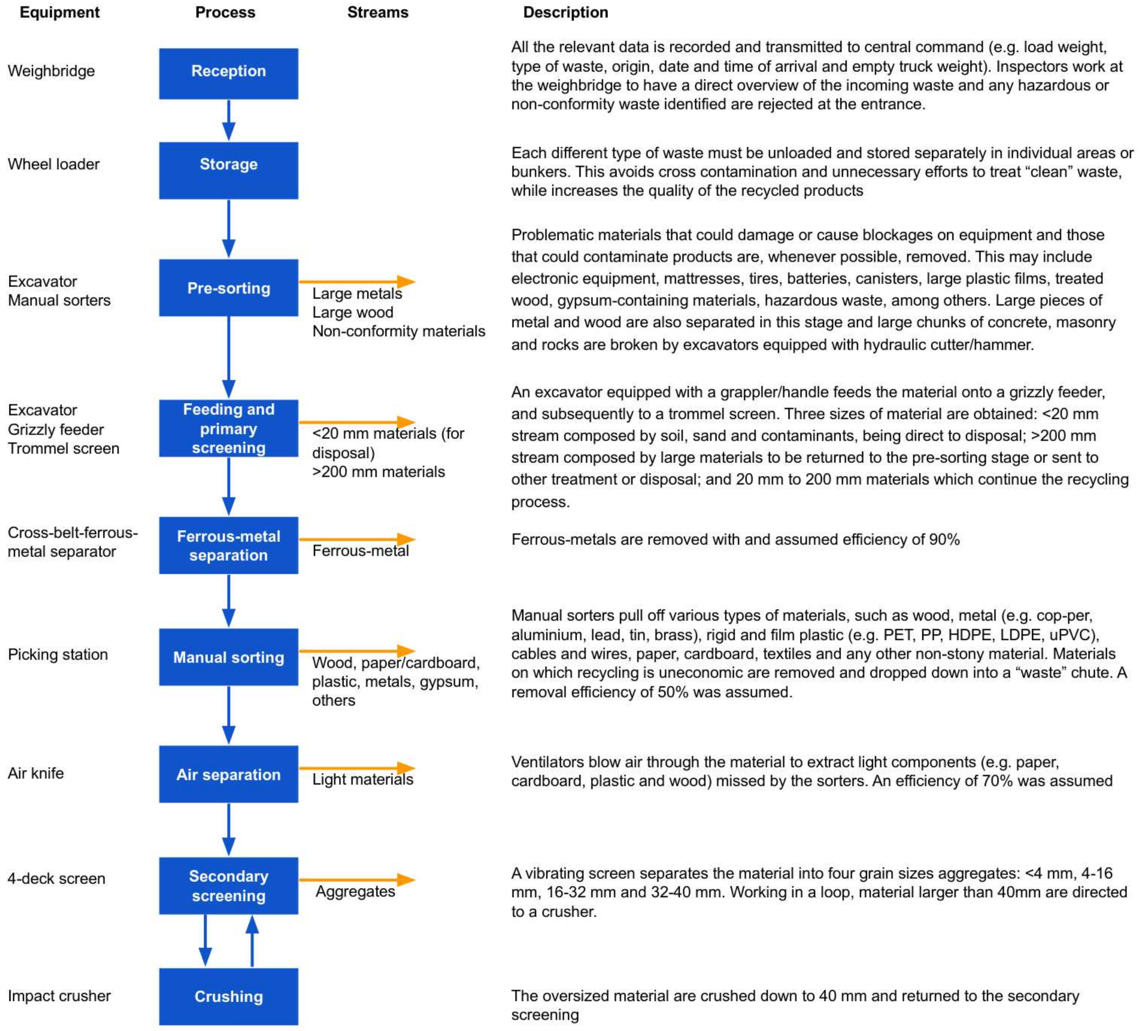
Equipment	Process	Streams	Description
Weighbridge	Reception		All the relevant data is recorded and transmitted to central command (e.g. load weight, type of waste, origin, date and time of arrival and empty truck weight). Inspectors work at the weighbridge to have a direct overview of the incoming waste and any hazardous or non-conformity waste identified are rejected at the entrance.
Wheel loader	Storage		Each different type of waste is unloaded and stored separately in individual areas or bunkers. This avoids cross contamination and unnecessary efforts to treat “clean” waste, while increases the quality of the recycled products
Excavator Manual sorters	Pre-sorting	Large metals Large wood Non-conformity materials	Problematic materials that could damage or cause blockages on equipment and those that could contaminate products are, whenever possible, removed. Large pieces of metal and wood are also separated in this stage and large chunks of concrete, masonry and rocks are broken by excavators equipped with hydraulic cutter/hammer.
Wheel loader Grizzly feeder	Feeding and primary screening	<20 mm materials (filling material)	A wheel loader feeds the material onto a grizzly feeder, which separates fine materials (<20 mm).
Jaw crusher	Primary crushing		The jaw crusher is set to reduce the size of the material down to 80 mm
Cross-belt-ferrous-metal separator	Ferrous-metal separation	Ferrous-metal	Ferrous-metals are removed with and assumed efficiency of 95%
4-deck screen	Secondary screening	Aggregates	A vibrating screen separates the material into four grain sizes aggregates: <4 mm, 4-16 mm, 16-32 mm and 32-40 mm. Working in a loop, material larger than 40mm are directed to a crusher.
Impact crusher	Crushing		The oversized material are crushed down to 40 mm and returned to the ferrous-metal separation and secondary screening

SOURCE: own elaboration

4.1.3 Totally mixed CDW (Scenario 3, 4, 5 and 6)

Due to the higher amount of contaminants of the input material, the treatment process for these scenarios is relatively more complex. As described by **Erro! Fonte de referência não encontrada.**, additional processes and equipment are required, such as air separation, manual separation, shredding, balling, among others. A detailed mass balance is provided in the ANNEX II.

FIGURE 19 - DESCRIPTION OF PROCESS FLOW FOR TOTALLY MIXED CDW SCENARIOS



All the relevant data is recorded and transmitted to central command (e.g. load weight, type of waste, origin, date and time of arrival and empty truck weight). Inspectors work at the weighbridge to have a direct overview of the incoming waste and any hazardous or non-conformity waste identified are rejected at the entrance.

Each different type of waste must be unloaded and stored separately in individual areas or bunkers. This avoids cross contamination and unnecessary efforts to treat "clean" waste, while increases the quality of the recycled products

Problematic materials that could damage or cause blockages on equipment and those that could contaminate products are, whenever possible, removed. This may include electronic equipment, mattresses, tires, batteries, canisters, large plastic films, treated wood, gypsum-containing materials, hazardous waste, among others. Large pieces of metal and wood are also separated in this stage and large chunks of concrete, masonry and rocks are broken by excavators equipped with hydraulic cutter/hammer.

An excavator equipped with a grappler/handle feeds the material onto a grizzly feeder, and subsequently to a trommel screen. Three sizes of material are obtained: <20 mm stream composed by soil, sand and contaminants, being direct to disposal; >200 mm stream composed by large materials to be returned to the pre-sorting stage or sent to other treatment or disposal; and 20 mm to 200 mm materials which continue the recycling process.

Ferrous-metals are removed with and assumed efficiency of 90%

Manual sorters pull off various types of materials, such as wood, metal (e.g. cop-per, aluminium, lead, tin, brass), rigid and film plastic (e.g. PET, PP, HDPE, LDPE, uPVC), cables and wires, paper, cardboard, textiles and any other non-stony material. Materials on which recycling is uneconomic are removed and dropped down into a "waste" chute. A removal efficiency of 50% was assumed.

Ventilators blow air through the material to extract light components (e.g. paper, cardboard, plastic and wood) missed by the sorters. An efficiency of 70% was assumed

A vibrating screen separates the material into four grain sizes aggregates: <4 mm, 4-16 mm, 16-32 mm and 32-40 mm. Working in a loop, material larger than 40mm are directed to a crusher.

The oversized material are crushed down to 40 mm and returned to the secondary screening

SOURCE: own elaboration

4.2 Investment costs (CAPEX)

Based on the process flow described in the previous section, the investments required to set up the recycling plant were estimated, including: investments on equipment, vehicles, civil works and other investments (land purchasing, engineering, installation, commissioning and contingencies).

Apart from the initial investment to set up the recycling plant, several additional expenditures are required through the years. These costs are related to the replacement of equipment, machinery, vehicles, etc. TABLE 9 presents the operation lifespan for different types of equipment assumed in the present work.

TABLE 9 - OPERATION LIFESPAN FOR EQUIPMENT AND CIVIL WORK

Equipment	Operation lifespan
Civil works	30
Mechanical (normal wear and tear)	20
Mechanical (high wear and tear, e.g. crushing)	10
Vehicles	8
Containers/Bins/computers	5

SOURCE: Oesterle (2020)

4.2.1 Investment on equipment

Investment on equipment comprises of all machinery and auxiliaries required to operate the plant, as show by TABLE 10. The prices of the main equipment (crushers, screens, feeders, shredders) were obtained directly from suppliers and the average values were considered whenever more than one suitable item was available. Auxiliaries and other equipment were estimated based on values frequently encountered in waste management projects Oesterle (2020).

TABLE 10 - INVESTMENT COSTS WITH EQUIPMENT IN €

Equipment	Unit price/factor	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)		Source
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	
Primary Jaw crusher	Jaw crusher (160 kW): 134.064 EUR/unit	134.064						Suppliers
	Jaw crusher (200 kW): 264.537		264.537					
Secondary Impact crusher	Impact crusher (200 kW): 62.352 EUR/unit	62.352		62.352		62.352		Suppliers
	Impact crusher (250 kW): 93.002		93.022		93.022		93.022	
Screen	screen-4 deck (30 kW): 36.747 EUR/unit		36.748					Suppliers
	screen-4 deck (18,5 kW): 23.772	23.772						
	screen-1 deck (30 kW): 28.586		28.586		28.586		28.586	
	screen-1 deck (22 kW): 21.438	21.438		21.438		21.438		
Grizzly feeder	Grizzly feeder (45 kW): 67.271 EUR/unit		67.271		67.271		67.271	Suppliers
	Grizzly feeder (30 kW): 38.663	38.663		38.663		38.663		
Drum Screen	250.000 EUR/unit	-	-	250.000	250.000	250.000	250.000	Oesterle (2020)
Shredding unit	50.000 EUR/unit	-	-	50.000	50.000	50.000	50.000	Suppliers
Air knife	100.000 EUR/unit	-	-	100.000	200.000	100.000	200.000	Allwood (2014b)
Water classification system	0 EUR/unit	-	-	-	-	-	-	
Picking station	50.000 EUR/unit	-	-	50.000	0	100.000	150.000	Oesterle (2020)
Magnetic separator	20.000 EUR/unit	20.000	20.000	20.000	20.000	20.000	20.000	Oesterle (2020)
Weighting bridge with accessories	25.000 EUR/unit	25.000	25.000	25.000	25.000	25.000	25.000	Oesterle (2020)
Belt conveyors and accessories	2.000 EUR/m	80.000	80.000	140.000	200.000	180.000	240.000	Oesterle (2020)
Balers (plastic/paper - metal)	50.000 EUR/unit	-	-	50.000	50.000	50.000	50.000	Oesterle (2020)
Ventilation unit - mechanical part	17 m² building	1.232	2.464	15.773	31.036	29.307	58.445	Oesterle (2020)
Fire protection	5.000 EUR/unit	5.000	5.000	5.000	5.000	5.000	5.000	Oesterle (2020)
Electric installation	5% of mechanical	20.326	30.881	41.161	50.746	46.338	61.616	Oesterle (2020)
I&C	0 of mechanical	20.326	30.881	38.661	50.746	41.338	54.116	Oesterle (2020)
Communication facilities	3.000 EUR/unit	3.000	3.000	3.000	3.000	3.000	3.000	Oesterle (2020)
Installation, commissioning	10% of total value	45.517	68.739	91.105	112.441	102.244	135.606	Oesterle (2020)
Total		500.691	756.131	1.002.154	1.236.848	1.124.680	1.491.662	

SOURCE: own elaboration

4.2.2 Investment on vehicles

It comprises of all vehicles required to operate the plant, as show by TABLE 11. Important to stress that, freight costs related to the transportation of CDW to the recycling plant and to the delivery of products to the client were assumed to be out of scope in the present work. Even though, these activities are commonly done by the recycling company, a freight is always applied to cover the costs. In that way, neither freight nor costs were considered. The only exception is the cost involved to transport residues generated by the recycling plant to the landfill site, as these residues are responsibility of the plant’s operator.

TABLE 11 - INVESTMENT ON VEHICLES (€) (NUMBER OF EQUIPMENT IN PARENTHESIS)

Mobile equipment	Main use	Unit price (€)	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
			Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Wheel Loader (150 kW)	Feeding of input material into the process	150.000	-	150.000 (1)	-	150.000 (1)	-	150.000 (1)
Wheel Loader (90 kW)	Feeding of input material into the process	80.000	240.000 (3)	80.000 (1)	240.000 (3)	80.000 (1)	240.000 (3)	80.000 (1)
Excavator (150 kW)	Management of storage, loading of trucks	150.000	-	150.000 (1)	-	150.000 (1)	-	150.000 (1)
Excavator (90 kW)	Management of storage, loading of trucks	90.000	90.000 (1)	90.000 (1)	90.000 (1)	90.000 (1)	90.000 (1)	90.000 (1)
Tipper Truck	Transportation of residues to the landfill site	65.000	65.000 (1)	65.000 (1)	130.000 (2)	260.000 (4)	130.000 (2)	260.000 (4)
Containers (40 m³)	Management of recycled material	8.000	16.000 (2)	16.000 (2)	16.000 (2)	32.000 (4)	16.000 (2)	32.000 (4)
Fork-lift	Management of recycled material	20.000	-	-	40.000 (2)	60.000 (3)	40.000 (2)	60.000 (3)
Total			411.000	551.000	516.000	822.000	516.000	822.000

SOURCE: own elaboration

4.2.3 Investment on civil works

Investment on civil works comprise of all costs to build up the infrastructure of the facility as show by TABLE 12.

TABLE 12 - INVESTMENT COST WITH EARTH, ROAD AND CIVIL WORKS (€)

(continue)

Mobile equipment	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Earth- and roadworks	**187.319**	**333.271**	**201.576**	**362.524**	**212.782**	**384.719**
Clearing and removal of top soil	32.612	62.249	33.861	64.791	34.918	66.876
Fence and gate	17.337	23.952	17.665	24.436	17.939	24.826
Parking, open storage areas, internal roads	28.000	34.300	37.100	53.200	43.867	66.733
Grading and compaction	86.386	170.626	89.147	176.328	91.566	181.181
Grassing, seeding, tree plantation	3.417	4.794	3.486	4.895	3.543	4.976

TABLE 12 - INVESTMENT COST WITH EARTH, ROAD AND CIVIL WORKS (€)

(conclusion)

Drainage of surface water	19.567	37.350	20.317	38.874	20.951	40.126
Civil works	**283.949**	**397.899**	**422.250**	**690.000**	**549.456**	**938.911**
Administrative building	190.000	270.000	200.000	310.000	210.000	320.000
Gate house	10.000	10.000	10.000	10.000	10.000	10.000
Weigh lodge and weighting bridge	50.000	50.000	50.000	50.000	50.000	50.000
Septic tank	23.077	46.154	23.077	46.154	23.077	46.154
Sorting part housed	10.872	21.745	139.173	273.846	256.379	512.758
Other works	**342.308**	**584.615**	**342.308**	**584.615**	**342.308**	**584.615**
Drinking water supply	50.000	50.000	50.000	50.000	50.000	50.000
Power supply and distribution	50.000	50.000	50.000	50.000	50.000	50.000
Lighting protection	126.923	253.846	126.923	253.846	126.923	253.846
Electrical protection and command	115.385	230.769	115.385	230.769	115.385	230.769
Total	**813.577**	**1.315.785**	**966.133**	**1.637.139**	**1.104.546**	**1.908.246**

SOURCE: own elaboration

4.2.4 Other investment

In addition to the above costs, other investments costs are also applied such as: land purchasing, installation, engineering/supervision and contingencies, as shown by TABLE 13.

TABLE 13 - OTHER INVESTMENT COST (€)

Mobile equipment	Unit price/factor	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Land purchasing	19,8 €/m²	645.082	1.231.305	669.783	1.281.575	691.130	1.322.443
Engineering/supervision							
Fixed investment	15%	197.140	310.787	295.243	431.098	334.764	508.848
Vehicles	15%	61.650	82.650	77.400	123.300	77.400	123.300
Contingencies							
Fixed investment	10%	131.427	207.192	196.829	287.399	223.176	339.232
Vehicles	10%	41.100	55.100	51.600	82.200	51.600	82.200
Total		1.076.399	1.887.034	1.290.854	2.205.572	1.378.071	2.376.024

SOURCE: own elaboration

4.2.5 Total investment costs and capital (annuity)

TABLE 14 presents the summary of the investment costs and the capital annuity resulting from it. The later was calculated based on the payment period for each type of investment (according to their lifespan presented on TABLE 9) and assuming that the whole project would be financeable with an interest rate of 8%.

TABLE 14 - SUMMARY OF THE INITIAL INVESTMENT COSTS AND CAPITAL ANNUITY (K€)

(continue)

Mobile equipment	Unit price/factor	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Investment costs (k€)							
Land purchasing		645	1.231	670	1.282	691	1.322
Civil works		814	1.316	966	1.637	1.107	1.901

TABLE 14 - SUMMARY OF THE INITIAL INVESTMENT COSTS AND CAPITAL ANNUITY (K€)
(conclusion)

Equipment		501	756	1.002	1.237	1.125	1.492
Vehicles		411	551	516	822	516	822
Others		431	656	621	924	687	1.054
Total		2.802	4.510	3.775	5.902	4.126	6.590
Annuity (k€/y)							
Land purchasing	8,00%	52	99	54	103	55	106
Civil works	8,88%	72	117	86	145	98	169
Equipment	14,90%	75	113	149	184	168	222
Vehicles	17,40%	72	96	90	143	90	143
Others	17,40%	75	114	108	161	120	183
Total		345	538	487	736	531	823

SOURCE: own elaboration

4.3 Operational expenditures (OPEX)

Operational expenditures consist of all cost related to the operation of the facility, including energy costs, maintenance and repair, labour, residues disposal, consumables and other operational costs.

4.3.1 Maintenance and repair costs

Maintenance and repair costs comprises all the expenses required to ensure the proper functioning of the equipment, including repairs, cleaning, replacement of parts, lubrification, etc, as well as maintenance of civil works. The maintenance costs were assumed as a certain percentage of the investment costs, according to TABLE 15.

TABLE 15 - MAINTENANCE AND REPAIR COSTS

Mobile equipment	Factor (% of the investment)	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Civil works	0,5%	4,1	6,6	4,8	8,2	5,5	9,5
Mechanical	5,0%	8,1	8,2	24,5	32,3	30,7	45,0
Mechanical (High wear)	8,0%	27,1	47,4	40,9	47,3	40,9	47,3
Vehicles	8,0%	32,9	44,1	41,3	65,8	41,3	65,8
Total		72,2	106,3	111,6	153,5	118,4	167,6

SOURCE: Oesterle (2020)

4.3.2 Labour costs

Manpower is required to operate a recycling facility. TABLE 16 presents the job positions and their related monthly costs for the entrepreneur, calculated based on regional labour salaries and its associated taxes and obligations in Brazil.

TABLE 16 - LABOUR COSTS (QUANTITY OF STAFF IN PARENTHESIS)

Staff(1)	Unit price (k€/year)(2)	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Facility Manager	51.4	51,4 (1)	51,4 (1)	51,4	51,4	51,4 (1)	51,4 (1)
Deputy Facility Manager	34.8	34,8 (1)	34,8 (1)	34,8	34,8	34,8 (1)	34,8 (1)
Foreman	18.1	36,4 (2)	54,6 (3)	36,4	54,6	36,4 (2)	54,6 (3)
Skilled worker	14.2	14,2 (1)	14,2 (1)	14,2	28,5	28,5 (2)	28,5 (2)
Administration clerk	14.2	42,7 (3)	71,2 (5)	42,7	71,2	42,7 (3)	71,2 (5)
Trained worker	14.2	14,2 (1)	14,2 (1)	14,2	14,2	14,2 (1)	28,5 (2)
Driver	14.2	28,5 (2)	28,5 (2)	42,7	71,2	42,7 (3)	71,2 (5)
Secretary/Porter	10.9	55,0 (5)	88,0 (8)	55,0	88,0	55,0 (5)	88,0 (8)
Unskilled staff	8.1	24,5 (3)	40,9 (5)	24,5	40,9	24,5 (3)	40,9 (5)
Sorters, unskilled staff	8.1	24,5 (3)	49,1 (6)	318,9	613,2	531,4 (65)	1.062,9 (130)
Total		326,4 (22)	446,9 (33)	634,9	1.068,0	861,7 (86)	1.531,9 (162)

SOURCE: own elaboration

NOTE: (1) Staff factor (additional workers) of 24% was applied, based on 228 working days/year, 8 hours/day and 5% of sick leave.

The number of sorters was calculated according to TABLE 17, which presents the removal capacity for each type of material. The removal capacity is higher at the pre-sorting considering that larger materials are separated in this stage.

TABLE 17 - MANUAL SORTER'S REMOVAL CAPACITY

Material	Removal capacity (kg/h)	
	at pre-sorting stage	at picking station
Wood	500	200
Metal	500	200
Gypsum	200	-
Plastic	-	50
Paper/cardboard	-	50
Others	500	100

SOURCE: Fischer (2020) and Oesterle (2020)

4.3.3 Residues disposal costs

Residues generated at the recycling facility that contain hazardous materials, are untreatable or have no commercial value are disposed off in appropriate landfills. Dumping fees vary according to the characteristics of the residues, as shown by TABLE 8. Residues that are not fit for use due to their high impurities content but do not pose significant environmental have lower dumping fee compared to non-inert and hazardous waste. This is the case of contaminated fine materials (<20 mm) generated by the totally mixed CDW scenarios. This material is composed mainly by soil and sand, but high contaminant fractions are also commonly present, which hinder its use as filling material. As verified in multiples recycling plants, this material is frequently sent to a landfill for inert waste.

On the other hand, fine materials for segregation at source scenarios present low contamination levels and can be used as filling material. However, the commercial use of this material is challenging, being frequently just given away for free. In that way, nor cost nor revenues were assumed in the present work. Important to note that disposal fees are applicable in the case of no takers.

According to TABLE 18**Erro! Fonte de referência não encontrada.**, Dumping costs are much more pronounced for the treatment of totally mixed CDW, as higher input contamination levels leads to higher quantities of improper materials.

TABLE 18 - DISPOSAL COSTS (K€/Y)

Residues	Unit cost(1)	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Residues to sanitary landfill (MSW)	16,02 €/t	5,5	11,0	55,8	111,6	108,1	216,1
Residues to Inert landfill	4,0 €/t	-	-	154,7	309,3	158,3	316,6
Total		5,5	11,0	210,5	421,0	266,4	532,8

SOURCE: own elaboration
NOTE: (1) data search for the metropolitan region of Curitiba.

4.3.4 Consumables

TABLE 19 presents the Scenarios` consumables, including electricity, diesel and miscellaneous (other consumption such as process water, reagents, etc). Typically, all mobile equipment and vehicles use diesel to operate, while the remaining fixed machinery use electricity. The average unit price in Brazil for diesel in Curitiba is 0,76 €/l (R$ 3,446/l) ANP (2019) and for electricity 177 €/MWh (R$ 535,28/MWh) FIRJAN (2016). The energy costs were obtained considering the machines` rated power and their operating period. Partial load factors were not considered.

TABLE 19 – CONSUMABLES

(continue)

Equipment	Power/factor	Unit	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
			Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Electricity consumption								
Primary Jaw crusher	160 kW	kWh/y	1.280	-	-	-	-	-
	200 kW			1.600	-	-	-	-
Secondary Impact crusher	200 kW	kWh/y	1.600		1.600	-	1.600	-
	250 kW	kWh/y	-	2.000	-	2.000	-	2.000
Screen	30 kW	kWh/y	-	240	-	240	-	240
	18,5 kW	kWh/y	176	-	176	-	176	-
	30 kW	kWh/y	-	240	-	240	-	240
	22 kW	kWh/y	148	-	148	-	148	-

TABLE 19 – CONSUMABLES

(conclusion)

Grizzly feeder	45 kW	kWh/y		360	-	360	-	360
	30 kW	kWh/y	240	-	240	-	240	-
Drum Screen	1 kWh/t/input	kWh/y	-	-	1.154	2.308	1.154	2.308
Shredding unit	50 kW	kWh/y	-	-		400		400
	40 kW	kWh/y	-	-	320		320	
Air knife	6,3 kWh/unit	kWh/y	-	-	50	101	50	101
Water classification system		kWh/y	-	-	-	-	-	-
Picking station	0,5 kWh/t/input	kWh/y	-	-	173	346	173	346
Magnetic separator	0,2 kWh/t/input	kWh/y	231	462	231	462	231	462
Weighting bridge with accessories	0,02 kWh/t/input	kWh/y	23	46	23	46	23	46
Belt conveyors and accessories	0,02 kWh/m/t	kWh/y	923	1.846	1.615	4.615	2.077	5.538
Balers	1 kWh/t recycled	kWh/y	0	0	54	108	106	213
Ventilation unit - mechanical part	20 kWh/100m²	kWh/y	14	29	186	365	345	688
Total Electricity		kWh/y	4.635	6.823	5.970	11.590	6.643	12.941
Total Electricity	177 €/MWh	k€/y	141	208	182	353	202	394
Diesel consumption								
Wheel Loader	150 kW	l/y	-	21.840	-	21.840	-	21.840
	90 kW	l/y	39.312	13.104	39.312	13.104	39.312	13.104
Excavator	150 kW	l/y	-	41.808	-	41.808	-	41.808
	90 kW	l/y	25.085	25.085	25.085	25.085	25.085	25.085
Truck[1]	2.5 l/km	l/y	207	414	25.262	50.525	27.765	55.530
Fork-lift	26 kW	l/y			21.632	32.448	21.632	32.448
Total Diesel		l/y	64.604	102.250	111.291	184.810	113.794	189.814
Total Diesel	0,76 €/l	k€/y	49	77	84	140	86	144
Miscellaneous consumption[2]								
Total Miscellaneous	3.00 €/l	k€/y	90	180	90	180	90	180
Total consumables		k€/y	280	465	287	479	394	776

Source: own elaboration

NOTE:

(1) base on an average travelled distance of 30 km per trip;

(2) referred to other consumptions (process water, reagents, etc)

4.3.5 Gross treatment costs

TABLE 20 presents the summary of the annual expenses and the gross treatment cost. In addition to the capital and operational expenditures, an additional 10% related to administration costs and 2% to taxes/insurance are applied.

TABLE 20 - GROSS TREATMENT COST

Residues	Unit	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Capital expenditures (annuity)	(k€/y)	345	538	487	736	531	823
Maintenance and repair	(k€/y)	72	106	112	154	118	168
Staff	(k€/y)	326	447	635	1.068	870	1.526
Consumables	(k€/y)	280	465	356	672	378	717
Residues Disposal	(k€/y)	6	11	210	421	266	533
Administration, taxes and insurance	(k€/y)	90	136	170	297	210	376
Total treatment	(k€/y)	1.119	1.704	1.969	3.348	2.373	4.142
Treatment cost per ton	(€/t)	3,7	2,8	6,56	5,58	7,91	6,90

SOURCE: own elaboration

4.4 Revenues from products commercialization

Revenues may be divided into 2 main sources: products commercialization and CDW's gate fees. TABLE 21 presents the annual revenues obtained for each product sold. Comparing the treatment costs presented in the previous section, it is noticeable that commercialization of the products alone is not enough to the scenarios' profitability.

TABLE 21 - REVENUES OBTAINED FROM PRODUCTS COMMERCIALIZATION (K€/Y)

Residues	Unit price	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Recycled sand	5,6 €/t	77	154	77	154	0	0
RCA	4,5 €/t	119	238	119	238	0	0
All-in-one MRA	3,1 €/t	670	1.339	670	1.339	660	1.320
RDF	free	0	0	0	0	0	0
Wood chips	9,9 €/t	10	20	10	20	146	292
Metals	136,6 €/t	11	21	11	21	109	218
Plastics	40,8 €/t	0	0	0	0	2	4
Paper/Cardboard	54,9 €/t	5	9	5	9	6	11
Gypsum	free	0	0	0	0	0	0
Total		890	1.781	890	1.781	923	1.846

SOURCE: own elaboration

4.5 Cash Flow and CDW`s gate fee

With the gross treatment costs and the revenues obtained from products commercialization estimated, it is possible to calculate the average CDW's gate fee value and its annual revenue required to provide a minimum profitability for the recycling facility. For that a discounted cash flow analysis was carried, method on which the economic attractiveness of an investment is evaluated based on the difference between cash inflows and outflows during a specific period of years.

The cash inflows are comprised of the sum of revenues from products commercialization and revenues obtained from the CDW`s gate fees. In turn, the cash outflows are comprised of initial investment, replacement costs, the annual capital and operational expenses and taxes. The later was fixed in 25%, according to Nocito; Cunha (2013). The graphics in the ANNEX III present for each scenario the cash outflows and cash inflows, in which the later was calculated in order to accomplish an Internal Rate of Return (IRR) of 15% for a 25 years period. The graphics also show the scenarios` IRR values in case that different operation periods were to be considered (e.g. 15, 20, 25 or 30 years of operation).

From the total revenues obtained through cash flow analysis, the average CDW’s gate fees were calculated, as show by TABLE 22. The table also presents the gate fees according to the type of CDW received (if it is concrete CDW or mixed mineral CDW). This is commonly done by recycling plants, since higher value products are obtained from concrete waste. For instance, concrete related products (RCA and recycled sand) are sold for a price 57,5% higher on average compared to MRA (TABLE 7).

TABLE 22 - REVENUES AND GATE FEES REQUIRED TO THE FINANCIAL FEASIBILITY OF CDW RECYCLING

Parameter	Unit	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Annual revenues							
Gate fee	k€/y	913	1.014	2.022	3.038	2.442	3.857
Products	k€/y	890	1.781	874	1.748	934	1.868
CDW`s gate fee							
Totally Mixed CDW	€/t	-	-	6,7	5,1	8,1	6,4
Concrete CDW	€/t	1,4	0,8	-	-	-	-
Mixed Inert CDW	€/t	3,3	1,9	-	-	-	-
Average Gate fee	€/t	3,0	1,7	6,7	5,1	8,1	6,4

SOURCE: own elaboration

5 DISCUSSION

The CDW gate fee values were estimated based on the assumption of a minimum profitability (IIR of 15%) for the construction and operation of a CDW recycling facility, under the parameters assumed in the present work. As aforementioned, the recycling of CDW competes with landfilling (as far it is legal), since waste generators tend to opt for the most economical option. In that way, as far the gate fee values are lower at the recycling facility than at the landfill, recycling is competitive. This is the case of the scenarios with segregation at source, in which the charged values (1,7-3,0 €/t) are considerably lower than in the landfill for CDW (4,0 €/t). This comparison also reveals a potential for further profits, as theoretically the same price for the incoming material could be charged at the recycling facility.

Moreover, the gate fee values are also competitive with those already applied by existing recycling plants in Brazil (0,84-5,07 €/t). However, caution is always required in this comparison, as different conditions are applied for each plant. Additionally, many of the recycling plants in Brazil only accept certain types of residues (e.g. concrete waste). The simulations carried out in the present work, however, considered the acceptance of all types of Class A materials (ceramics, mortar, soil, etc). This assumption may have a profound impact, considering that higher value products are produced from concrete waste.

For totally mixed CDW scenarios the same comparison with landfilling is not possible. According to the ABNT (2004a), only Class A materials or inert waste can be disposed of in landfill for CDW. Other classes of materials (Class B, C and D) must be previously sorted (at the generating source, in transfer areas or in the landfill itself) and sent to an appropriate treatment or final disposal. In reality, however, the final disposal of totally mixed CDW is frequently observed, much due to the lack of control and environmental knowledge. This is one of the many difficulties encountered to consolidate recycling in Brazil. Nevertheless, the values estimated (5,1-8,1 €/t) are an indicative of the costs to treat totally mixed CDW (with the waste compositions simulated in the present work).

It is noteworthy that cash flow analysis is based on projections of most likely values. Needless to say, uncertainty will always be present in any project and the cash flow will be undoubtedly different as originally formulated. In that way, sensitivity analysis is well suitable to verify how sensitive the variation of a component is to the profitability of a given project. In this respect, many analyses can be performed, as follows:

5.1 Sensitivity analysis of CDW's contamination level

TABLE 23 shows the result's comparison when the input waste contamination level is considered. As already expected, the gross treatment cost per ton is higher when totally mixed CDW is treated compared to segregated mineral materials. Considering a capacity of 300 kt/y, the CDW's gate fee have increased 121% (from 3,0 €/t to 6,7 €/t) and 168% (from 3,0 €/t to 6,7 €/t), for the average case and worst case, respectively. For a capacity of 600 kt/y the increase is even more pronounced, the CDW's gate fee have increased 200% (from 1,7 €/t to 5,1 €/t) and 280% (from 1,7 €/t to 6,4 €/t), for the average case and worst case, respectively. These results highlight the importance of the practice of segregation at source. Even a relatively small change in contamination level (e.g. from 2% to 9,7%) have a profound impact on the feasibility of a recycling plant. Many factors contribute to this increase.

Staff cost is the factor which contributes the most with around 36-43% of the total increase in expenses. This disparity is mainly due to the great number of manual sorters demanded to treat highly contaminated materials. The number of sorters may increase from a few sorters, to a couple of dozens or even more than a hundred, as it can be seen on TABLE 16. This increase is even more accentuated if other additional costs related staff would be accounted, such as administration buildings, workshop, canteen, parking, etc.

Important to highlight that relatively low wages for unskilled workers are applied in Brazil. The increase in staff costs would be even more pronounced in other countries, especially in developed countries, where higher wages are paid. In these cases, the use of more automated recycling process may be economically favourable.

TABLE 23 - SCENARIOS' OUTCOME COMPARISON CONSIDERING CONTAMINATION LEVEL OF INPUT MATERIAL

		Totally mixed CDW (average case)				Totally mixed CDW (worst case)			
Parameter	Scenario 1	Scenario 3	Δ (3-1)	Δ (3-1)	Participation in total variation	Scenario 5	Δ (5-1)	Δ (5-1)	Participation in total variation
	(k€/y)	(k€/y)	(k€/y)	%	%	(k€/y)	(k€/y)	%	%
Capacity (300 kt/y)									
Capital expenditures (annuity)	345	487	142	41%	16,7%	531	186	54%	14,8%
Maintenance and repair	72	112	39	55%	4,6%	118	46	64%	3,7%
Staff	326	635	309	95%	36,3%	870	544	167%	43,3%
Consumables	280	356	76	27%	8,9%	378	98	35%	7,8%
Residues Disposal	6	210	205	3713%	24,1%	266	261	4725%	20,8%
Administration, taxes and insurance	90	170	80	88%	9,4%	210	119	132%	9,5%
Total treatment	1.119	1.969	850	76%	100,0%	2.373	1.254	112%	100,0%
Treatment cost per ton	3,7	6,6	3	76%	-	8	4	112%	
CDW's gate fee	3,0	6,7	3,7	121%	-	8,14	5	168%	
Parameter	Scenario 2	Scenario 4	Δ (4-1)	Δ (4-1)	Participation in total variation	Scenario 6	Δ (6-2)	Δ (6-2)	Participation in total variation
	(k€/y)	(k€/y)	(k€/y)	%	%	(k€/y)	(k€/y)	%	%
Capacity (600 kt/y)									
Capital expenditures (annuity)	538	736	198	37%	12,0%	823,3	285	53%	11,7%
Maintenance and repair	106	154	47	44%	2,9%	167,6	61	58%	2,5%
Staff	447	1.068	621	139%	37,8%	1525,9	1.079	241%	44,2%
Consumables	465	672	208	45%	12,6%	717,4	252	54%	10,3%
Residues Disposal	11	421	410	3713%	24,9%	532,8	522	4725%	21,4%
Administration, taxes and insurance	136	297	161	118%	9,8%	375,6	239	176%	9,8%
Total treatment	1.704	3.348	1.645	97%	100,0%	4142,4	2.439	143%	100,0%
Treatment cost per ton	3	6	3	97%	-	6,9	4	143%	
CDW's gate fee	1,7	5,1	3	200%	-	6,4	5	280%	

SOURCE: own elaboration

Residues disposal is the second largest contributor with around 21-25% of the total increase of the treatment cost. For totally mixed CDW scenarios, considerable amounts of contaminated fine material (<20 mm) are generated. This material is separated in the early stages of the treatment and is composed mainly by soil and sand. However, high contaminant fractions are also commonly present, which hinder its use as filling material. As verified in multiples recycling plants, this material is frequently sent to a landfill for inert waste. Another possible solution is to further treat it to avoid high fees related to landfilling and to recover valuable recyclable materials. This can be done by air separation, magnetic separation and even manual picking. This option, however, was not simulated in the present work. Additionally, part of the material separated in the recycling processes is not fit for recycling/recovering and has to be sent to a sanitary landfill (e.g. contaminated gypsum, other materials, etc).

Capital expenditures contribute with around 12-17% of the total increase of the treatment cost. From that, expenditures related to equipment contribute the most with around 36-53%, as shown by TABLE 24. This increase is related to the additional machinery required by the plant, such as: air knife, ballers, trommel screen, shredder, picking stations and additional belt conveyors. Moreover, additional vehicles are required, considering the higher amount of residues produced.

TABLE 24 - CAPITAL EXPENDITURES COMPARISON CONSIDERING CONTAMINATION LEVEL OF INPUT MATERIAL

		Totally mixed CDW (average case)				Totally mixed CDW (worst case)			
Parameter	Scenario 1	Scenario 3	Δ (3-1)	Δ (3-1)	Participation in total variation	Scenario 5	Δ (5-1)	Δ (5-1)	Participation in total variation
	(k€/y)	(k€/y)	(k€/y)	%	%	(k€/y)	(k€/y)	%	%
Capacity (300 kt/y)									
Ground	52	54	2	4%	1,4%	55,3	4	7%	2,0%
Civil works	72	86	14	19%	9,6%	98,3	26	36%	14,1%
Equipment	75	149	75	100%	52,8%	167,6	93	125%	50,1%
Vehicles	72	90	18	26%	12,9%	89,8	18	26%	9,8%
Engineering, commissioning, contingencies	75	108	33	44%	23,3%	119,5	44	59%	24,0%
Total	345	487	142	41%	100,0%	530,6	186	54%	100,0%
Parameter	Scenario 2	Scenario 4	Δ (4-1)	Δ (4-1)	Participation in total variation	Scenario 6	Δ (6-2)	Δ (6-2)	Participation in total variation
	(k€/y)	(k€/y)	(k€/y)	%	%	(k€/y)	(k€/y)	%	%
Capacity (600 kt/y)									
Ground	99	103	4	4%	2,0%	105,8	7	7%	2,6%
Civil works	117	145	29	24%	14,4%	168,8	52	44%	18,2%
Equipment	113	184	72	64%	36,2%	222,3	110	97%	38,4%
Vehicles	96	143	47	49%	23,8%	143,0	47	49%	16,5%
Engineering, commissioning, contingencies	114	161	47	41%	23,6%	183,3	69	61%	24,3%
Total	538	736	198	37%	100,0%	823,3	285	53%	100,0%

SOURCE: own elaboration

Expenses with consumables such as diesel and electricity have also increased. The increase in diesel consumption is incurred essentially to transport higher quantities of residues from the recycling facility to the landfill site, while the increase in electricity is related to the additional operating machinery.

5.2 Sensitivity analysis of facility’s capacities

The results support the principle of gain of scale and energy efficiency of the system. As shown by TABLE 25, all the simulations’ outcomes such as CDW's gate fee, CAPEX, electricity and diesel consumption and treatment costs are reduced in a per ton basis. For scenarios with segregation at source, the average CDW’s gate fees are reduced in more than 44% when the waste is treated in a 600 kt/y plant (1,7 €/t), compared to a 300 kt/y plant (3,0 €/t). On the contrary, if the average CDW’s gate fee is kept constant (in 3,0 €/t), the IRR in this case would increase from 15% to 30,6%. These results reveal the potential for gains when higher capacities are applied, as well as, the high importance of the CDW's gate fee on the feasibility of a recycling plant.

For the same increase in capacity, the gain of scale is less pronounced for totally mixed CDW scenarios, in which the CDW's gate fee was reduced in 25% (from 6,7 to 5,1 €/t) and 21% (from 8,1 to 6,4 €/t), for the average case and worst case, respectively. One of the reasons for that is the relatively high share of staff cost on the total OPEX. While the use of staff may be considerable reduced when larger equipment are used (e.g. the same driver may operate a 90 kW or a 150 kW wheel loader), the same does not necessary happen for picking stations, which rely mainly on the removal capacity of each sorter.

TABLE 25 - SCENARIOS' OUTCOME COMPARISON

Parameter	Unit	Segregation at Source			Totally mixed CDW (average case)			Totally mixed CDW (worst case)		
		Scenario 1	Scenario 2	Δ	Scenario 3	Scenario 4	Δ	Scenario 5	Scenario 6	Δ
CDW's gate fee	€/t	3,0	1,7	-44%	6,7	5,1	-25%	8,1	6,4	-21%
Investment	k€/(y.t)	9,3	7,5	-20%	12,6	9,8	-22%	13,8	11,0	-20%
Electricity	€/t	4,0	3,0	-26%	5,2	5,0	-3%	5,8	5,6	-3%
Diesel	€/t	0,2	0,2	-21%	0,4	0,3	-17%	0,4	0,3	-17%
Gross cost	€/t	3,7	2,8	-24%	6,6	5,6	-15%	7,9	6,9	-13%

SOURCE: own elaboration

The results indicate that a concentrated treatment of CDW may be an appropriate strategy in the metropolitan region of Curitiba, a highly densely populated area like many others in Brazil. It is important to take into account that higher capacities may lead to excessively freight costs. This may occur if longer distances are required to be travelled to sustain the input rate of the plant.

5.3 Sensitivity analysis of transportation costs

In order to verify influence of transportation on the feasibility of a recycling plant, all the costs related to the transportation of CDW to the plant and to the delivery of products to the costumer were included in the simulations, such as: diesel consumption, additional trucks and drivers, maintenance and repair, replacement costs, profit, etc. TABLE 26 presents the estimated freight costs according to the average distance travelled. As it can be seen, the number of trucks is appreciable and the final price for the costumer may increase considerably when freight is included. In some cases, the later is comparable or can even surpass the CDW's gate fee values.

TABLE 26 - FREIGHT COSTS ACCORDING TO TOTAL DISTANCE TRAVELLED

Parameter	Unit	Segregation at Source		Totally mixed CDW (average case)		Totally mixed CDW (worst case)	
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Total trucks (15 km)(1)	units	15	27	14	26	14	26
Total trucks (30 km)(1)	units	21	39	20	38	20	38
Total trucks (50 km)(1)	units	27	53	26	52	26	52
CDW`s gate fee	€/t	3,0	1,7	6,7	5,1	8,1	6,4
+freight (15 km)	€/t	1,9	1,8	1,67	1,54	1,63	1,54
+freight (30 km)	€/t	2,9	2,8	2,7	2,5	2,6	2,5
+freight (50 km)	€/t	4,0	4,0	3,7	3,7	3,7	3,7

SOURCE: own elaboration

NOTE: (1) the total number of trucks was estimated based on an average transportation speed of 40 km/h, load capacity of 20 t per truck and a loading/discharging period of 30 min;

It is apparent, therefore, that the location plant's location and the logistic associated to it is one of the most important parameters for the feasibility of a recycling plant. It also shows that recycling is more attractive in densely populated areas, where the supply and demand can be guaranteed with shorter transportation distances.

In order to verify if this is the case of the metropolitan region of Curitiba, the plant's radius of operation was estimated by using a generation rate of 500 kg/year per capita Contreras et al. (2016) and a population density of Curitiba of 4.443,6 inhabitants per km² IBGE (2020). In that way, for a capacity of 300 kt/y, the required radius to sustain the input rate of the plant is approximately 6,9 km. For a larger capacity of 600 kt/y, 9,7 km would be required.

Important to note that these distances ignore the difference between linear and road distance and considers that the totally of CDW generated is transported to the recycling plant. With no doubt, it is necessary, when setting up a recycling plant, a more precise evaluation of the quantities generated by each district in the region. However, this information was not available as fair the author acknowledge. Nevertheless, the radius estimated suggest that the metropolitan region of Curitiba can sustain a large capacity CDW recycling plant without compromising the costs associated with transportation.

5.4 Sensitivity analysis of product's commercialization prices

By comparing the sales prices of RA with the prices of natural aggregates (TABLE 27), it is possible to observe the great competitiveness of recycled products. Significant savings could be achieved in construction activities considering the “discount” price applied for RA. In the case of MRA, RCA and recycled sand, the sales prices are lower than the related natural material on average 56,5%, 37,3% and 22,1%, respectively. The great variability in RA’s prices also exacerbates even more these figures. For example, while the average price for MRA is 3,1 €/t, values as low as 0,6 €/t and as high as 6,7 were also found.

TABLE 27 - SALES PRICE COMPARISON BETWEEN NATURAL AND RECYCLED MATERIAL (€/T)

Component	Recycled material			Natural material
	minimum	maximum	average	average
Sand	3,3	8,9	5,4	8,8
Aggregate (graded)	2,9	7,7	4,1	7,2
Aggregate (All-in-one)	0,6	6,7	3,1	7,2

SOURCE: own elaboration (data from TABLE 7)

This variability may be caused by many reasons, such as local demand, availability of comparable products, distance and quality. The later is particularly critical for MRA, considering that standardization of this product is problematic, as it is composed of a mixture of mineral materials.

In order to verify the price variation effect on the feasibility of a recycling plant, a sensitivity analysis was carried out. TABLE 28 presents the CDW’s gate fee estimated according to a given price of RA (assuming all other variables unaltered, including IRR).

TABLE 28 - AVERAGE CDW'S GATE FEE VALUES FOR DIFFERENT SALE PRICE FOR RECYCLED MATERIALS (€/T)

Average CDW's gate fee	Segregation at Source				Totally mixed CDW (average case)				Totally mixed CDW (worst case)			
	Scenario 1	Δ	Scenario 2	Δ	Scenario 3	Δ	Scenario 4	Δ	Scenario 5	Δ	Scenario 6	Δ
Price equivalent to natural Aggregates	-0,3	-	-1,6	-	3,3	-49,6%	1,6	-66,5%	5,5	-34,7%	3,8	-43,5%
RA +30%	2,2	-28,4%	0,8	-51,2%	5,8	-11,3%	4,2	-15,1%	7,7	-7,9%	6,0	-9,9%
RA (average)	3,0	-	1,7	-	6,6	-	4,9	-	8,4	-	6,7	-
RA -30%	3,9	28,9%	2,6	52,0%	7,3	11,4%	5,6	15,3%	9,1	8,1%	7,4	10,0%
RA (MRA=0,6 €/t)	5,0	65,0%	3,7	117,6%	8,5	29,8%	6,9	40,0%	10,2	20,9%	8,5	26,1%

SOURCE: own elaboration

According to the results, scenarios with segregation at source are highly susceptible to the price of RA, due to their lower recycling costs and greater participation of products commercialization on the total revenues. An 30% increase in the price of RA could reduce the gate fee from 28,4% to 51,2%, depending on the capacity of the plant. In extreme circumstances, if aggregates were commercialized at a price equivalent to those of natural aggregates, the CDW's gate fee would be negative. Of course, this situation is not realistic. The negative value just means that the recycling plant would still be profitable even without charging for the incoming CDW.

For totally mixed scenarios, the effect of the RA's price is less pronounced, but still significant. These plants rely primarily on revenues from CDW's gate fees, due to their high recycling costs. The same increase of 30% on the price of RA could reduce the gate fee from 7,9% to 15,1%, depending on the capacity of the plant.

All in all, the marketability of the recycled products is a key factor to increase the economic attractiveness of recycling projects. However, the low prices for RA compared to natural materials reveal the difficulty to commercialize these products. Among other reasons, recycled materials are generally perceived as being of lower quality and a "discount" factor is frequently applied. In order to increase the added value of the products, it is essential to ensure that RA are produced with properties equivalent to those from natural aggregate.

Two main approaches could be used for that. One is related to the promotion of segregation at source itself, i.e. to remove non-mineral materials prior to the treatment process at the recycling plant. Equally important, the different types of mineral materials must be sorted based on their characteristics, in order to separate potentially high-grade RA (e.g. high-quality RCA) from lower quality ones. By doing so, several types of certifiable recycled product with higher added value can be commercialized. Otherwise, only non-certifiable MRA will be produced.

The other approach is related to the use of more efficient separation methods, such as wet separation system. These systems can separate lightweight and organic materials and remove soluble components. In the case of wet jigging, even different types of mineral materials could be obtained from a mixed matrix (e.g. concrete rubble could be separated from masonry rubble). Although, these system presents higher investment and operational costs and requires additional processes to treat wastewater and sludge, the increase in profits from products commercialization may overbalance these costs.

6 CONCLUSION

Even though, regulatory mechanisms exist in Brazil, which require, or even demand, recycling/recovering of CDW, the reality is far from optimal. Large quantities of CDW are generated each year, from which just a fraction (approximately 21%) is currently recycled or recovered. It is fair to say, therefore, that segregation at source is not a very common practice in Brazil and most of the CDW generated is mixed and contaminated, compromising the recyclability of the material. Under these circumstances and in conjunction with the lack of policies and control by the authorities, landfilling, or even illegally dumping, is the most frequent practice nowadays.

For that reason, the present work focused on the influence of the CDW's contamination level on the technical and economical aspects of recycling. Three level of contamination, representing different degrees of segregation, were simulated, namely: mineral CDW (segregation at source), totally mixed CDW (average conditions) and totally mixed CDW (worst conditions). Based on that, a pre-design of several scenarios of recycling facilities was carried out. All related costs to treat the incoming materials were estimated, including, initial investments, replacement costs and the annual capital and operation expenses, as well as, revenues from products commercialization.

Although the technologies employed and the parameters can vary enormously from one plant to another, or from country to country, the present study was carried out in an attempt to represent and reproduce processes economically already applied in the CDW recycling sector. For that, specific conditions in Brazil were considered, more specifically in the metropolitan region of Curitiba, including market price, applied technologies, economical conditions, among others. With all this information, a cash flow analysis was carried out for each scenario and from it the CDW's gate fee required to accomplish a minimum profitability of 15% (IRR) in a 25 years period was calculated. A sensitivity analysis was carried in order to evaluate the main variables that influence the profitability of a recycling plant.

Regarding the influence of the CDW's contamination level, the results demonstrate that segregation at source is essential to the development of CDW recycling, in terms of economy, environmental impacts and market conditions. The simulations have shown that even a contamination level around 10% (average case) may have a profound impact on treatment costs. In this case, the average gate fee values range between 5,1-6,7 €/t, depending on the capacity of the plant. These values are 121-

200% higher when compared to scenarios with segregation at source (1,7-3,0 €/t). The difference is even larger for a waste contamination of 20% (worst case), with an 168-280% of increase.

Many variables are responsible for this. Staff cost is the factor which contributes the most with around 36-43% of the total increase, mainly as a result of the greater number of manual sorters demanded to treat highly contaminated materials. The number of sorters increase from a few sorters to a couple of dozens or even hundreds of sorters. Residues disposal is the second largest contributor with around 21-25%, due to the considerable higher amounts of contaminated fine materials (<20 mm) generated, as well as, materials separated but not fit for recycling/recovery. Capital expenditures contribute with approximately 12-17%, as additional equipment, vehicles and civil works are required. Another advantage of segregation at source is the possibility to produce recycled concrete aggregates (RCA), a higher value product applicable to non-structural concrete applications. On the other hand, when mixed CDW is treated, only mixed recycled aggregates (MRA) of lower value are produced.

Regarding the influence of the capacity of the plant, the results strongly support the principle of gain of scale and energy efficiency of the system, indicating that a concentrated treatment of CDW may be an appropriate strategy in the metropolitan region of Curitiba, a highly densely populated area like many others in Brazil. By increasing the plant`s capacity, all the parameters such as CAPEX, OPEX, energy consumption and treatment costs are reduced in a per ton basis. For scenarios with segregation at source, the average CDW’s gate fees are reduced in more than 50% when the waste is treated in a 600 kt/y plant (3,0 €/t), compared to a 300 kt/y plant (1,7 €/t). For the same increase in capacity, the gain of scale was less pronounced for totally mixed CDW scenarios, in which the CDW’s gate fee was reduced in 21% (worst case) from 8,1 €/t to 6,4 €/t and in 25% (average case) from 6,7 to 5,1 €/t. One of the reasons for that is the relatively high share of staff costs on the total OPEX. This operation relies solely on the removal capacity of each sorter and is not modified, as per ton basis, with the increase of the plant’s capacity.

Regarding the influence of freight costs, the final price for the costumer may increase considerably when transportation is included, both to bring CDW to the plant and to deliver products to the client. Depending on the distance travelled, these costs may be comparable to or even surpass the CDW’s gate fee charged at the recycling plant. Safe to say, recycling is most attractive in densely populated areas, where the supply and demand can be guaranteed with shorter transportation distances. This is the case of the metropolitan region of Curitiba, a highly densely populated area like many others in Brazil.

Lastly, regarding the price of commercialization of the products, the promotion of the marketability of RA is an opportune strategy to consolidate the recycling industry, given that, the gap between prices for natural aggregates and RA are substantial. To overcome this situation, it is imperative to ensure that RA are produced with properties equivalent to those from natural resources. For that, more efficient separation methods, such as wet separation system, could be used. However, proper segregation at source is the ideal approach considering its double effect of increasing the quality of the RA and decreasing the recycling costs.

7 RECOMMENDATION

For future research the following fields are of interest:

-Life Cycle Costing for CDW recycling considering the whole recycling chain. The present research has focused on the impact of segregation at source on the treatment costs at the recycling plant. Increases in costs related to the segregation of the waste at the generating site were not regarded in the present research;

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ANNEX

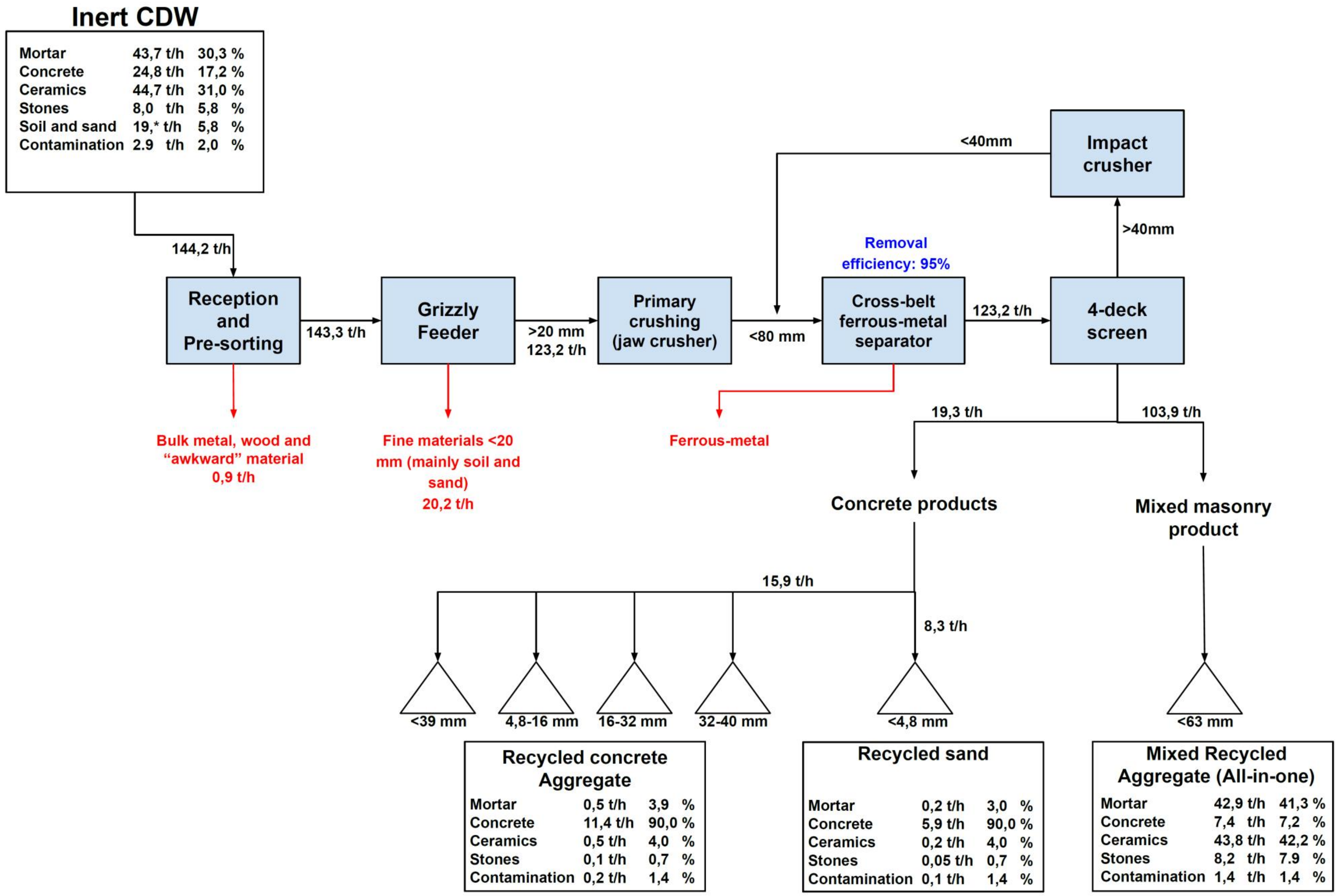
I. The European List of Waste (Commission Decision 2000/532/EC) - Chapter 17

17	**CONSTRUCTION AND DEMOLITION WASTES (INCLUDING EXCAVATED SOIL FROM CONTAMINATED SITES)**
17 01	**concrete, bricks, tiles and ceramics**
17 01 01	Concrete
17 01 02	Bricks
17 01 03	tiles and ceramics
17 01 06*	mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances
17 01 07	mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
17 02	**wood, glass and plastic**
17 02 01	Wood
17 02 02	Glass
17 02 03	Plastic
17 02 04*	glass, plastic and wood containing or contaminated with dangerous substances
17 03	**bituminous mixtures, coal tar and tarred products**
17 03 01*	bituminous mixtures containing coal tar
17 03 02	bituminous mixtures other than those mentioned in 17 03 01
17 03 03*	coal tar and tarred products
17 04	**metals (including their alloys)**
17 04 01	copper, bronze, brass
17 04 02	Aluminum
17 04 03	Lead
17 04 04	Zinc
17 04 05	iron and steel
17 04 06	Tin
17 04 07	mixed metals
17 04 09*	metal waste contaminated with dangerous substances
17 04 10*	cables containing oil, coal tar and other dangerous substances
17 04 11	cables other than those mentioned in 17 04 10
17 05	**soil (including excavated soil from contaminated sites), stones and dredging spoil**
17 05 03*	soil and stones containing dangerous substances
17 05 04	soil and stones other than those mentioned in 17 05 03
17 05 05*	dredging spoil containing dangerous substances
17 05 06	dredging spoil other than those mentioned in 17 05 05
17 05 07*	track ballast containing dangerous substances
17 05 08	track ballast other than those mentioned in 17 05 07
17 06	**insulation materials and asbestos-containing construction materials**
17 06 01*	insulation materials containing asbestos

17 06 03*	other insulation materials consisting of or containing dangerous substances
17 06 04	insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05*	construction materials containing asbestos
17 08	**gypsum-based construction material**
17 08 01*	gypsum-based construction materials contaminated with dangerous substances
17 08 02	gypsum-based construction materials other than those mentioned in 17 08 01
17 09	**other construction and demolition wastes**
17 09 01*	construction and demolition wastes containing mercury
17 09 02*	construction and demolition wastes containing PCB (for example PCB containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
17 09 03*	other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

APPENDIX – PROCESS FLOW

Process flow: Scenario 1 - Mineral CDW (segregation at source)



Inert CDW

Mortar	43,7 t/h	30,3 %
Concrete	24,8 t/h	17,2 %
Ceramics	44,7 t/h	31,0 %
Stones	8,0 t/h	5,8 %
Soil and sand	19,* t/h	5,8 %
Contamination	2.9 t/h	2,0 %

Recycled concrete Aggregate

Mortar	0,5 t/h	3,9 %
Concrete	11,4 t/h	90,0 %
Ceramics	0,5 t/h	4,0 %
Stones	0,1 t/h	0,7 %
Contamination	0,2 t/h	1,4 %

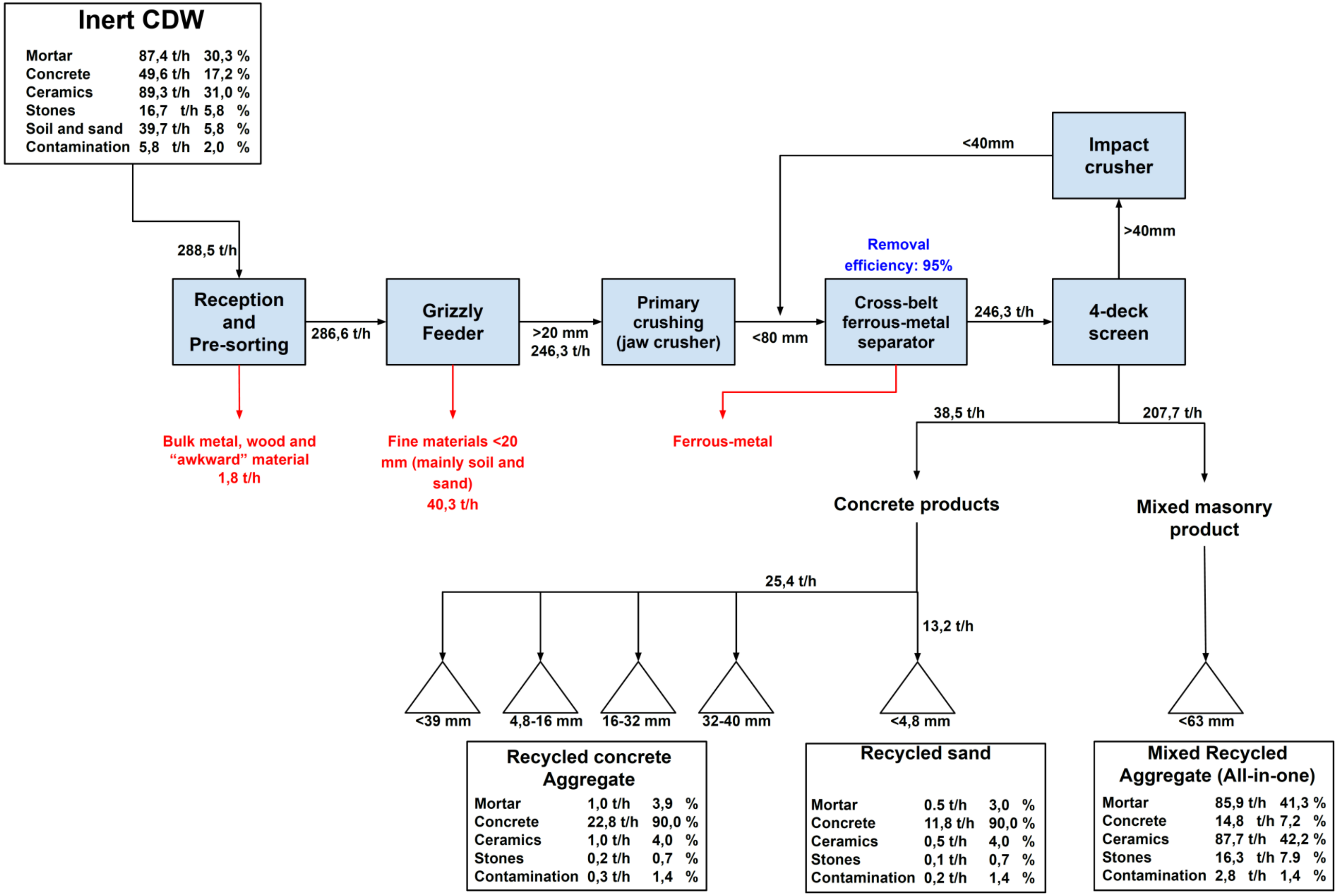
Recycled sand

Mortar	0,2 t/h	3,0 %
Concrete	5,9 t/h	90,0 %
Ceramics	0,2 t/h	4,0 %
Stones	0,05 t/h	0,7 %
Contamination	0,1 t/h	1,4 %

Mixed Recycled Aggregate (All-in-one)

Mortar	42,9 t/h	41,3 %
Concrete	7,4 t/h	7,2 %
Ceramics	43,8 t/h	42,2 %
Stones	8,2 t/h	7.9 %
Contamination	1,4 t/h	1,4 %

Process flow: Scenario 2 - Mineral CDW (segregation at source)



Inert CDW

Mortar	87,4 t/h	30,3 %
Concrete	49,6 t/h	17,2 %
Ceramics	89,3 t/h	31,0 %
Stones	16,7 t/h	5,8 %
Soil and sand	39,7 t/h	5,8 %
Contamination	5,8 t/h	2,0 %

Recycled concrete Aggregate

Mortar	1,0 t/h	3,9 %
Concrete	22,8 t/h	90,0 %
Ceramics	1,0 t/h	4,0 %
Stones	0,2 t/h	0,7 %
Contamination	0,3 t/h	1,4 %

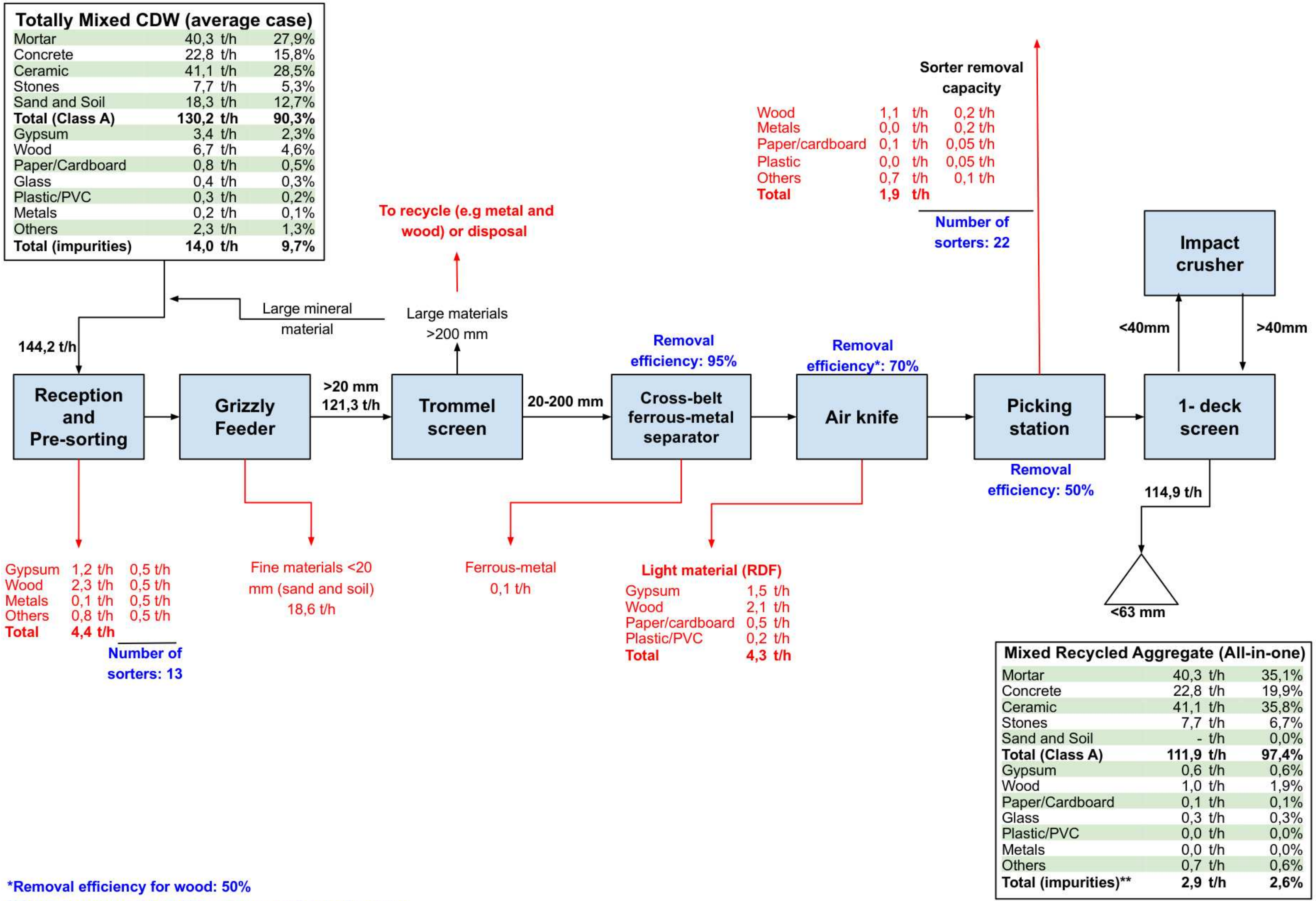
Recycled sand

Mortar	0.5 t/h	3,0 %
Concrete	11,8 t/h	90,0 %
Ceramics	0,5 t/h	4,0 %
Stones	0,1 t/h	0,7 %
Contamination	0,2 t/h	1,4 %

Mixed Recycled Aggregate (All-in-one)

Mortar	85,9 t/h	41,3 %
Concrete	14,8 t/h	7,2 %
Ceramics	87,7 t/h	42,2 %
Stones	16,3 t/h	7.9 %
Contamination	2,8 t/h	1,4 %

Process flow: Scenario 3 - Totally mixed CDW (average case)



Totally Mixed CDW (average case)

Mortar	40,3 t/h	27,9%
Concrete	22,8 t/h	15,8%
Ceramic	41,1 t/h	28,5%
Stones	7,7 t/h	5,3%
Sand and Soil	18,3 t/h	12,7%
Total (Class A)	**130,2 t/h**	**90,3%**
Gypsum	3,4 t/h	2,3%
Wood	6,7 t/h	4,6%
Paper/Cardboard	0,8 t/h	0,5%
Glass	0,4 t/h	0,3%
Plastic/PVC	0,3 t/h	0,2%
Metals	0,2 t/h	0,1%
Others	2,3 t/h	1,3%
Total (impurities)	**14,0 t/h**	**9,7%**

144,2 t/h

Reception and Pre-sorting

Gypsum	1,2 t/h	0,5 t/h
Wood	2,3 t/h	0,5 t/h
Metals	0,1 t/h	0,5 t/h
Others	0,8 t/h	0,5 t/h
Total	**4,4 t/h**	

Number of sorters: 13

Grizzly Feeder

Fine materials <20 mm (sand and soil) 18,6 t/h

>20 mm 121,3 t/h

Trommel screen

Large materials >200 mm

To recycle (e.g metal and wood) or disposal

Large mineral material

20-200 mm

Cross-belt ferrous-metal separator

Removal efficiency: 95%

Ferrous-metal 0,1 t/h

Air knife

Removal efficiency*: 70%

Light material (RDF)

Gypsum	1,5 t/h
Wood	2,1 t/h
Paper/cardboard	0,5 t/h
Plastic/PVC	0,2 t/h
Total	**4,3 t/h**

Picking station

Removal efficiency: 50%

		Sorter removal capacity
Wood	1,1 t/h	0,2 t/h
Metals	0,0 t/h	0,2 t/h
Paper/cardboard	0,1 t/h	0,05 t/h
Plastic	0,0 t/h	0,05 t/h
Others	0,7 t/h	0,1 t/h
Total	**1,9 t/h**	

Number of sorters: 22

1- deck screen

<40mm

Impact crusher

>40mm

114,9 t/h

<63 mm

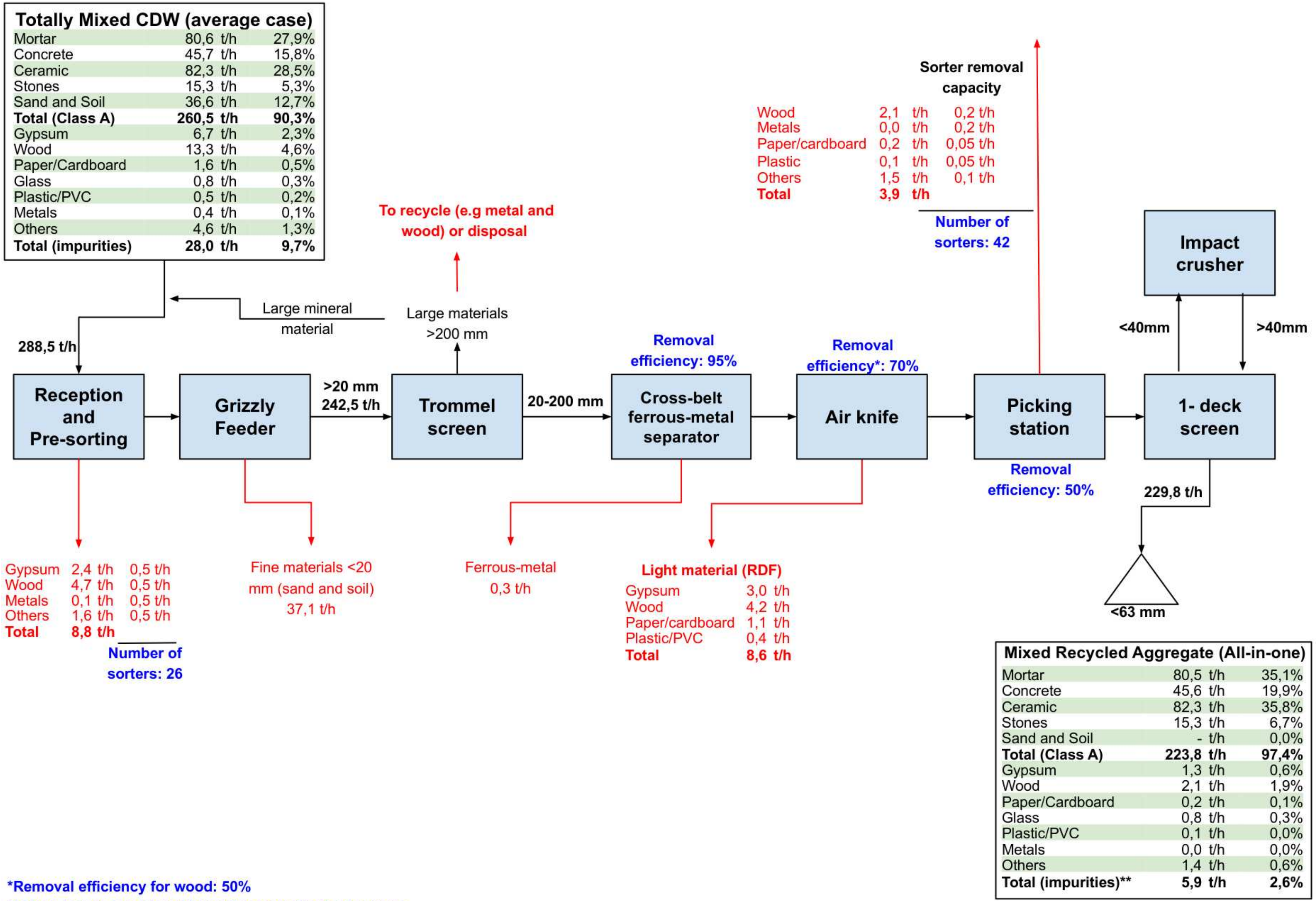
Mixed Recycled Aggregate (All-in-one)

Mortar	40,3 t/h	35,1%
Concrete	22,8 t/h	19,9%
Ceramic	41,1 t/h	35,8%
Stones	7,7 t/h	6,7%
Sand and Soil	- t/h	0,0%
Total (Class A)	**111,9 t/h**	**97,4%**
Gypsum	0,6 t/h	0,6%
Wood	1,0 t/h	1,9%
Paper/Cardboard	0,1 t/h	0,1%
Glass	0,3 t/h	0,3%
Plastic/PVC	0,0 t/h	0,0%
Metals	0,0 t/h	0,0%
Others	0,7 t/h	0,6%
Total (impurities)**	**2,9 t/h**	**2,6%**

***Removal efficiency for wood: 50%**

****Glass is not considered impurity according to the norm**

Process flow: Scenario 4 - Totally mixed CDW (average case)



Totally Mixed CDW (average case)		
Mortar	80,6 t/h	27,9%
Concrete	45,7 t/h	15,8%
Ceramic	82,3 t/h	28,5%
Stones	15,3 t/h	5,3%
Sand and Soil	36,6 t/h	12,7%
Total (Class A)	**260,5 t/h**	**90,3%**
Gypsum	6,7 t/h	2,3%
Wood	13,3 t/h	4,6%
Paper/Cardboard	1,6 t/h	0,5%
Glass	0,8 t/h	0,3%
Plastic/PVC	0,5 t/h	0,2%
Metals	0,4 t/h	0,1%
Others	4,6 t/h	1,3%
Total (impurities)	**28,0 t/h**	**9,7%**

Gypsum	2,4 t/h	0,5 t/h
Wood	4,7 t/h	0,5 t/h
Metals	0,1 t/h	0,5 t/h
Others	1,6 t/h	0,5 t/h
Total	**8,8 t/h**	

Number of sorters: 26

		Sorter removal capacity
Wood	2,1 t/h	0,2 t/h
Metals	0,0 t/h	0,2 t/h
Paper/cardboard	0,2 t/h	0,05 t/h
Plastic	0,1 t/h	0,05 t/h
Others	1,5 t/h	0,1 t/h
Total	**3,9 t/h**	

Number of sorters: 42

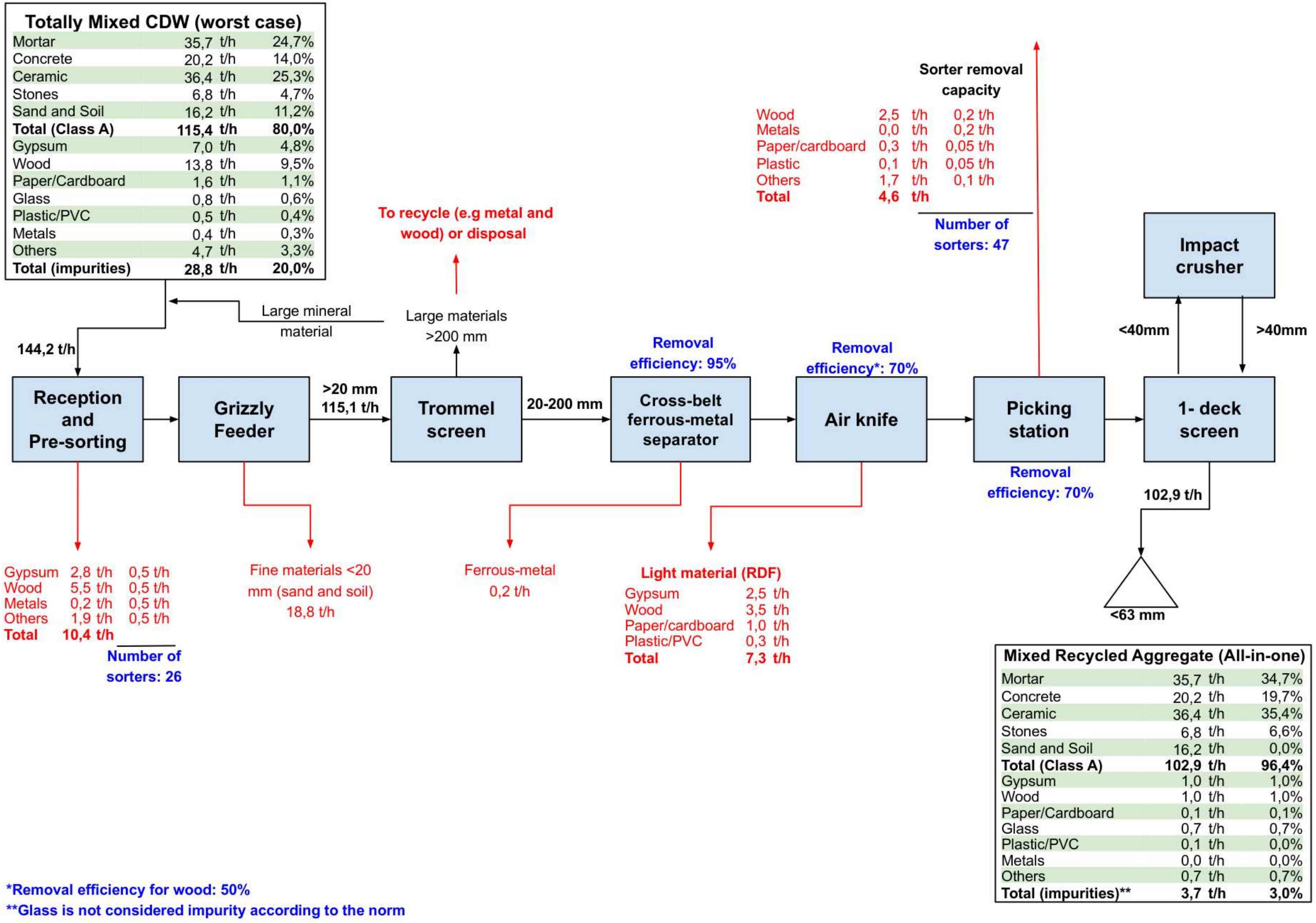
Light material (RDF)	
Gypsum	3,0 t/h
Wood	4,2 t/h
Paper/cardboard	1,1 t/h
Plastic/PVC	0,4 t/h
Total	**8,6 t/h**

Mixed Recycled Aggregate (All-in-one)		
Mortar	80,5 t/h	35,1%
Concrete	45,6 t/h	19,9%
Ceramic	82,3 t/h	35,8%
Stones	15,3 t/h	6,7%
Sand and Soil	- t/h	0,0%
Total (Class A)	**223,8 t/h**	**97,4%**
Gypsum	1,3 t/h	0,6%
Wood	2,1 t/h	1,9%
Paper/Cardboard	0,2 t/h	0,1%
Glass	0,8 t/h	0,3%
Plastic/PVC	0,1 t/h	0,0%
Metals	0,0 t/h	0,0%
Others	1,4 t/h	0,6%
Total (impurities)**	**5,9 t/h**	**2,6%**

***Removal efficiency for wood: 50%**

****Glass is not considered impurity according to the norm**

Process flow: Scenario 5 - Totally mixed CDW (worst case)



Totally Mixed CDW (worst case)

Mortar	35,7	t/h	24,7%
Concrete	20,2	t/h	14,0%
Ceramic	36,4	t/h	25,3%
Stones	6,8	t/h	4,7%
Sand and Soil	16,2	t/h	11,2%
Total (Class A)	**115,4**	**t/h**	**80,0%**
Gypsum	7,0	t/h	4,8%
Wood	13,8	t/h	9,5%
Paper/Cardboard	1,6	t/h	1,1%
Glass	0,8	t/h	0,6%
Plastic/PVC	0,5	t/h	0,4%
Metals	0,4	t/h	0,3%
Others	4,7	t/h	3,3%
Total (impurities)	**28,8**	**t/h**	**20,0%**

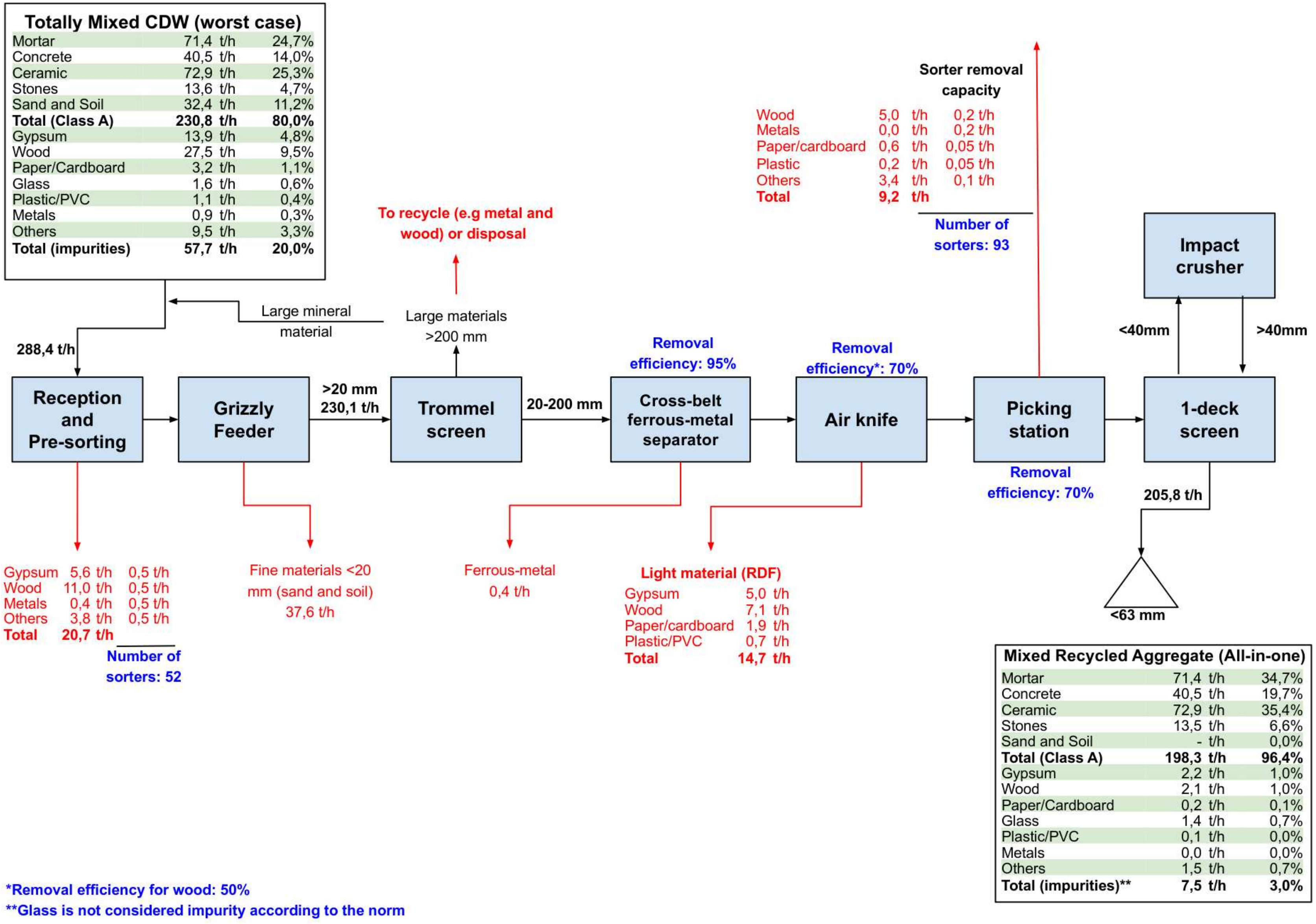
Mixed Recycled Aggregate (All-in-one)

Mortar	35,7	t/h	34,7%
Concrete	20,2	t/h	19,7%
Ceramic	36,4	t/h	35,4%
Stones	6,8	t/h	6,6%
Sand and Soil	16,2	t/h	0,0%
Total (Class A)	**102,9**	**t/h**	**96,4%**
Gypsum	1,0	t/h	1,0%
Wood	1,0	t/h	1,0%
Paper/Cardboard	0,1	t/h	0,1%
Glass	0,7	t/h	0,7%
Plastic/PVC	0,1	t/h	0,0%
Metals	0,0	t/h	0,0%
Others	0,7	t/h	0,7%
Total (impurities)**	**3,7**	**t/h**	**3,0%**

***Removal efficiency for wood: 50%**

****Glass is not considered impurity according to the norm**

Process flow: Scenario 6 - Totally mixed CDW (worst case)



Totally Mixed CDW (worst case)

Mortar	71,4 t/h	24,7%
Concrete	40,5 t/h	14,0%
Ceramic	72,9 t/h	25,3%
Stones	13,6 t/h	4,7%
Sand and Soil	32,4 t/h	11,2%
Total (Class A)	**230,8 t/h**	**80,0%**
Gypsum	13,9 t/h	4,8%
Wood	27,5 t/h	9,5%
Paper/Cardboard	3,2 t/h	1,1%
Glass	1,6 t/h	0,6%
Plastic/PVC	1,1 t/h	0,4%
Metals	0,9 t/h	0,3%
Others	9,5 t/h	3,3%
Total (impurities)	**57,7 t/h**	**20,0%**

Gypsum	5,6 t/h	0,5 t/h
Wood	11,0 t/h	0,5 t/h
Metals	0,4 t/h	0,5 t/h
Others	3,8 t/h	0,5 t/h
Total	**20,7 t/h**	

Light material (RDF)

Gypsum	5,0 t/h
Wood	7,1 t/h
Paper/cardboard	1,9 t/h
Plastic/PVC	0,7 t/h
Total	**14,7 t/h**

		Sorter removal capacity
Wood	5,0 t/h	0,2 t/h
Metals	0,0 t/h	0,2 t/h
Paper/cardboard	0,6 t/h	0,05 t/h
Plastic	0,2 t/h	0,05 t/h
Others	3,4 t/h	0,1 t/h
Total	**9,2 t/h**	

Mixed Recycled Aggregate (All-in-one)

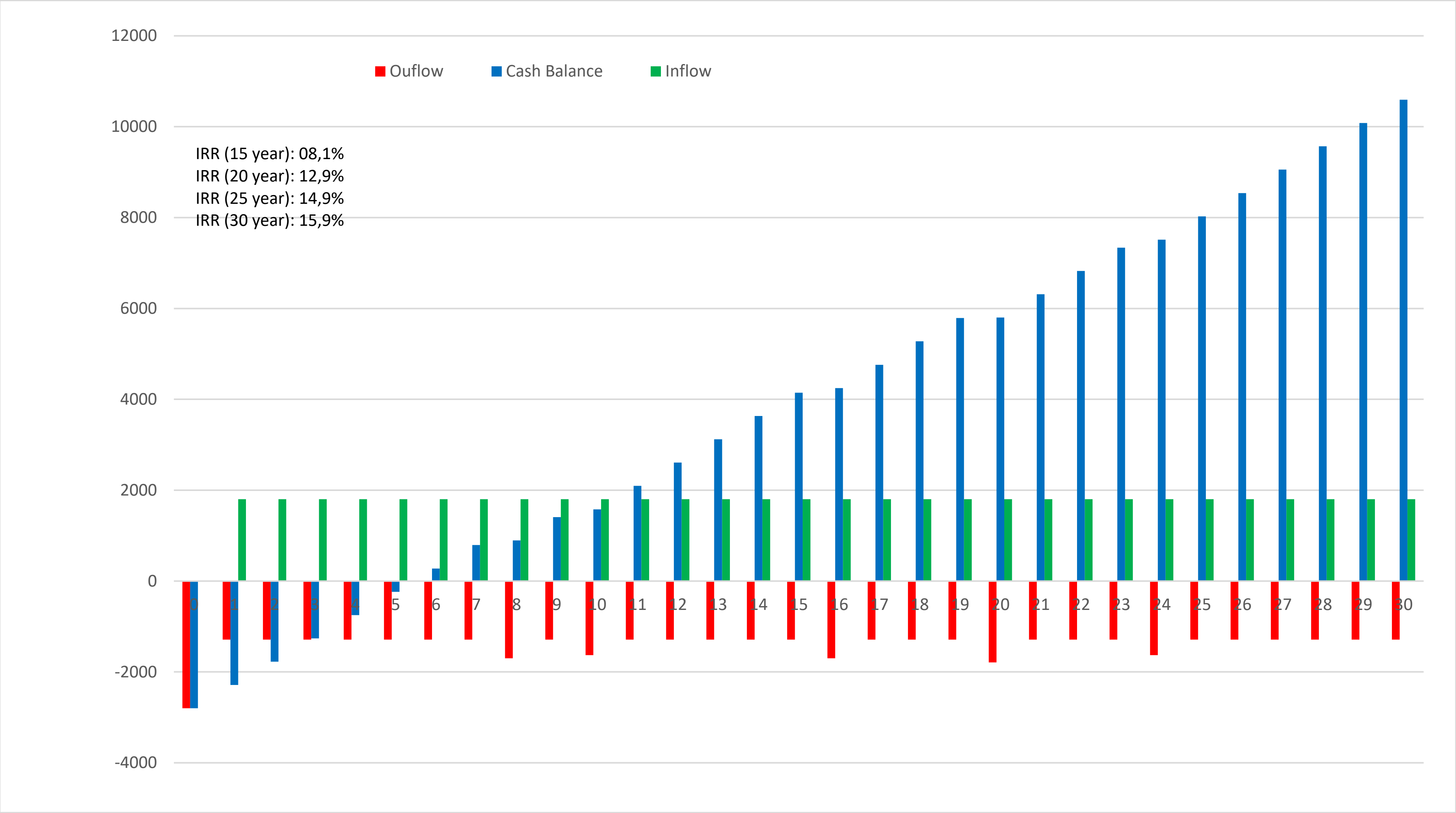
Mortar	71,4 t/h	34,7%
Concrete	40,5 t/h	19,7%
Ceramic	72,9 t/h	35,4%
Stones	13,5 t/h	6,6%
Sand and Soil	- t/h	0,0%
Total (Class A)	**198,3 t/h**	**96,4%**
Gypsum	2,2 t/h	1,0%
Wood	2,1 t/h	1,0%
Paper/Cardboard	0,2 t/h	0,1%
Glass	1,4 t/h	0,7%
Plastic/PVC	0,1 t/h	0,0%
Metals	0,0 t/h	0,0%
Others	1,5 t/h	0,7%
Total (impurities)**	**7,5 t/h**	**3,0%**

***Removal efficiency for wood: 50%**

****Glass is not considered impurity according to the norm**

APPENDIX – CASH FLOW

Cash flow: Scenario 1 - Mineral CDW (segregation at source) - 300 kt/y



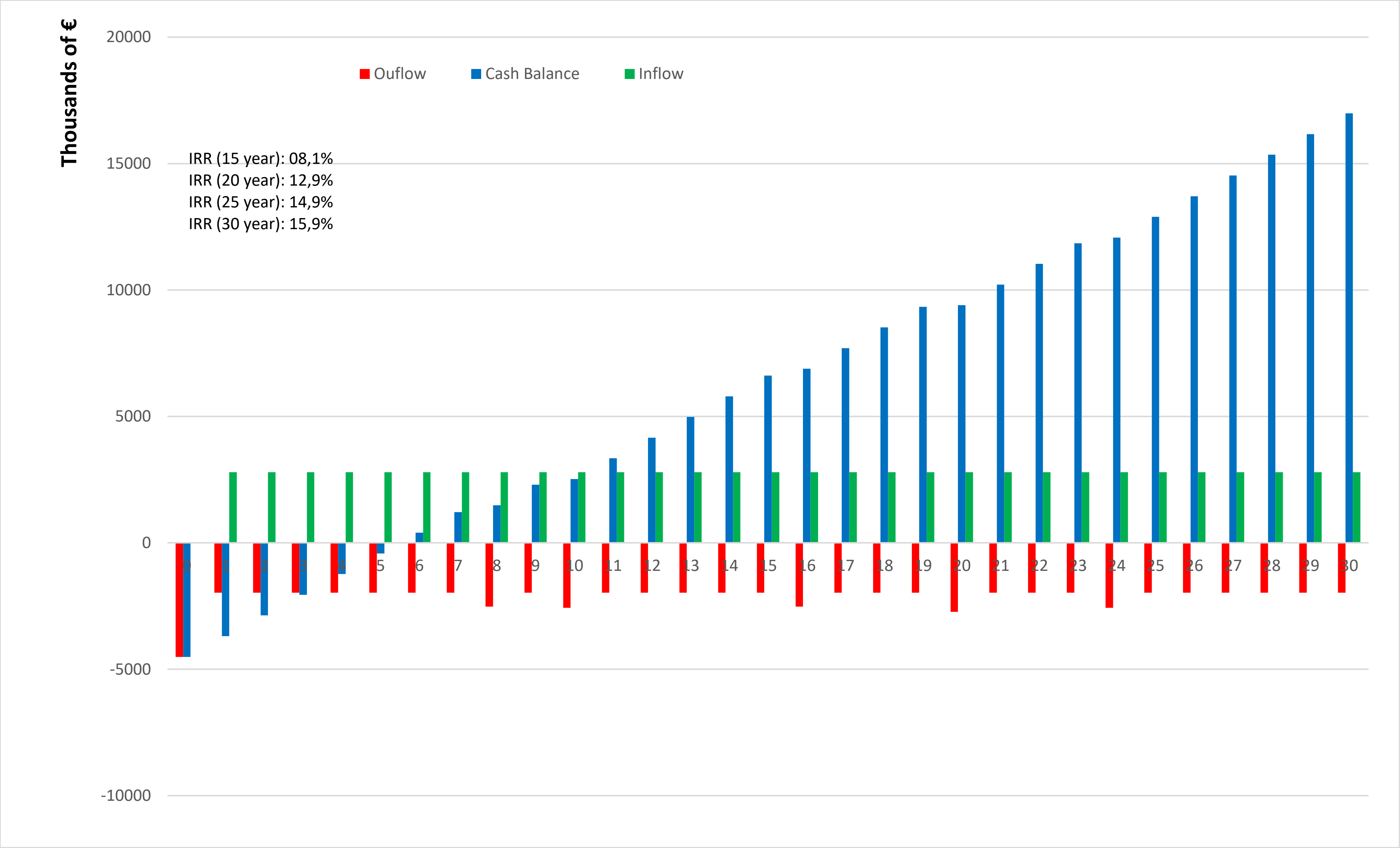
Source: own elaboration

Cash flow: Scenario 1 - Mineral CDW (segregation at source) - 300 kt/y

Cash flow (k€)	**Years of operation**															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Balance	-2802	-2288	-1774	-1260	-746	-233	281	795	898	1412	1586	2100	2614	3128	3642	4155
Outflow	-2802	-1291	-1291	-1291	-1291	-1291	-1291	-1291	-1702	-1291	-1630	-1291	-1291	-1291	-1291	-1291
Initial investment and replacement	-2802								-411		-339					
Ground	-645															
Civil works	-814															
Equipment	-501										-339					
Mechanical (normal wear and tear)	-162															
Mechanical (high wear and tear, e.g. crushing)	-339										-339					
Vehicles	-411								-411							
Engineering, commissioning, contingencies	-431															
Capital expenditures		-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345
Ground		-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52
Civil works		-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72
Mechanical		-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
Vehicles		-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72
Others		-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
Operation Expenditure (OPEX)		-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774
Maintenance and repair		-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72
Staff		-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326
Consumables		-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280
Residues Disposal		-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
Administration		-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68
Insurance		-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22
Taxes (25%)		-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171
Inflow		1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804
Products		891	891	891	891	891	891	891	891	891	891	891	891	891	891	891
CDW`s Gate fee		914	914	914	914	914	914	914	914	914	914	914	914	914	914	914

Cash flow (k€)	Years of operation															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Balance	4258	4772	5286	5800	5813	6327	6840	7354	7529	8043	8557	9070	9584	10098	10612	4258
Outflow	-1702	-1291	-1291	-1291	-1791	-1291	-1291	-1291	-1630	-1291	-1291	-1291	-1291	-1291	-1291	-1702
Initial investment and replacement	-411				-501				-339							-411
Ground																
Civil works																
Equipment					-501											
Mechanical (normal wear and tear)					-162											
Mechanical (high wear and tear, e.g. crushing)					-339											
Vehicles	-411								-339							-411
Engineering, commissioning, contingencies																
Capital expenditures	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345	-345
Ground	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52	-52
Civil works	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72
Mechanical	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
Vehicles	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72
Others	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75	-75
Operation Expenditure (OPEX)	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774	-774
Maintenance and repair	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72	-72
Staff	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326	-326
Consumables	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280	-280
Residues Disposal	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6	-6
Administration	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68	-68
Insurance	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22	-22
Taxes (25%)	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171	-171
Inflow	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804	1804
Products	891	891	891	891	891	891	891	891	891	891	891	891	891	891	891	891
CDW`s Gate fee	914	914	914	914	914	914	914	914	914	914	914	914	914	914	914	914

Cash flow: Scenario 2 - Mineral CDW (segregation at source) - 600 kt/y



IRR (15 year): 08,1%
IRR (20 year): 12,9%
IRR (25 year): 14,9%
IRR (30 year): 15,9%

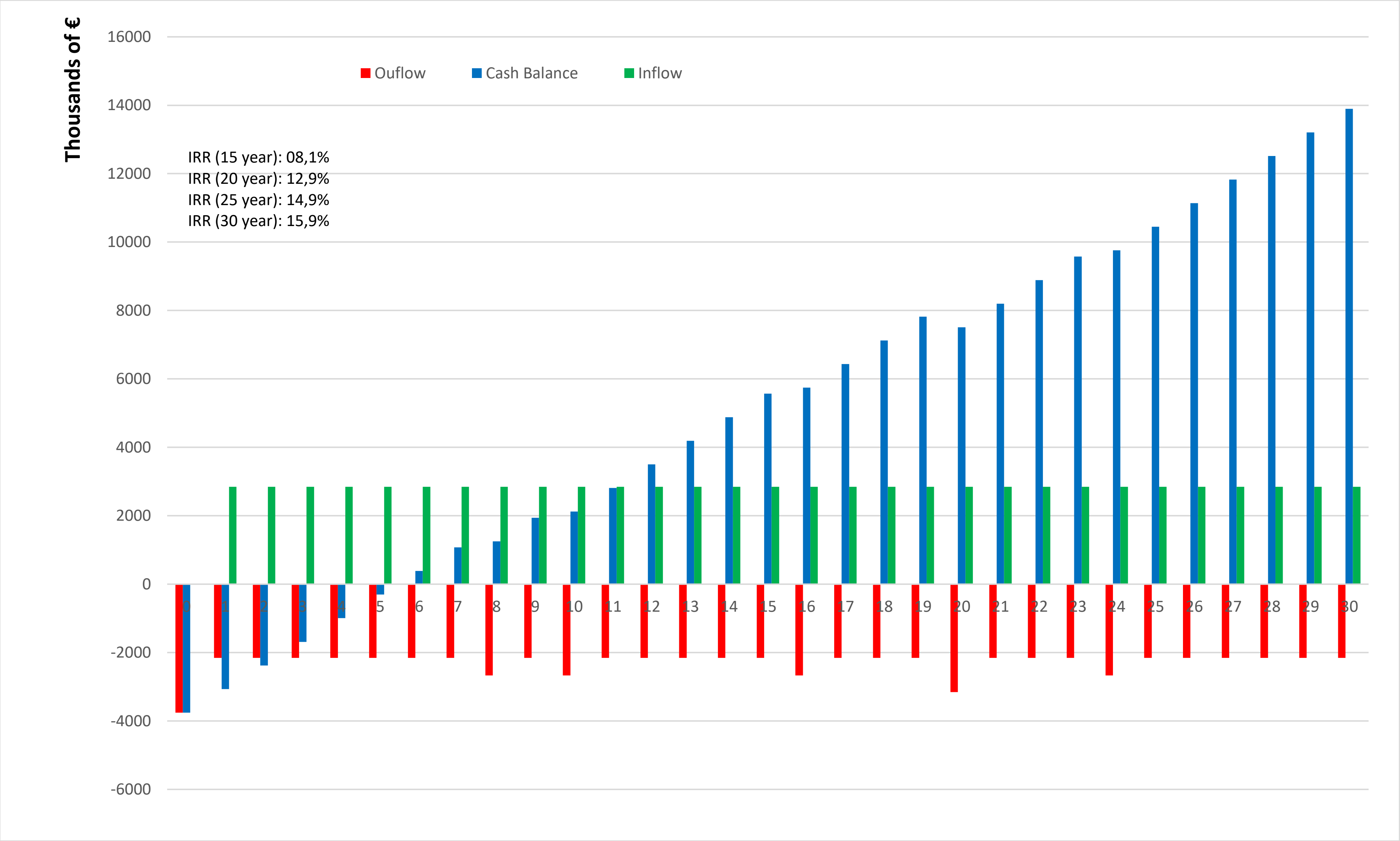
Source: own elaboration

Cash flow: Scenario 2 - Mineral CDW (segregation at source) - 600 kt/y

Cash flow (k€)	Years of operation															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Balance	-4510	-3692	-2874	-2056	-1238	-421	397	1215	1482	2300	2525	3343	4160	4978	5796	6614
Outflow	-4510	-1976	-1976	-1976	-1976	-1976	-1976	-1976	-2527	-1976	-2569	-1976	-1976	-1976	-1976	-1976
Initial investment and replacement	-4510								-551		-593					
Ground	-1231															
Civil works	-1316															
Equipment	-756										-593					
Mechanical (normal wear and tear)	-163															
Mechanical (high wear and tear, e.g. crushing)	-593										-593					
Vehicles	-551								-551							
Engineering, commissioning, contingencies	-656															
Capital expenditures		-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538
Ground		-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99
Civil works		-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117
Mechanical		-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113
Vehicles		-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96
Others		-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114
Operation Expenditure (OPEX)		-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165
Maintenance and repair		-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106
Staff		-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447
Consumables		-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465
Residues Disposal		-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11
Administration		-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103
Insurance		-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33
Taxes (25%)		-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273
Inflow		2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794
Products		1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782
CDW`s Gate fee		1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012

Cash flow (k€)	Years of operation															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Balance	6881	7699	8517	9335	9396	10214	11032	11850	12075	12893	13711	14528	15346	16164	16982	6881
Outflow	-2527	-1976	-1976	-1976	-2732	-1976	-1976	-1976	-2569	-1976	-1976	-1976	-1976	-1976	-1976	-2527
Initial investment and replacement	-551				-756				-593							-551
Ground																
Civil works																
Equipment					-756											
Mechanical (normal wear and tear)					-163											
Mechanical (high wear and tear, e.g. crushing)					-593											
Vehicles	-551								-593							-551
Engineering, commissioning, contingencies																
Capital expenditures	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538	-538
Ground	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99
Civil works	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117	-117
Mechanical	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113	-113
Vehicles	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96	-96
Others	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114	-114
Operation Expenditure (OPEX)	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165	-1165
Maintenance and repair	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106	-106
Staff	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447	-447
Consumables	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465	-465
Residues Disposal	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11
Administration	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103	-103
Insurance	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33
Taxes (25%)	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273	-273
Inflow	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794	2794
Products	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782	1782
CDW`s Gate fee	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012	1012

Cash flow: Scenario 3 - Totally mixed CDW (average case) - 300 kt/y



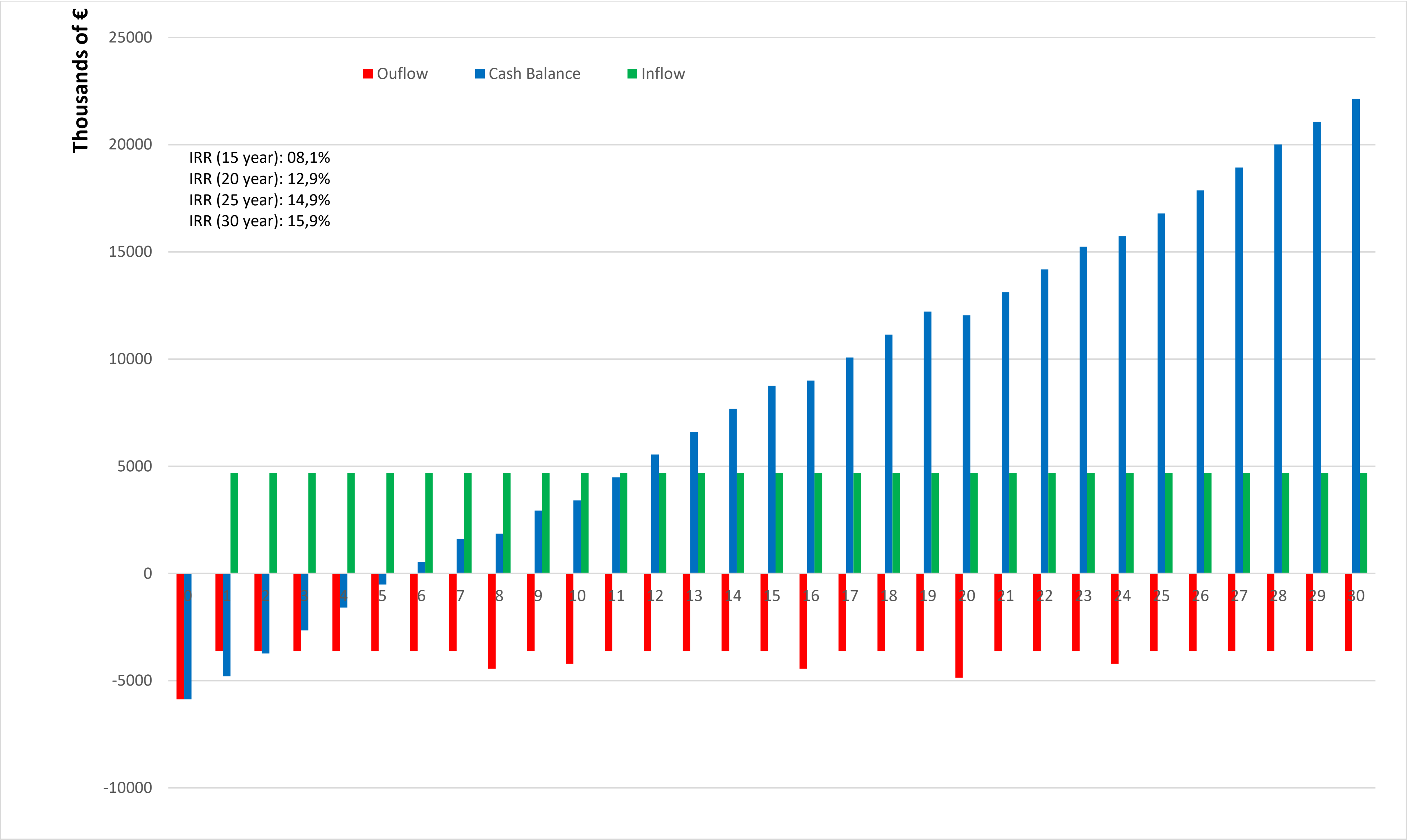
Source: own elaboration

Cash flow: Scenario 3 - Totally mixed CDW (average case) - 300 kt/y

Cash flow (k€)	Years of operation															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Balance	-3756	-3066	-2376	-1685	-995	-305	386	1076	1250	1941	2120	2810	3501	4191	4881	5572
Outflow	-3756	-2154	-2154	-2154	-2154	-2154	-2154	-2154	-2670	-2154	-2666	-2154	-2154	-2154	-2154	-2154
Initial investment and replacement	-3756								-516		-511					
Ground	-668															
Civil works	-954															
Equipment	-1001										-511					
Mechanical (normal wear and tear)	-490															
Mechanical (high wear and tear, e.g. crushing)	-511										-511					
Vehicles	-516								-516							
Engineering, commissioning, contingencies	-618															
Capital expenditures		-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485
Ground		-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53
Civil works		-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85
Mechanical		-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149
Vehicles		-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90
Others		-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107
Operation Expenditure (OPEX)		-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440
Maintenance and repair		-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111
Staff		-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602
Consumables		-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355
Residues Disposal		-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206
Administration		-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127
Insurance		-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38
Taxes (25%)		-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230
Inflow		2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845
Products		873	873	873	873	873	873	873	873	873	873	873	873	873	873	873
CDW`s Gate fee		1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971

Cash flow (k€)	Years of operation															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Balance	5746	6436	7127	7817	7507	8197	8887	9578	9757	10447	11137	11828	12518	13208	13899	5746
Outflow	-2670	-2154	-2154	-2154	-3155	-2154	-2154	-2154	-2666	-2154	-2154	-2154	-2154	-2154	-2154	-2670
Initial investment and replacement	-516				-1001				-511							-516
Ground																
Civil works																
Equipment					-1001											
Mechanical (normal wear and tear)					-490											
Mechanical (high wear and tear, e.g. crushing)					-511											
Vehicles	-516								-511							-516
Engineering, commissioning, contingencies																
Capital expenditures	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485	-485
Ground	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53
Civil works	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85
Mechanical	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149	-149
Vehicles	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90
Others	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107
Operation Expenditure (OPEX)	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440	-1440
Maintenance and repair	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111	-111
Staff	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602	-602
Consumables	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355	-355
Residues Disposal	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206	-206
Administration	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127	-127
Insurance	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38	-38
Taxes (25%)	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230	-230
Inflow	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845	2845
Products	873	873	873	873	873	873	873	873	873	873	873	873	873	873	873	873
CDW`s Gate fee	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971	1971

Cash flow: Scenario 4 - Totally mixed CDW (average case) - 600 kt/y



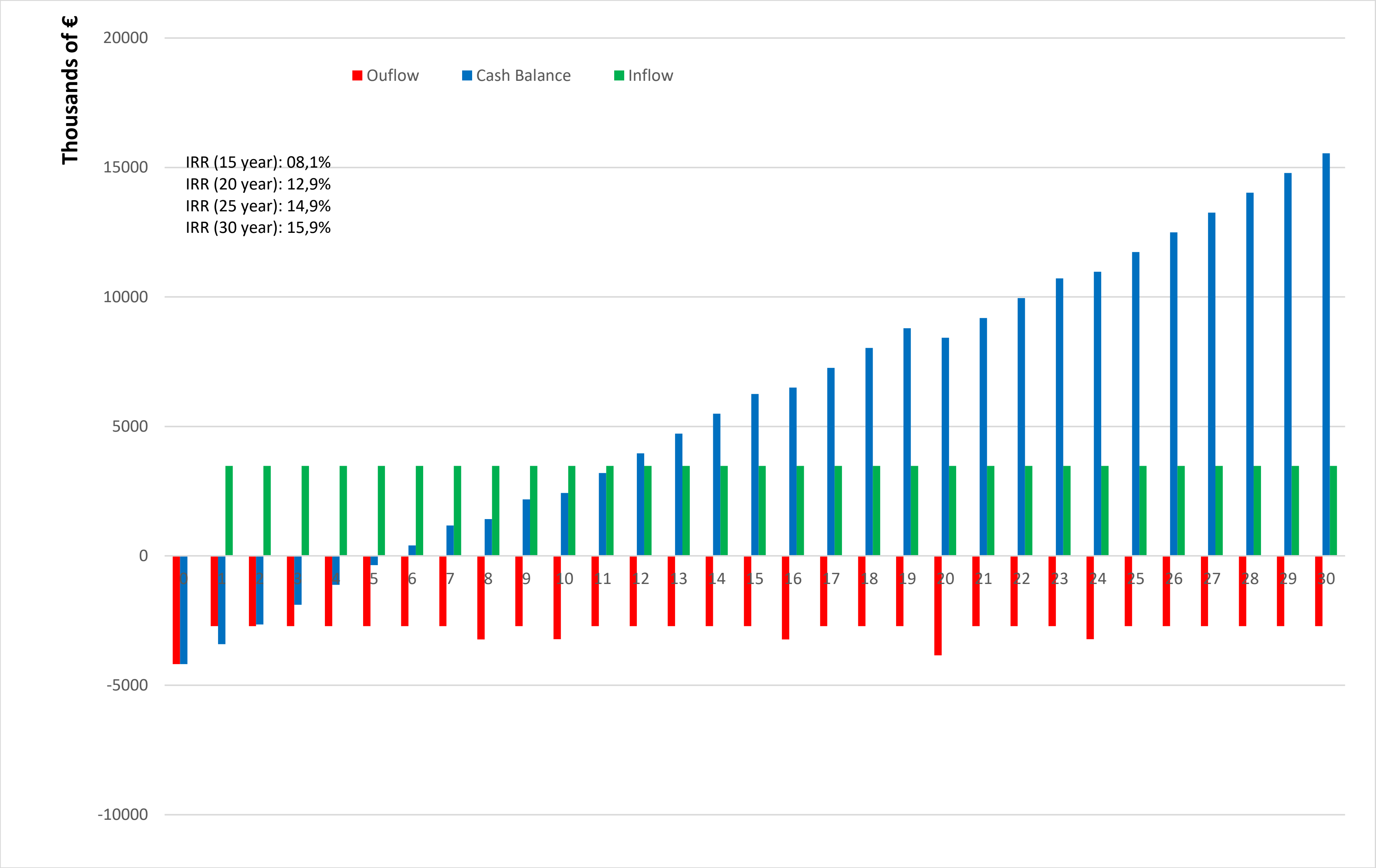
Source: own elaboration

Cash flow: Scenario 4 - Totally mixed CDW (average case) - 600 kt/y

Cash flow (k€)	**Years of operation**															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Balance	-5867	-4798	-3729	-2660	-1591	-522	547	1616	1863	2932	3409	4478	5547	6616	7685	8754
Outflow	-5867	-3624	-3624	-3624	-3624	-3624	-3624	-3624	-4446	-3624	-4215	-3624	-3624	-3624	-3624	-3624
Initial investment and replacement	-5867	0	0	0	0	0	0	0	-822	0	-592	0	0	0	0	0
Ground	-1278															
Civil works	-1615															
Equipment	-1234	0	0	0	0	0	0	0	0	0	-592	0	0	0	0	0
Mechanical (normal wear and tear)	-643															
Mechanical (high wear and tear, e.g. crushing)	-592										-592					
Vehicles	-822								-822							
Engineering, commissioning, contingencies	-918															
Capital expenditures		-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732
Ground		-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102
Civil works		-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143
Mechanical		-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184
Vehicles		-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143
Others		-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160
Operation Expenditure (OPEX)		-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535
Maintenance and repair		-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153
Staff		-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011
Consumables		-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671
Residues Disposal		-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411
Administration		-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225
Insurance		-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64
Taxes (25%)		-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356
Inflow		4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693
Products		1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747
CDW`s Gate fee		2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946

Cash flow (k€)	Years of operation															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Balance	9001	10070	11139	12208	12043	13112	14180	15249	15727	16796	17865	18934	20003	21072	22141	9001
Outflow	-4446	-3624	-3624	-3624	-4858	-3624	-3624	-3624	-4215	-3624	-3624	-3624	-3624	-3624	-3624	-4446
Initial investment and replacement	-822	0	0	0	-1234	0	0	0	-592	0	0	0	0	0	0	-822
Ground																
Civil works																
Equipment	0	0	0	0	-1234	0	0	0	0	0	0	0	0	0	0	0
Mechanical (normal wear and tear)					-643											
Mechanical (high wear and tear, e.g. crushing)					-592											
Vehicles	-822								-592							-822
Engineering, commissioning, contingencies																
Capital expenditures	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732	-732
Ground	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102	-102
Civil works	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143
Mechanical	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184	-184
Vehicles	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143
Others	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160	-160
Operation Expenditure (OPEX)	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535	-2535
Maintenance and repair	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153	-153
Staff	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011	-1011
Consumables	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671	-671
Residues Disposal	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411	-411
Administration	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225	-225
Insurance	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64	-64
Taxes (25%)	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356	-356
Inflow	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693	4693
Products	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747	1747
CDW`s Gate fee	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946	2946

Cash flow: Scenario 5 - Totally mixed CDW (average case) - 300 kt/y



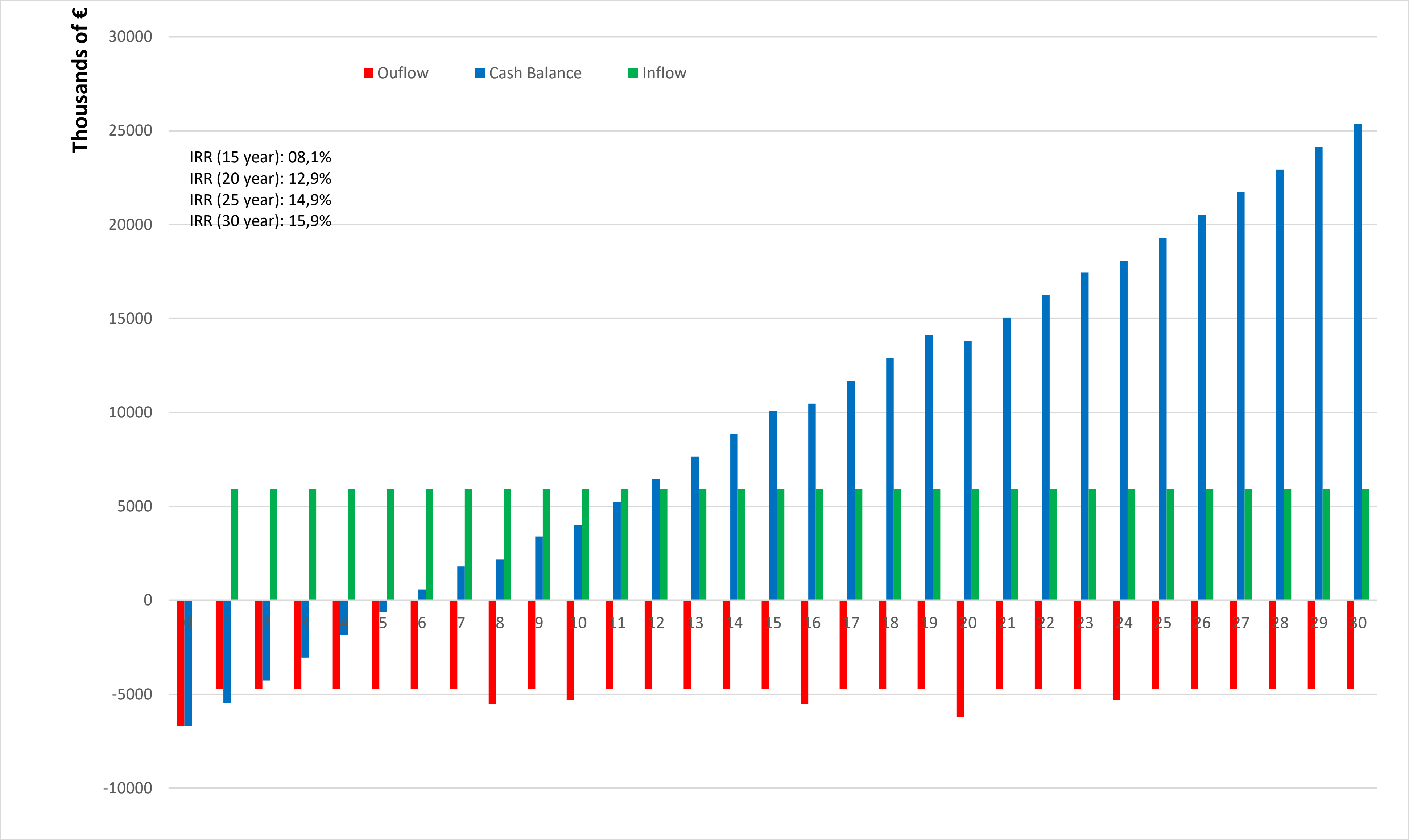
Source: own elaboration

Cash flow: Scenario 5 - Totally mixed CDW (worst case) - 300 kt/y

Cash flow (k€)	Years of operation															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Balance	-4177	-3414	-2650	-1886	-1122	-359	405	1169	1416	2180	2433	3196	3960	4724	5488	6251
Outflow	-4177	-2712	-2712	-2712	-2712	-2712	-2712	-2712	-3228	-2712	-3223	-2712	-2712	-2712	-2712	-2712
Initial investment and replacement	-4177								-516	0	-511					
Ground	-696															
Civil works	-1140															
Equipment	-1129										-511					
Mechanical (normal wear and tear)	-618															
Mechanical (high wear and tear, e.g. crushing)	-511										-511					
Vehicles	-516								-516							
Engineering, commissioning, contingencies	-696															
Capital expenditures		-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536
Ground		-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56
Civil works		-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101
Mechanical		-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168
Vehicles		-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90
Others		-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121
Operation Expenditure (OPEX)		-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921
Maintenance and repair		-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119
Staff		-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927
Consumables		-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380
Residues Disposal		-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277
Administration		-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170
Insurance		-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48
Taxes (25%)		-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255
Inflow		3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476
Products		947	947	947	947	947	947	947	947	947	947	947	947	947	947	947
CDW`s Gate fee		2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528

Cash flow (k€)	**Years of operation**															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Balance	6499	7263	8027	8790	8425	9189	9953	10716	10969	11733	12496	13260	14024	14788	15551	6499
Outflow	-3228	-2712	-2712	-2712	-3841	-2712	-2712	-2712	-3223	-2712	-2712	-2712	-2712	-2712	-2712	-3228
Initial investment and replacement	-516				-1129				-511							-516
Ground																
Civil works																
Equipment					-1129											
Mechanical (normal wear and tear)					-618											
Mechanical (high wear and tear, e.g. crushing)					-511											
Vehicles	-516								-511							-516
Engineering, commissioning, contingencies																
Capital expenditures	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536	-536
Ground	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56	-56
Civil works	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101	-101
Mechanical	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168
Vehicles	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90	-90
Others	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121
Operation Expenditure (OPEX)	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921	-1921
Maintenance and repair	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119	-119
Staff	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927	-927
Consumables	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380	-380
Residues Disposal	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277	-277
Administration	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170	-170
Insurance	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48	-48
Taxes (25%)	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255	-255
Inflow	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476
Products	947	947	947	947	947	947	947	947	947	947	947	947	947	947	947	947
CDW`s Gate fee	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528	2528

Cash flow: Scenario 6 - Totally mixed CDW (average case) - 600 kt/y



Source: own elaboration

Cash flow: Scenario 6 - Totally mixed CDW (worst case) - 600 kt/y

Cash flow (k€)	**Years of operation**															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cash Balance	-6693	-5481	-4268	-3055	-1843	-630	582	1795	2186	3398	4019	5232	6445	7657	8870	10082
Outflow	-6693	-4715	-4715	-4715	-4715	-4715	-4715	-4715	-5537	-4715	-5306	-4715	-4715	-4715	-4715	-4715
Initial investment and replacement	-6693								-822		-592					
Ground	-1333															
Civil works	-1966															
Equipment	-1500										-592					
Mechanical (normal wear and tear)	-908															
Mechanical (high wear and tear, e.g. crushing)	-592										-592					
Vehicles	-822								-822							
Engineering, commissioning, contingencies	-1072															
Capital expenditures		-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834
Ground		-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107
Civil works		-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175
Mechanical		-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224
Vehicles		-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143
Others		-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187
Operation Expenditure (OPEX)		-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476
Maintenance and repair		-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168
Staff		-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640
Consumables		-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721
Residues Disposal		-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554
Administration		-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308
Insurance		-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85
Taxes (25%)		-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404
Inflow		5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927
Products		1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894
CDW`s Gate fee		4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033

Cash flow (k€)	Years of operation															
	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cash Balance	10473	11686	12898	14111	13823	15036	16249	17461	18082	19295	20508	21720	22933	24145	25358	10473
Outflow	-5537	-4715	-4715	-4715	-6215	-4715	-4715	-4715	-5306	-4715	-4715	-4715	-4715	-4715	-4715	-5537
Initial investment and replacement	-822				-1500				-592							-822
Ground																
Civil works																
Equipment					-1500											
Mechanical (normal wear and tear)					-908											
Mechanical (high wear and tear, e.g. crushing)					-592											
Vehicles	-822								-592							-822
Engineering, commissioning, contingencies																
Capital expenditures	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834	-834
Ground	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107	-107
Civil works	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175	-175
Mechanical	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224	-224
Vehicles	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143	-143
Others	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187	-187
Operation Expenditure (OPEX)	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476	-3476
Maintenance and repair	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168	-168
Staff	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640	-1640
Consumables	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721	-721
Residues Disposal	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554	-554
Administration	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308	-308
Insurance	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85	-85
Taxes (25%)	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404	-404
Inflow	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927	5927
Products	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894	1894
CDW`s Gate fee	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033	4033