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PRE-TREATMENT OF SOUTHEAST ASIAN WASTE FOR CIRCULATING FLUIDIZED BED BOILER

Analyzing Biological-Mechanical Pre-Treatment Modification Effects on Boiler

Master of Science Thesis
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ABSTRACT

Mika Multaharju: Pre-Treatment of Southeast Asian Waste for Circulating Fluidized Bed Boiler;
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In developing regions of the world increase in population, wealth, and urbanization increases the amount of generated waste. One solution for disposing the waste is to burn it as fuel in boiler. Compared to grate-fired boiler, circulating fluidized bed boiler requires typically more pre-treatment for the waste fuel. Also, in developing regions such as Southeast Asia waste management is not efficient, which would lead to highly heterogeneous waste stream entering the pre-treatment process in the region. To understand the factors affecting the quality of RDF entering the boiler in a specific region, it is necessary to study waste generation and management in the region and pre-treatment process suitable for handling such waste.

The purpose of this thesis was to study a pre-treatment case process for wet Asian waste, for which a potentially cost-saving modification was proposed. Removing an air classifier from the process would reduce investment and operating costs. Also, the air classifier rejects would end up being combusted, which would remove their disposal costs. To make conclusions on the effects of the modification, modelling of the process had to be made. First, waste generation and management in Southeast Asia were studied to understand what kind of waste enters the boiler and what factors are affecting its composition. Then the study focused on what kind of pre-treatment equipment is required in the region to make suitable waste fuel for CFB boiler and how the equipment work. Waste fuel related issues in CFB boiler and the causes of them were identified. Based on the literature findings, model of the case was made, and results were analyzed with sensitivity analysis to make conclusions on the effects of the modification.

Study on waste generation and management in Southeast Asia showed that waste composition is affected by many factors and varies between locations in the region, thus one conclusive profile on Southeast Asian waste cannot be made. In the region awareness and political willingness to improve waste management and implement environment-friendly waste solutions are increasing. Study on the pre-treatment process and equipment showed that each pre-treatment unit has many variables affecting their performance, which makes modelling the process difficult. Identifying issues on CFB boiler caused by waste fuel and the material sources of them can help to make design decisions on pre-treatment process for reducing the problematic components in the fuel. The results of this thesis show that removing the air classifier for undersized refuse would worsen the RDF quality and have mainly adverse effects on the boiler. It should be noted that the analysis made in this thesis shows only one possible outcome with the studied conditions, and changes in waste composition and preceding process units can make a difference in the effects of removing the air classifier.

This thesis shows an example of waste pre-treatment modelling in estimating quality of RDF entering the boiler. It is also shown that because of many variables related to waste and its pre-treatment reliability of this kind of modelling depends on how detailed the available data is. Public domain data available on pre-treatment processes is limited, and some equipment would need more up-to-date studies, for example, on PSD of different materials. Overall, this thesis provides information on how municipal solid waste, pre-treatment process and CFB boiler are interconnected and how each step in the waste-to-energy process affects the following phases.

Keywords: waste fuel, pre-treatment, CFB, Southeast Asia, waste management

TIIVISTELMÄ

Mika Multaharju: Kaakkoisaasialaisen jätteen esikäsittely kiertoleijupetikattilaa varten; Biologis-mekaanisen esikäsittelyn muutoksesta kattilaan aiheutuvien vaikutusten analysointi
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Maapallon kehittyvillä alueilla kasvava väestönmäärä, vauraus ja kaupungistuminen lisäävät tuotetun jätteen määrää. Yksi ratkaisu hävittää jätettä on polttaa sitä polttoaineena kattilassa. Verrattuna arinakattiloihin kiertoleijupetikattilat vaativat tyypillisesti enemmän esikäsittelyä jätepolttoaineelle. Lisäksi kehittyvillä alueilla, kuten Kaakkois-Aasiassa, jätehuolto ei ole tehokasta. Tämä johtaisi kyseisellä alueella siihen, että erittäin heterogeenista jätettä päätyisi esikäsittelyprosessiin. Jotta voidaan ymmärtää, mitkä tekijät vaikuttavat kattilaan syötettävän RDF:n laatuun tietyllä alueella, on tarpeen tukia jätteen tuottamista ja jätehuoltoa kyseisellä alueella, sekä alueen jätteelle sopivaa esikäsittelyprosessia.

Tämän diplomityön tarkoituksena oli tutkia märälle Aasialaiselle jätteelle esikäsittelyn case-prosessia, josta esitettiin mahdollinen kustannuksia säästävä muutos. Ilmaseulan poistaminen prosessista vähentäisi investointi- ja käyttökustannuksia. Lisäksi ilmaseulan rejektit päätyisivät poltettavaksi, ja näin ollen muutos poistaisi niiden hävittämisen kustannukset. Muutoksesta aiheutuvien vaikutusten johtopäätöksiä varten täytyi tehdä mallinnus esikäsittelyprosessista. Ensin tutkittiin jätteen tuottamista ja jätehuoltoa Kaakkois-Aasiassa, jotta ymmärretään, minkälaista jätettä syötetään kattilaan ja mitä tekijöitä vaikuttaa sen koostumukseen. Tämän jälkeen työssä keskityttiin siihen, minkälaista esikäsittelylaitteistoa tarvitaan alueella CFB kattilaan sopivan jätepolttoaineen tuottamista varten ja miten laitteet toimii. Jätepolttoaineisiin liittyviä ongelmia CFB kattilassa ja niiden syitä tunnistettiin. Kirjallisuuteen perustuen case-prosessista tehtiin malli ja tuloksia analysoitiin herkkyystarkastelun avulla, jotta voitiin tehdä johtopäätöksia muutoksen aiheuttamista vaikutuksista.

Tutkimus jätteen tuottamisesta ja jätehuollosta Kaakkois-Aasiassa osoitti, että jätteen koostumus riippuu monista tekijöistä ja vaihtelee alueittain, joten yhtä lopullista profiilia Kaakkois-Aasialaiselle jätteelle ei voida tehdä. Alueella tietoisuus ja poliittinen halu parantaa jätehuoltoa ja ottaa käyttöön ympäristöystävällisiä jäteratkaisuita on lisääntymässä. Tutkimus esikäsittely-prosessista ja -laitteistosta osoitti, että jokaisessa esikäsittelylaitteessa on monia suorituskykyyn vaikuttavia tekijöitä, mikä vaikeuttaa prosessin mallintamista. CFB kattilaan syötetyn jätepolttoaineen aiheuttamien ongelmien ja niiden materiaalilähteiden tunnistaminen voi auttaa tekemään esikäsittelyyn suunnitteluratkaisuita, joilla voidaan vähentää haitallisia ainesosia polttoaineessa.Työn tuloksena saatiin selvitettyä, että alitteelle tarkoitetun ilmaseulan poistaminen heikentäisi RDF:n laatua ja sillä olisi pääosin haitallisia vaikutuksia kattilaan. On huomioitava, että tässä työssä tehty analyysi näyttää yhden lopputuloksen vain tarkastelluin edellytyksin, ja muutokset jätteen koostumuksessa ja edeltävissä laitteissa voivat muuttaa ilmaseulan poiston vaikutuksia.

Tämä diplomityö näyttää esimerkin jätteen esikäsittelyn mallintamisesta arvioidessa kattilaan menevän RDF:n laatua. Työssä myös tuodaan esille se, että lukuisista jätteeseen ja esikäsittelyyn liittyvistä muuttujista johtuen tämän tyyppisen mallintamisen luotettavuus riippuu saatavilla olevan tiedon tarkkuudesta. Yleisesti vapaaseen käyttöön tarkoitettua julkista tietoa esikäsittelyprosesseista on rajoitetusti saatavilla, ja osa laitteistosta tarvitsisi ajantasaista tutkimustietoa, esimerkiksi eri materiaalien kokojakaumista. Kokonaisuudessaan tämä diplomityö tarjoaa tietoa siitä, miten yhdyskuntajäte, esikäsittelyprosessi ja CFB kattila muodostavat yhtenäisen kokonaisuuden, jossa jätteiden energiakonversion jokainen edeltävä askel vaikuttaa seuraaviin vaiheisiin.

Avainsanat: jätepolttoaine, esikäsittely, CFB, Kaakkois-Aasia, jätehuolto

PREFACE

This Master of Science Thesis has been done for the R&D department of the Pulp and Energy business line in Valmet Technologies. I would like to thank all the co-workers who have helped me and made it possible to finish the work. Especially I would like to express my gratitude to Ilkka Alander for helping me to find this thesis subject and Riku Nurminen for guiding me through the thesis process. I would also like to thank the whole steering group for helping me to limit the thesis subject and point me to the right direction in what to focus on.

I would like to thank University Lecturer Henrik Tolvanen for the guidance and feedback on the work. The guidance allowed me to focus on the correct things from an academic perspective and the feedback allowed me to make the thesis the best I could.

I am grateful to my family, friends, and girlfriend for giving me support and encouragement, and you all have helped me to manage through these times of the coronavirus pandemic. Finally, I would like to thank all the people that have supported me during my life and have helped me to achieve a long-time goal of graduating from university.

Tampere, 24 April 2021

Mika Multaharju

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Air classifier
ASEAN	Association of Southeast Asian Nations
BMT	Biological-mechanical treatment
CEN	European Committee for Standardization
CDR	Certain type of waste fuel mixture
CFB	Circulating fluidized bed
EAP	East Asia and Pacific
ECA	Europe and Central Asia
ECS	Eddy current separator
EPA	Environmental Protection Agency
EURITS	European Union for Responsible Incineration and Treatment of Special Waste
GDP	Gross domestic product
GNI	Gross national income
HDI	Human development index
HDPE	High density polyethylene
HH	Horizontal hammermill
HHV	Higher heating value
HHW	Household hazardous waste
ICI	Institutional, commercial, industrial
LAC	Latin America and Caribbean
LDPE	Low density polyethylene
LHV	Lower heating value
MBT	Mechanical-biological treatment
MENA	Middle East and North Africa
MFA	Material flow analysis
MSW	Municipal solid waste
NA	North-America
NIR	Near-infrared
PET	Polyethylene terephthalate
PP	Polypropylene
PS	Polystyrene
PSD	Particle size distribution
PVC	Polyvinyl chloride
RDF	Refuse-derived fuel
SA	South-Asia
SOW	Stabilized organic waste
SRF	Solid recovered fuel
SS	Shear shredder
SSA	Sub-Saharan Africa
TC	Technical comittee
UNDP	United Nations Development Programme
UNEP	UN Environment Programme
UNI	Italian National Unification
US	United States
VH	Vertical hammermill
VS	Volatile solids
VTT	Technical Research Centre of Finland

1. INTRODUCTION

As the population and urbanization in Southeast Asia are increasing greatly, this also increases the amount of waste generated and demand for better utilization of waste-to-energy solutions in the region. Waste management in the region is still mostly in development stage and is affected for example by governmental policies, co-operation of different stakeholders and public awareness on the environmental impact of waste disposal. Countries in Southeast Asia have great variance in the human development index and income generated per capita, which makes it necessary to study the challenges and opportunities of waste-to-energy sector regarding each country individually. In Southeast Asia some countries are more ahead in the waste-to-energy development than the others and in the last decade huge increase in the energy production from waste in China is providing lessons on sustainable operation and effective utilization of waste-to-energy technologies in Asia (Tun et. al., 2020; UNDP, 2019; UNEP, 2019). Southeast Asian countries can work together and learn from each other in order to improve waste managing, and waste-to-energy technology providers can meet the market demands better by understanding what kind of waste is in Southeast Asia and how waste sector is developing in the area.

Three types of combustion processes exist for municipal waste: grate-firing, fluidized bed and rotary furnace. Rotary furnace is mostly used for hazardous and other special wastes. Grate-fired boilers are more common than fluidized-bed boilers likely because of longer history and the process developments that have happened alongside with the emerging of more modern fluidized-bed technology (Leckner and Lind, 2020, p. 95). Cost of a waste fuel pre-treatment system is estimated to be larger for CFB boilers than grate-fired boilers due to necessity to remove large and heavy waste (Leckner and Lind, 2020, p. 106). Thus, one way to improve the competitiveness of CFB boilers against grate-firing technology is by making savings in the pre-treatment process, if the waste fuel quality would still be good enough to be incinerated in the CFB boiler.

Most of the process units in waste pre-treatment have been developed first in the mining industry and later adapted for waste streams. The first generations of RDF production plants in United States and Europe had high levels of contaminants and a high level of variability in RDF quality. To produce more homogenous waste fuel output, processes to separate potentially harmful biological and chemical elements from the waste stream have been developed. The first mechanical-biological treatment plants were established in 1995 in Europe, and since then interest in them has grown due to European Union Landfill Directive, which has a goal of reducing the amount of biodegradable waste disposed to landfills (Velis et al., 2010). As Southeast Asian waste typically has high contents of organic matter, a MBT plant with biodrying technology could be one potential waste pre-treatment option for the RDF entering CFB boiler, since biodrying effectively reduces the moisture content of RDF.

Extensive studies have been made on the waste fuel pre-treatment process. For example, Worrell and Vesilind (2012) provides a basic framework on solid waste management systems based on their research experience in the fields of MSW beginning from 60's and 70's, and Velis. et. al. (2010) have provided a comprehensive review on the mechanical-biological treatment plants and their equipment currently in use. As Velis. et. al. points out, there is not much scientifically derived public domain data available on the performance of individual process units, there is limited material flow analysis research for MBT plants and RDF/SRF production lines, and the data reliability of the existing MFA studies is questionable because in most of the cases they are based on theoretical models and assumptions derived from existing practices (Velis et. al., 2010, p. 1011-1012, 1086).

To understand what kind of waste fuel would be available for combustion in Southeast Asia, it is first necessary to study what kind of variables are affecting municipal waste generation, management, and quality. Then needs to be studied how the process units work in a pre-treatment process suitable for Southeast Asian waste and how they change the waste characteristics and material flows. And then by understanding what components in the waste fuel are problematic for the boiler, combustibility of the RDF produced by the pre-treatment system from Southeast Asian waste can be evaluated. After finding answers to these subjects, then can be evaluated how making cost-saving modifications to the pre-treatment system would affect RDF quality and what are the effects on boiler performance.

The main focus of this thesis is on evaluating the waste fuel pre-treatment process modification effects on CFB boiler in Southeast Asia. A suitable waste pre-treatment process case for the wet Asian waste is used, and in this study the process is modified so that an air classifier for undersized refuse is removed, thus reducing the amount of rejects and costs associated with the unit. The goal of this thesis is to gain an understanding on the waste fuel pre-treatment process from the CFB boiler point of view. Secondary goal is to understand how different variables in the waste source and pre-treatment process will affect RDF quality and therefore affect the boiler performance. To make conclusions, modelling of the pre-treatment process has to be made. As was mentioned before, there is limited public domain data available on the process units and mass flows of pre-treatment plants. To make the model, data from different sources has to be combined and for this thesis focus in creating the model was on getting RDF characteristics output data that would allow making estimations on the effects on the boiler.

First as the theoretical background of this thesis is discussed what are the trends in Southeast Asian waste generation, management, and composition. For this thesis Malaysia, Indonesia and Viet Nam will be chosen for further study so that different development tiers will be presented. Then is discussed what is the waste pre-treatment process case studied in this thesis and what typical process units are used. Information found in that chapter will be used for modelling the pre-treatment process. Then is discussed how waste fuel derived from municipal solid waste affects CFB boiler. Information found in that chapter will be used for choosing what output results should the model show and for evaluating and discussing the results. Then in the modelling part model will be made on the pre-treatment process case based on theoretical process performance data found from public domain. Model will be used to see how RDF characteristics change when the air classifier is removed. Since there is no existing plant with the studied pre-treatment process case available to validate the results experimentally, reliability of the results will be increased by studying the results with different variable parameter values in the waste input and different process units. Research questions that will be discussed in this thesis are:

- 1. What kind of waste goes to boiler in Southeast Asia?
- 2. What kind of pre-treatment is required to burn waste in CFB boiler?
- 3. What waste components are problematic for CFB boiler and how?
- 4. How does the examined pre-treatment process modification affect the boiler performance?

The first research question is answered in Chapter 2. The second research question is answered in Chapter 3 in terms of what kind of pre-treatment units are used and how they will affect the waste, while Chapter 4 gives answer to what kind of waste quality should the pre-treatment process aim for so that the waste can be burned in CFB boiler. The third research question is answered in Chapter 4 in terms of what chemical compounds or physical characteristics of the waste are problematic for CFB boiler, while in Chapter 5 is identified what waste materials are associated with them and in Chapter 6 is analyzed what waste materials are causing the adverse effects resulting from pre-treatment modification. The final question is answered in Chapter 6.

2. WASTE IN SOUTHEAST ASIA

This chapter studies trends in Southeast Asian waste generation, management and composition. These matters will affect later phases of the waste-to-energy process shown in Figure 1.

Figure 1. Waste-to-energy phase studied in this chapter: municipal solid waste

2.1 Waste generation

Municipal solid waste has different definitions, but generally it is waste generated in population centres and collected and treated by or for municipalities (Hoornweg and Bhada-Tata, 2012, p. 4). Figure 2 shows an example of global trends in waste generation. In the last six decades USA has shown noticeable relative MSW material increases in plastics, textiles, wood, aluminum, and food waste, while there is decrease in yard trimmings, paper and paperboard, glass, and ferrous metals. This does not necessarily represent how waste generation in Asia will develop, but because of global trade and international companies affecting products manufactured and consumed in the Asian market similar trends could occur.

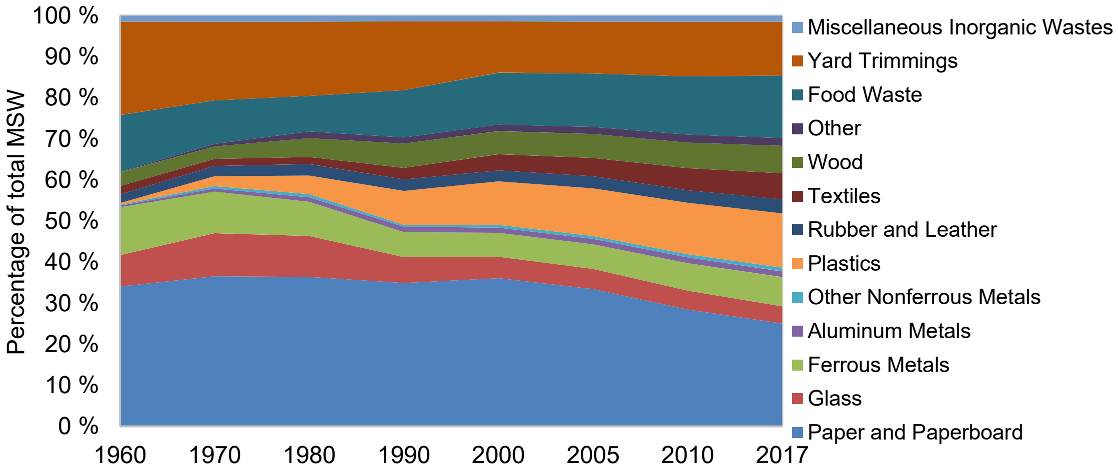

Figure 2. Materials by percentage of total MSW generated in USA (U.S. EPA, 2017)

Table 1 shows how each region of countries in the world generates waste now and how much rates are estimated to increase in the future. Also, the amount of people living in urban areas is shown to indicate differences between different parts of the world. MSW generation overall and per capita will increase everywhere, but not by equal rates.

Table 1. Global MSW generation (Sharma and Jain, 2020, p. 922)

	MENA	SSA	LAC	NA	SA	ECA	EAP
Degree of urbanization (%)	65	38	81	82	33	71	57
2016 MSW generation share (%)	6	9	11	14	17	20	23
2016 MSW (kg/capita/day)	0.81	0.46	0.99	2.21	0.52	1.18	0.56
2025 MSW (kg/capita/day)	0.9	0.5	1.11	2.37	0.62	1.3	0.68
2050 MSW (kg/capita/day)	1.06	0.63	1.3	2.5	0.79	1.45	0.81
MSW generation growth from 2016 to 2050 (MT/year)	129->255 (+75%)	174->516 (+197%)	231->369 (+60%)	289->396 (+37%)	334->661 (+98%)	392->490 (+25%)	468->714 (+53%)

Amount of generated waste in ASEAN (Association of Southeast Asian Nations) countries (Table 2) is likely to increase due to industrialization, rapid urbanization and strong economic growth (UNEP, 2019, p. 9). After China banned waste importing from other countries in 2017 due to cutting back on pollution generated from processing and recycling all the waste, plastic and electronic waste from all around the world started being dumped into Southeast Asia. This was because labour in the region is cheap and regulations were loose. Even though some of the waste can be recycled for manufacturing purposes, much of the waste is useless and ends up being incinerated or dumped into landfills. ASEAN countries have started taking political action to prevent illegal waste streams and banning plastic waste importing, but countries such as Canada have shown reluctancy to receive back waste streams exported by them (Zsombor, 2019). Optimal results are yet to be achieved, but this is a good example on the political willingness to increase ecological waste management in Southeast Asia.

Table 2. HDI and GNI per capita of ASEAN countries (UNDP, 2019)

Country	Human Development Index (HDI)	Development tier	GNI per capita	Income group
Singapore	0.935	Very high	83 793	High income
Brunei	0.845	Very high	76 389	High income
Malaysia	0.804	Very high	27 227	High income
Thailand	0.765	High	16 129	High income
Philippines	0.712	High	9 540	Upper-middle
Indonesia	0.707	High	11 256	Upper-middle
Viet Nam	0.693	Medium	6 220	Upper-middle
Laos	0.604	Medium	6 317	Upper-middle
Myanmar	0.584	Medium	5 764	Upper-middle
Cambodia	0.581	Medium	3 597	Lower-middle

Municipal solid waste is generated from domestic, commercial, institutional, industrial, and various other sources (Bundhoo, 2018, p. 1868). Figure 3 shows results from a forecasting study on waste generation in Kuala Lumpur, Malaysia. Almost half of the generated waste comes from residential sources. Commercial sources include business offices, hotels, restaurants, transportation, and marketplaces selling wet goods such as meat, fish, vegetables, and fruits. Institutional waste sources include educational institutes, healthcare providers, and public administration offices (Bandar and Tempatan, 2013, p. 51). In Southeast Asian countries the amount of construction and demolition waste, e-waste, industrial waste, and healthcare waste is increasing due to economic growth (UNEP, 2019, p. vi), resulting their fractions to be most likely higher than in the Kuala Lumpur study published decade ago.

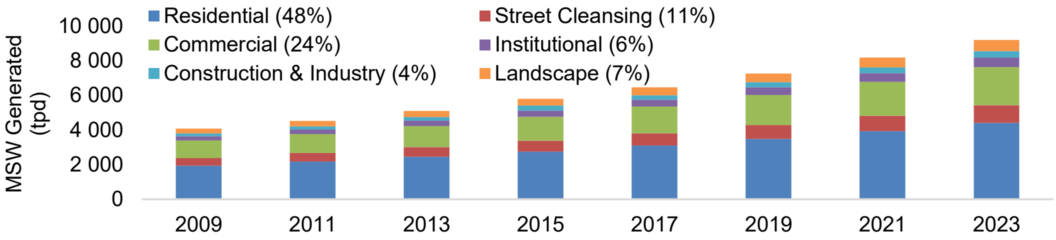

Figure 3. Waste generation prediction for 2009-2023 in Kuala Lumpur, Malaysia (Saeed et. al., 2008, p. 4)

Generally, waste generation rate per capita increases when GDP per capita and HDI of country increases (Bundhoo, 2018, p. 1868). Figure 4 shows how much waste is generated per capita in ASEAN countries. According to Bandar and Tempatan (2013, p. 43) waste generation rate is affected by how wealth is divided in the society, what are the living conditions, urbanization and industrialization of the area, what are the public habits, and how is the local climate. Also cost of housing increases waste generation (Bandar and Tempatan, 2013, p. 43). Figure 5 shows how waste generation rates differ between urban and rural areas in Malaysia. This is because urban areas are more industrialized and have greater economic development. In the case of industrial, commercial, and institutional (ICI) waste construction/demolition waste and industrial scraps are not included in the referred study (Bandar and Tempatan, 2013, p. 48).

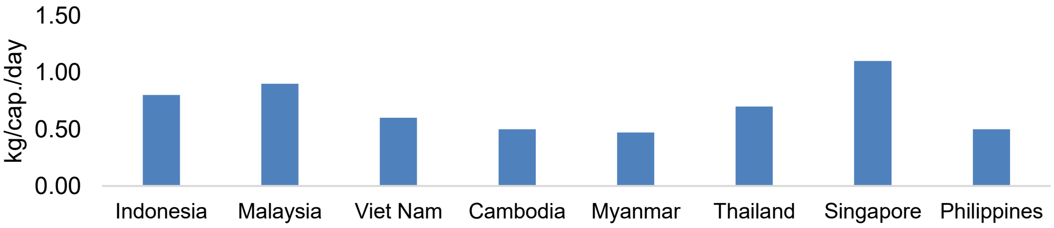

Figure 4. MSW generated per capita in ASEAN countries (Mordor Intelligence, 2019)

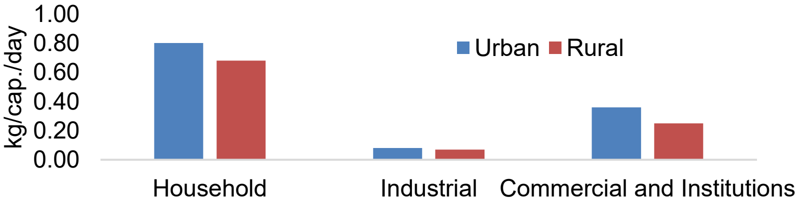

Figure 5. MSW generated per capita between urban and rural areas in Malaysia (Bandar and Tempatan, 2013, p. 47, 50)

2.2 Waste trends

Each country in ASEAN region has its own trends and policies regarding waste generation and management. Each country, except Brunei Darussalam, has basic Act on Environment (UNEP, 2019, p. 24). Information on Malaysia, Indonesia, and Viet Nam are shown to demonstrate heterogeneity of waste segment in Southeast Asia. Also, each country represents a different development tier. Table 3 shows results from a gap analysis identifying how ASEAN countries have achieved waste management goals regarding relevance, policies, programmes, plan/strategy, and projects (UNEP, 2019, p. 28).

Table 3. Waste management goals gap analysis results in ASEAN countries (UNEP, 2019, p. 28)

Country	Significant reduction of MSW generated	Full-scale utilization of the organic component of MSW as a valuable resource	Significant increase in recycling rate of recyclables	Building green cities by encouraging "zero waste" policy (waste minimization)
Malaysia	Implemented	Implemented	Implemented	Partially implemented
Indonesia	Implemented	Pilot level implementation	Implemented without strategy	In pilot level without policies and strategy
Viet Nam	Implemented without ongoing projects	Implemented without ongoing projects	Implemented with partial policies and without ongoing projects	Implemented

2.2.1 Malaysia

74% of the Malaysian population lives in urban areas. Population growth rate in urban areas is higher (2.7%) than in rural areas (-1.2%). 28.4% of the employed works in the industrial sector and 12.6% in the agricultural sector. Some important business areas are electronical appliances and palm oil producing. Service sector, for example tourism, has been promoted by the government to reduce economic dependency on exported goods. The number of households living below the national poverty line has been reduced to under 1% and almost every inhabitant uses improved drinking water sources and sanitation facilities. Even so, Malaysia still faces development challenges including renewable energy sources utilization, energy efficiency, and transportation by land (UNEP, 2019, p. 6).

According to UN report Malaysia does not have integrated solid waste management system and there is a poor understanding on waste composition, which makes developing waste management strategies harder. Some of the problems include lack of coordination between different agencies, legislations being restricted to only certain regions, waste is not always segregated properly at the source, capital and operating costs of managing solid waste are high, and recycling rates have not yet reached the set target (UNEP, 2019, p. 31-32).

2.2.2 Indonesia

53% of the Indonesian population lives in urban areas. Population growth rate in urban areas is higher (2.7%) than in rural areas (-0.4%). 46.4% of the total labour force works in service sector, 38.9% in agricultural sector and 13.2% in industrial sector. Business by natural resources, such as crude oil and metals, has important role and Indonesia is one of the biggest palm oil producers. Indonesia faces development challenges including environmental sustainability issues caused by fast urbanization and economic development, and ineffective land and natural resources management (UNEP, 2019, p. 5).

MSW management has major policies, programmes, strategy/plan, and projects launched, but they are not implemented well enough at all governmental levels. This results in MSW collection, resources recovery and recycling rate being relatively weak. Some of the problems include poor segregation rate of waste, half of the waste is collected by informal sector, waste incineration only exists in three locations, and waste handling and treatment facilities at municipal level are insufficient (UNEP, 2019, p. 30).

2.2.3 Viet Nam

33% of the population lives in urban areas and annual increase in urban area population is 3%. Agriculture sector employs 47% of total work force, and the next largest employers are manufacturing sector and service industry. Within the last quarter of century Viet Nam has improved its economical status from being one of the poorest in the world to have middle income status. In addition to agricultural products, manufacturing, information technology, and high-tech industries play important role in the economy. Viet Nam has increased its integration with international economics but development is constrained by lacking linkage with local firms (UNEP, 2019, p. 8-9).

Viet Nam has policies and programmes for MSW, but implementation mechanics needs improvement, for example development of green cities does not have specific regulations. Some of the problems include lack of waste-to-energy projects due to high cost, poor source segregation of waste, lack of financial resources to improve waste treatment and disposal systems, municipal solid waste is not officially defined, and there is a lack of awareness and cooperation to solve the waste related issues (UNEP, 2019, p. 35).

2.3 Waste management methods

ASEAN countries have differences in waste management technology profiles. Table 4 shows summary on waste management between waste generation and end disposal for Malaysia, Indonesia, and Viet Nam.

Table 4. Technology profile for MSW management in ASEAN countries (UNEP, 2019, p. 20)

Country	Source Segregation	Collection Rate (Urban)	Recycling Rate	Treatment/Disposal Technology
Malaysia	<50%	>70%	50%-60% (Metal, Paper, Plastic) <50% (Others)	Incineration, Sanitary Landfill, Open Dump
Indonesia	<50%	56%-75%	<50%	Composting, Incineration, Sanitary Landfill, Open Dump, Open Burning
Viet Nam	<50%	80%-82%	>90% (Metal) >70% (Plastic, E-waste) 50% (Paper) <50% (Others)	Composting, Open Dump

Source segregation means separating waste at the source of generation to different categories. One useful method would be to separate wet and dry waste, and dry waste could be further separated into hazardous waste and e-waste. Biodegradable wet waste could be deposited for composting, dry waste treatment would be easier, and recyclable materials would be more easily utilized. Lack of source segregation results in mixed waste, which is harder to treat, and waste segregation will occur in toxic and hazardous dump sites (Tyagi, 2016). According to Table 4, source segregation rate is less than 50% in Malaysia, Indonesia and Viet Nam. This leads to, for example, mixed waste containing lots of organic waste.

Table 4 shows that waste collection rate varies between different countries, and even within one country there can be big variation. Waste collection rate indicates how much of the generated waste in municipal areas is collected by waste collection services (Curea, 2016, p. 404-405). Effectiveness of waste collection service is highly dependent on the number of waste collection trucks in use and how much fees are collected from the community. In Asian cities and towns waste that is not collected is typically thrown into open dumps, which can cause environmental hazards into surrounding area (Khajuria, Yamamoto and Morioka, 2008, p. 644). Waste collection data from Viet Nam in 2010 shows that collection rate in rural areas (45%) can be significantly lower than in urban areas (85%) (Curea, 2016, p. 409). Outsourcing waste collection and disposal to private companies can bring problems. In Malaysia such companies have illegally collected commercial and industrial waste in addition to MSW to increase trips to landfill to get more money from the local authorities (Ng and Iacovidou, 2020). Phenomenon like this could make collected and disposed waste quality inconsistent.

Recycling rates can change from one country to another as is shown in Table 4, but overall recovery rates have room for improvement. In addition to recycling practiced by household, industrial, commercial, and institutional sources, recyclable materials are also collected by scavengers and waste collection truck workers (Bandar and Tempatan, 2013, p. 67). Informal sector collects most of the recyclables in Southeast Asia. Waste collectors collect used materials from households and streets and sell them to junk shops, which will then sell the junk to larger warehouse-type aggregators based on material type. Aggregators will then sell the materials to recyclers which will convert waste materials into raw materials, for example PET bottles into plastic pellets (Amirul, 2020). According to inquiry on reasons for recycling in Malaysia, the most important reasons are environmental protection, charity, and money incentive. In urban areas all three are highly valued and money incentive is a bit less valued than the others. In rural areas environmental protection and money incentive are highly valued equally, and charity is considered less important (Bandar and Tempatan, 2013, p. 98). Informal waste collection sector is facing challenges, as price of the recyclables has lowered and income from scavenging is not enough for covering increasing living costs, and improvements in waste collection system, for example using waste compactor trucks, will make collecting recyclables harder (Amirul, 2020).

Open dump waste disposal is common method among Southeast Asian countries, but Table 4 shows that otherwise there is difference in where waste that is not recycled ends at. In sanitary landfill emissions such as leachate and gases are collected and treated and waste is isolated from the environment, while open dump sites are uncontrolled. Lack of financing and awareness and long development times for new landfills are forces that are driving towards open dumping. Open burning is common method to reduce volumes of waste in dump sites (Hogland et al., 2005, p. 87-88). Composting is not yet common practice, although it is more suitable for treatment method than incineration because of the high content of organic matter. Some problems in composting include high operation and maintenance costs of composting facilities and the need to separate non-compostable materials (Dhokhikah and Trihadiningrum, 2012, p. 331). Incineration as a waste treatment option is effective way to get rid of the waste, but to be cost effective and efficient it requires waste pre-sorting. If waste sorting is limited, more pollution from incineration is expected to happen. Southeast Asian public opinion is concerned over toxic emissions, ash disposal, and health concerns, which are limiting incineration development. China shows progress in waste-to-energy trends that could be useable for wet Southeast Asian waste too, such as using CFB boilers or feeding mixture of sludge and food waste into anaerobic digester to produce biogas. For these emerging waste-to-energy technologies to be efficient, waste-sorting issues in Southeast Asia must be solved first (Weatherby, 2019).

2.4 Southeast Asian waste characteristics

Southeast Asian waste is typically highly heterogeneous and wet. Table 5 shows waste composition in Malaysia, Indonesia, and Vietnam, with Finland added as European comparison. Data in the table is inconsistent because some waste stream data is missing, such as construction waste (UNEP, 2019, p. 17). If a city has a lot of ongoing construction projects and demolition and construction waste are not collected separately, MSW is expected to have high contents of inert materials (Mutz et al., 2017, p. 16). Recycling rates will also affect the quality of MSW. High amounts of food and organic waste and heavy rainfalls hitting open storage and transport makes the waste arriving at landfills have high moisture content (Hogland et al., 2005, p. 88).

Table 5. Composition of MSW in the studied countries (UNEP, 2019, p. 12-13; KIVO, 2020)

Country	Food/Organic Waste	Paper	Plastic	Metal	Glass	Textile	Rubber	Others
Malaysia	45%	8.2%	13.2%		3.3%			27.3%
Indonesia	60%	9%	14%	4.3%	1.7%	3.5%	5.5%	2.4%
Viet Nam	55%	5%	10%	5%	3%		4%	
Finland	33.1%	9.0%	17.0%	2.4%	2.5%	6.3%		29.7%

Figure 6 shows how much variance can be between different waste generation sources. For example, higher amounts of industrial waste would significantly increase plastic contents or lesser amount of household waste would decrease the amount of diapers in landfill. Figure 5 showed that overall waste generated by industrial sector is much lower than waste generated by household sector, but different regulations and levels of industrialization in different zones could make waste quality variable.

Figure 6. Malaysian waste composition by different waste generation sources (Bandar and Tempatan, 2013, p. 69, 80-82)

Figure 7 shows an example of how waste quality can change within one country between different regions. More detailed table on average Malaysian waste quality is available in Appendix A. Sabah has much lower recycling rate than other regions (Bandar and Tempatan, 2013, p. 70), which might for example explain higher contents of plastic and metal. Sabah and Sarawak are less urbanized than rest of the Malaysia and waste generation per capita is smaller (Bandar and Tempatan, 2013, p. 44-45, 49). Regions can have differences between the amount of waste generated by different sectors. In Peninsular Malaysia households generate 0.80 kg/capita/day (~65%), industrial sector 0.09 kg/capita/day (~7%), commercial and institutions sector 0.34 kg/capita/day (~28%), with total of 1.23 kg/capita/day. In Sabah and Sarawak households generate 0.60 kg/capita/day (~65%), industrial sector 0,03 kg/capita/day (~3%), commercial and institutions sector 0.28 kg/capita/day (~30%), with total of 0.92 kg/capita/day. Variables such as these can make waste quality change within one country much from the average quality.

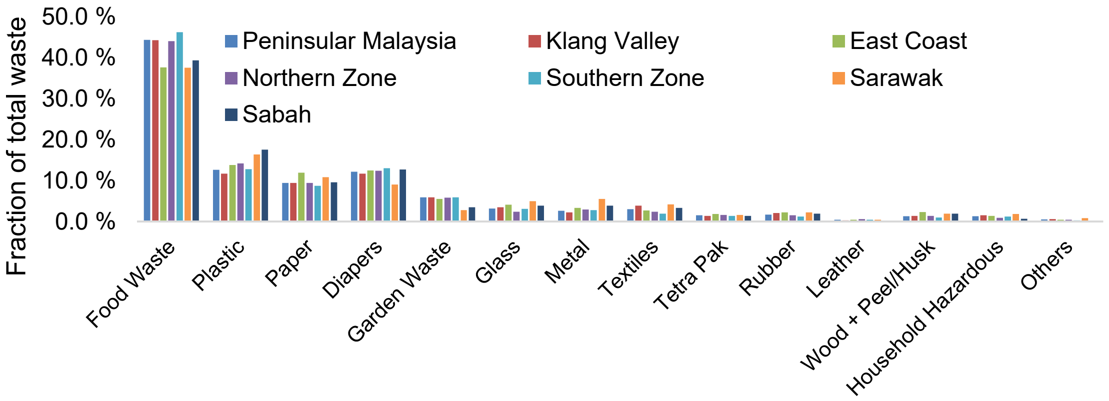

Figure 7. Variance of generated waste composition in different Malaysian regions (Bandar and Tempatan, 2013, p. 74-77)

According to a detailed waste component table (Table 31) showing amounts of waste generated, discarded and disposed by Malaysian households, Table 6 has summary of different components generated and disposed in Malaysia. Waste generated includes materials in the waste management system before waste treatment such as recovery or combustion. As discarded is solid waste at waste collection points. As disposed includes waste delivered to solid waste management facilities such as sanitary landfills from waste collection points (Bandar and Tempatan, 2013, p. 9). When comparing the Malaysian waste quality to the waste quality in United States (shown in Figure 2) to show comparison to western waste quality, percentage of organics is much higher in Malaysia (in US ~35%). This increases Malaysian waste moisture and decreases heating value, because according to Table 32 food waste has 82% moisture content. Amount of metals is lower (in US ~9.4%) and so is amount of paper (in US ~25%). Amount of different materials changes during waste management from generation to disposal. For example, amount of food waste reduces because of rapid degradation of the waste over time and release of moisture as leachate, newspaper is recycled and amount of rocks and dirt increases because of waste collected from areas where waste is placed on the ground instead of bins (Bandar and Tempatan, 2013, p. 71).

Table 6. Summry of waste disposed by Malaysian households (Bandar and Tempatan, 2013, p. 70)

Material	As generated	As disposed
Organics	51.9 %	53.0 %
Paper	8.5 %	6.3 %
Plastics	13.2 %	11.9 %
Glass	3.3 %	3.0 %
Metals	2.8 %	1.6 %
Household Hazardous	1.3 %	1.5 %
Others	19.1 %	22.7 %

Table 7 shows ultimate analysis results for Malaysian waste. Moisture content is high compared to western waste. A study on municipal solid waste in China (Zhou et al., 2014) shows that research on MSW composition has number of problems. Many factors affect the composition that is already complex, there is great variance between different research sources, MSW composition varies inside the whole country in different regions and composition varies in different times of year, for example, harvest seasons for fruits and vegetables will increase moisture content (Haukohl, Rand and Marxen, 1999, p. 11).

Table 7. Average ultimate and proximate analysis results for wet Malaysian waste (Bandar and Tempatan, 2013, p. 86, 88)

	As Discarded	As Disposed
Moisture content	57.34 %	59.45 %
Carbon content	21.57 %	17.36 %
Sulphur content	0.05 %	3.35 %
Hydrogen content	4.29 %	5.89 %
Nitrogen content	1.37 %	1.05 %
Oxygen content	7.47 %	5.89 %
Organic chlorine content	0.06 %	0.04 %
Ash content	7.85 %	6.96 %
HHV_{dry}	21 671 kJ/kg	21 185 kJ/kg
LHV_{wet}	6 950 kJ/kg	6 325 kJ/kg

Worrell and Vesilind (2012, p. 46) suggest that moisture content of refuse is typically about 20% and rain can increase moisture content to 40%. Niessen (2015, p. 138) suggests that typical municipal refuse fuel has higher heating value of dry basis 14 393 kJ/kg and lower heating value of wet basis 9 142 kJ/kg, with moisture content being 28.16% and ash content 20.82%. Comparing to these reference values Malaysian municipal waste must be treated so that moisture content decreases, increasing lower heating value and decreasing amount of energy required for latent heat of water vaporization (Worrell and Vesilind, 2012, p. 271).

3. WASTE PRE-TREATMENT FOR COMBUSTION

This chapter studies waste fuel pre-treatment process. Input data is affected by MSW matters studied in previous chapter, and pre-treatment process will have impact on the CFB boiler performance, as is shown in Figure 8.

Figure 8. Waste-to-energy phase studied in this chapter: pre-treatment

3.1 Demands for pre-treatment

Pre-treating waste makes its quality better for thermal treatment. Some main purposes of pre-treatment is to decrease high-moisture and non-combustible content to increase heating value for better energy recovery efficiency, to reduce heavy metals in the fly ash and to make quality of flue gases better (Di Lonardo, Lombardi and Gavasci, 2012, p. 355). Pre-treatment system combining mechanical and biological processes is called MBT. Purpose of MBT is to minimize environmental impact by reducing residues to be landfilled and by adding value to waste side-streams. Main outputs of typical MBT plant are refuse derived fuel (RDF), product of biological treatment called stabilized organic waste (SOW), ferrous and nonferrous metals, and scraps and residues, which are taken into landfills (Di Lonardo, Lombardi and Gavasci, 2012, p. 353-354). Refuse could be defined as solid wastes produced by communities, out of which construction and demolition debris, water and wastewater treatment plant sludges, bulky items, and green waste collected from streets and parks are not included (Worrell and Vesilind, 2012, p. 30-31). In RDF pre-treatment process rejection rate is typically 20-35% (Niessen, 2015, p. 654). Niessen (2015, p. 347) gives example on how pre-treatment changes the characteristics of refuse waste compared to direct mass burn: yield decreases from 100% to 70-83%, amount of landfill reject increases from 0% to 17-30%, ash content decreases from 23.6% to 8.9-11.7%, and heating value increases from 11 192 kJ/kg to 13 117-13 556 kJ/kg. Table 8 shows examples of RDF quality in different countries. Different qualities can be explained by variance in input MSW quality, different types of mechanical units used in processing plants, and varying sampling and analytical methodologies (Di Lonardo, Lombardi and Gavasci, 2012, p. 357). Moisture content is typically lower and lower calorific value is typically higher when comparing with Malaysian waste quality in Table 7. These are some of the indications, that Malaysian waste requires pre-treatment to be used as RDF.

Table 8. Characteristics of RDF in different countries (Di Lonardo, Lombardi and Gavasci, 2012, p. 358)

Parameter	Units	Italy	Taiwan	Brazil	Thailand	Spain
Particle size		>80 mm	25-100 mm	>100 mm	>70 mm	>40 mm
Moisture content	%	18.31	47.55	40.28	34.4	11.5
Ash content	%		11.75	9.96		11.8
Chlorine content	%	0.18	0.16	0.23	0.7	0.58
Higher calorific value	kJ/kg				24 700	20 800
Lower calorific value	kJ/kg	17 139	8 772.6	13 790.5		19 401

3.2 Waste fuel terminology

Difference between commonly used terms refuse derived fuel (RDF) and solid recovered fuel (SRF) is that SRF is produced with quality assurance and quality control that complies with CEN/TC 343 standard and achieves CEN certification. That does not always mean that SRF is better quality than RDF, as certification takes a stand only on quality management (Velis et al., 2010, p. 982-983). In Europe different countries have different quality standards for RDF. Table 35 shows summary of different standard quality limit values for SRF, in which the definition of refuse fuel quality varies a lot and quality standards are not fully defined. It however gives some idea on what levels chemical composition and heating value should be.

3.3 Pretreatment possibilities

Results from a research on MBT plants suggests that data available comes from plants with different configurations and applications, so comparing them is difficult (Velis et al., 2010, p. 1040). Also, there is differences in the order of mechanical and biological treatments in the process, which are shown in Figure 9. This thesis focuses on the BMT process where biological treatment comes before mechanical treatment. In MBT process organic part of the MSW is separated and the biogas produced by anaerobic digestion can be used for further energy recovery, and compost-like output from maturation can be used as fertilizer (Defra 2013, p. 10-14).

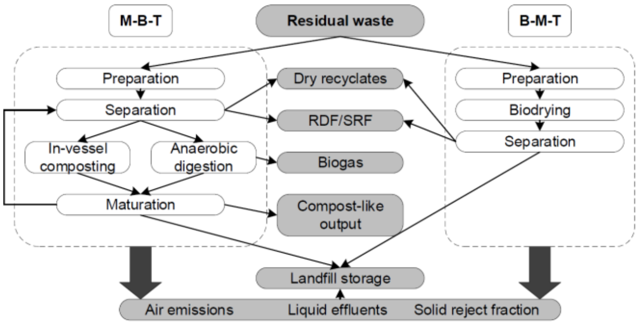

Figure 9. Potential flowsheet options for MBT plants (Velis et al., 2010, p. 986)

3.4 Biological-mechanical treatment process

3.4.1 Biodrying

When aerobic decomposition starts in biological material, heat is released. Heat will dry and biostabilize the waste partially and is supported by controlled air ventilation (Velis et al., 2010, p. 985). Mass loss is significant due to water and volatile solids loss and can be more than 25%. LHV can increase during biodrying by 33% (Rada, Ragazzi and Panaitescu, 2009, p. 117). Theoretically 5.5 kg of water evaporation requires energy from degration of 1 kg of volatile solids. Research shows experimental values of water loss to volatile solids loss ratio being 85%-110% of the theoretical value. Therefore ~15% of the mass loss during biodrying is due to organic matter volatile solids degration (Shao et al., 2012, p. 1276-1277). Reduction of moisture benefits further process units. Amount of lumpy material sticking together is reduced, making separation more efficient (Velis et al., 2010, p. 1039-1040).

3.4.2 Pre-treatment process flowchart

Figure 10 shows example of typical BMT process flowchart with equipment according to generalized concept shown in Figure 9. This is only one of many different variations. Biodrying is located early in the process, and rest of the process consists units treating refuse stream mechanically. RDF fuel could be considered as primary output and side streams or rejects as secondary outputs.

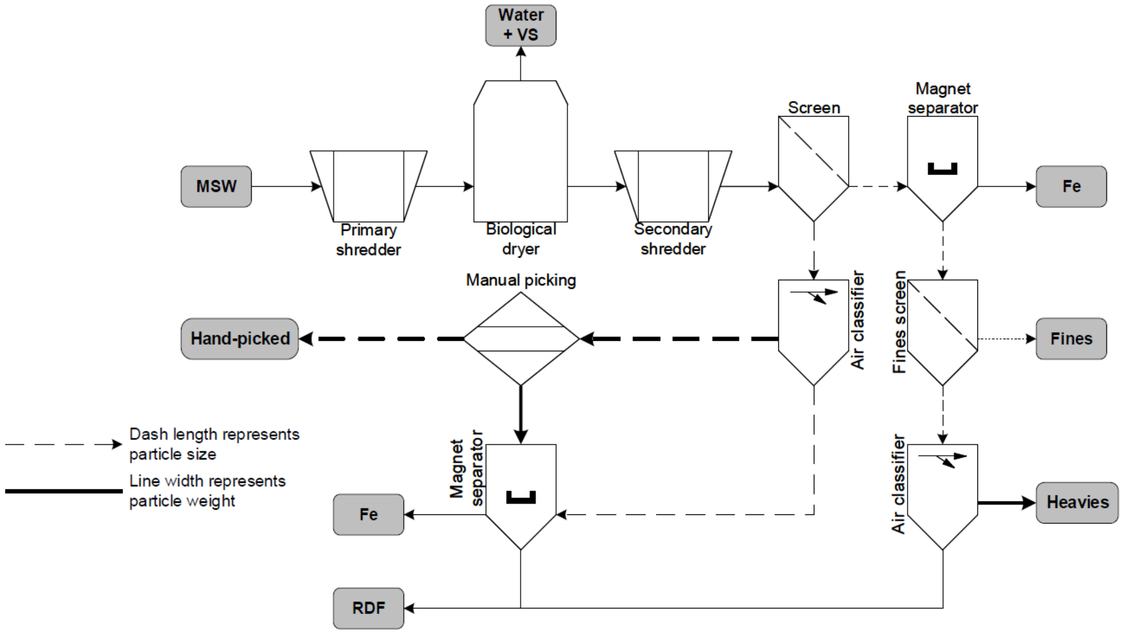

Figure 10. Typical flowchart of BMT process

3.5 Mechanical processes

At the beginning of a pre-treatment system waste is usually picked from the waste storage by an overhead crane and dropped into a feed chute or a conveyor belt. Rubber-belted conveyors, live bottom feeders, and pneumatic conveyors are used to move refuse between different pre-treatment units, while vibratory feeders, screw feeders, and drag chains are used to feeding refuse to load-sensitive devices (Worrell and Vesilind, 2012, p. 162-163). Some typical mechanical equipment categories in pre-treatment system are size reduction or comminution and separation of materials (Worrell and Vesilind, 2012, p. 171, 208). Table 9 lists currently used mechanical equipment in MBT plants, including equipment for both systems in Figure 9. Typical equipment for pre-treatment system showed in Figure 10 will be further discussed. Table 10 shows summary of what components are affected by different separation technologies.

Table 9. Currently used mechanical equipment in MBT plants (Velis et al., 2010, p.988)

Pretreatment Comminution	Separation Classification Homogenization	Compaction	Wet processing
• Bag identification crusher • Bag splitter • Cascade/ball mill • Hammermill • Hydro-pulper • Pulper • Pulverizer • Rotary shear (shear shredder) • Washer	• Air knife • Air-drum separator • Ballistic separator • Cross-wise air classifier • Cyclone • Disk screen • Drum screen (trommel, drum sieve) • Eddy-current separator • Electromagnet • Heavy solids trap • Hydrocyclone • Image detection • Inert separator (stoner) • Kinetic streamer • Magnetic drum • Manual picking line • NIR separator • Overband magnet • Rotating drum mixer • Vibrating screen • Zig-zag air classifier	• Baler (baling press) • Pelletizer	• Flotation tank • Sand filter • Sedimentation • Settling tank • Sludge centrifuge

Table 10. Common refuse components separation technologies (Niessen, 2015, p. 346)

Method	Component affected
Visual	Aluminum cans Corrugated paper Newsprint Glass containers (by color) Plastic containers (by type)
Eddy current magnet	Aluminum
Magnetic separation (belt and drum)	Ferrous metal
Air classification	Lights (paper, cardboard) Heavies (glass, metal, stone, very wet)
Photodetection of color	Glass (green, brown, flint)
X-ray emission by chlorine atoms	Plastic (unchlorinated from PVC)
Trommels and disk screens	Separate by particle size to reject glass and sand and enrich fuel value. Also, separate over-sized for recycling and size reduction of fuel particles

3.5.1 Shredder

Municipal waste has different materials physically connected to each other and size differences can be huge. According to Worrell and Vesilind (2012, p. 171-173) shredding is size reduction method whose main purpose is used to help separating materials and making waste stream more uniform. There are dozens of different size-reduction devices, but Worrell and Vesilind (2012, p. 173-176) lists hammermill (Figure 11), shear shredder, and flail mill as typical in MSW handling.

In the pre-treatment system shown in Figure 10 primary shredder could also be called pre-shredder. Its main purpose is to open plastic bags of the incoming waste stream. Minimal size reduction occurs, and glasses are likely shattered (Worrell and Vesilind, 2012, p. 176). Primary shredding can be also used to homogenize particle size distribution for next process units by reducing maximum particle size to for example 200 mm (Vecoplan, 2016, p. 2). A flail mill is commonly used as bag opener. It is similar in design to hammermill (shown in Figure 11), but instead of closely packed hammers it has thin 1-2.5 cm thick flail arms that are spaced farther apart. This allows larger input particles to pass without size reduction and better shredding of paper and cardboard is achieved than with hammermill (Velis et al., 2010, p. 999).

Secondary shredding is used to produce appropriate particle size distribution after biodrying (Velis et al., 2010, p. 993). Most important properties affecting performance of shredders are ductility, moisture content, temperature, bulk density, and shear strength of waste material (Velis et al. 2010, p. 996). Hammermill shredder and rotary shear are the most used shredder types (Velis et al., 2010, p. 995, 998). In hammermill shredder (Figure 11) central high-speed rotor spins hammers, which will hit the feed material against breaker plate. Discharge grate at the bottom will pass particles that are smaller than grate opening (Worrell and Vesilind, 2012, p. 173-174). Size reduction is due to impaction and tearing motion. Some important parameters affecting particle size distribution are residence time of particle remaining in the shredder and how fully hammermill is loaded. Hammermill shredder can be either horizontal or vertical (Velis et al., 2010, p. 996-997). In rotary shear (Figure 12) knives or hooks rotate slowly with high torque and material size is reduced by shearing motion. Usually rotary shears consist of two or four parallel counterrotating shafts and overlapping cutting tools act similarly to scissors. Distance of the shafts can be adjusted to change size of the passing particles (Velis et al., 2010, p. 998). According to Velis et al. (2010, p. 1039) recently rotary shears have been preferred over hammermills to avoid overpulverisation. Shear shredders produce more uniform particle size distribution and smaller non-combustible particles will less contaminate combustable materials, for example small shards of glass sticking into paper (Velis et al., 2010, p. 998). Hammermill shredder spreads particle size distribution of materials compared to raw municipal waste. For brittle materials such as sand, rocks, and glass sorting becomes easier but the risk of contamination of other materials exists, which would lead to higher ash concentration in RDF fuel (Velis et al., 2010, p. 997). Some limitations of rotary shears are coarsely shredded output and need to remove potentially damaging large and durable items before shredding (Velis et al., 2010, p. 999).

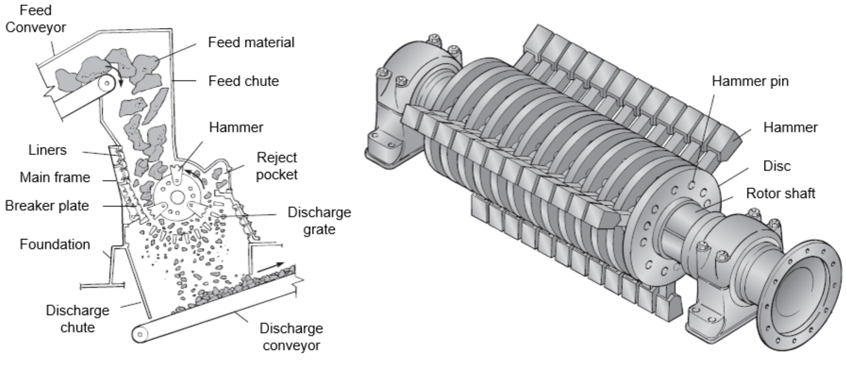

Figure 11. Horizontal hammermill shredder (Worrell and Vesilind, 2012, p. 174)

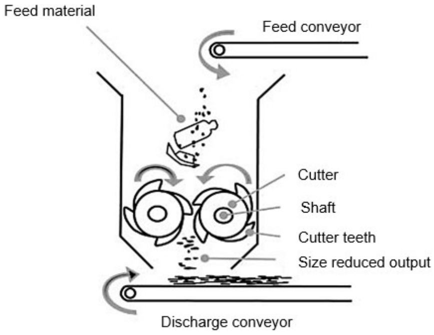

Figure 12. Rotary shear (Velis et al., 2010, p. 996)

Figure 13 shows particle size distribution of different materials in household waste and Figure 14 shows particle size distribution after hammermill shredding. Different materials have different variations in size. This makes possible to further separate materials in size-based separation equipment. Validation of hammermill modelling has shown unsatisfactory results and modelling of rotary shears is thought to be impossible because of large number of variables affecting the results (Velis et al., 2010, p. 997-999).

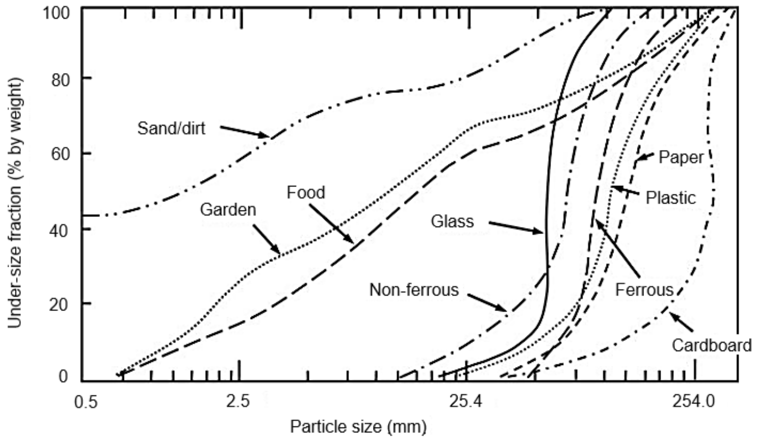

Figure 13. Particle size distribution of raw mixed household waste (Velis et al., 2010, p. 994)

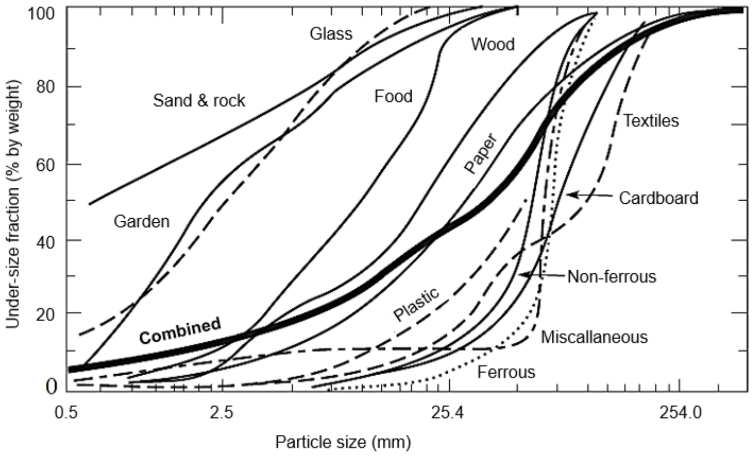

Figure 14. Particle size distribution after horizontal hammermill shredder (Worrell and Vesilind, 2012, p.178)

Different materials react differently to the mechanical shredding. For example, newspaper is greatly affected by shredding, but not by crushing. Also, different materials might take more time for fractures to build up and eventually break the material, thus applying force more slowly could be more efficient. Then again faster shredding rates results in finer particle sizes but requires more energy. Energy usage is also increased as feed rate and moisture content increases. Lower moisture content results in smaller particle sizes after shredding. Waste shredding requires optimization to get wanted results with efficient energy usage (Worrell and Vesilind, 2012, p. 182-183).

Shredding hammers are prone to wear and tear. The most damage happens to the side of area of impact and is caused more by abrasive materials than impact with hard objects. This results in poorer size reducing performance which in turn affects the next phases of pre-treatment. Slowing the speed of shredding or adding abrasion-resistant alloys to the hammer can reduce the wearing. (Worrell and Vesilind, 2012, p. 187)

According to Worrell and Vesilind (2012, p. 187) Some typical health and safety problems in shredding include high noise level up to 100 dBA, dust that can have unhealthy effects on human by entering through respiratory system or cause explosions ignited by spark when dust concentration and oxygen content is high, and air around shredder contains 20 times more bacteria than in ambient air.

3.5.2 Screening

Screening is used to separate different sized particles by allowing smaller sized particles to pass through specific size apertures. Primary purpose of screening is removing glass that has been shattered into fine particles in shredding. Passing materials are called extract and those that are too large to pass are called reject. Some fraction of the undersized material will always leave with reject flow. It is also possible for oversized material to enter through apertures if material is flexible. Screens are typically operated so that 85% to 95% of extract is recovered and increase of recovery rate would require decreasing the flow rate (Worrell and Vesilind, 2012, p. 213-215). Based on operational experience it is suggested that prescreening 100-300 mm coarse material is beneficial in preventing agglomeration of smaller particles into bigger ones, which would lead to more undersized particles leaving with oversized (Velis et al., 2010, p. 1039).

There are three common screen types in MSW processing: trommel screen (Figure 15), disc screen, and vibrating screen. Vibrating screen is limited cleaner feeds because it is prone to being plugged by rags, paper, and other objects. Trommel is the most popular one in MSW handling because it is resistant to clogging, although some of the material will remain attached to the walls but will eventually drop. Rotating speed of trommel drum is 10-15 rpm. As the drum speed increases, waste motion inside the drum will start to change from cascading to cataracting and parabolic flight path gets longer, making particle separation more efficient. When material rotates around and returns to drum bottom, the side facing drum apertures changes and allows smaller particles go through as extract. Trommel speed should not be so fast that the waste material clings to walls because of centrifuging (Worrell and Vesilind, 2012, p. 215). Trommel drum is aligned so that reject flows out. Trommel slope angle will affect the time that waste stays inside the drum, and according to Worrell and Vesilind optimal time is 30-60 seconds and materials should make 5-6 revolutions inside the drum (Worrell and Vesilind, 2012, p. 221).

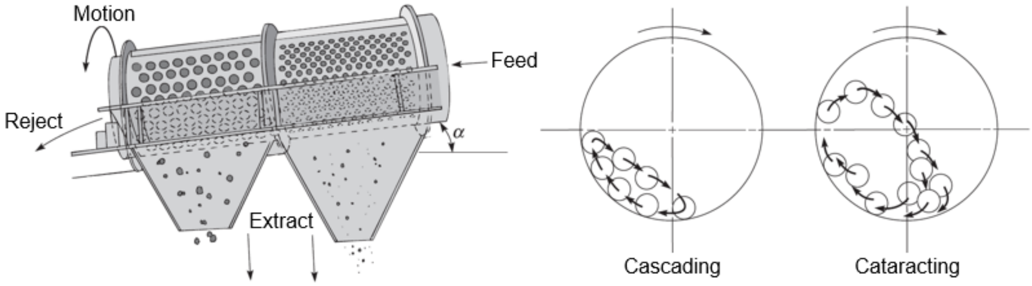

Figure 15. Trommel screen (Worrell and Vesilind, 2012, p. 216)

Disc screen (Figure 16) has rotating discs that carry waste above them and fitting waste goes between discs as extract. Compared to trommel screens disc screen has the advantage that for example long strips of thin paper would enter between discs more easily than through round apertures. In horizontal or aligned vibrating screen apertures get easily blocked by waste such as cloths and papers and is limited to sorting cleaner waste, such as glass-only particles by size. (Worrell and Vesilind, 2012, p. 221)

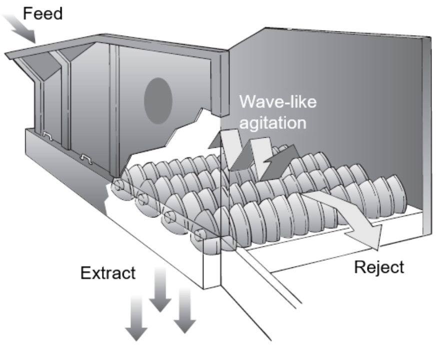

Figure 16. Disc screen (Worrell and Vesilind, 2012, p. 222)

3.5.3 Air classifier

Purpose of air classifier (Figure 17) is to separate different materials based on their density using air. Denser materials are mostly inorganic and less dense organic. When air flow increases, more heavier particles are affected. For air classification to be more efficient, different materials that have formed clumps can be separated first with vibration. Lighter particles are carried with air as extract and are separated from air stream in cyclone and heavier particles are separated as reject (Worrell and Vesilind 2012, p. 230-233). Separating principle of a cyclone is so that mixture of air and solids enters the cyclone chamber tangentially and solids with greater mass move towards the outer edge of the rotating air vortex, drop speed as they touch the wall of the cyclone and drop down from the cyclone because of gravity, and air flows upwards out of central tube (Worrell and Vesilind 2012, p. 238).

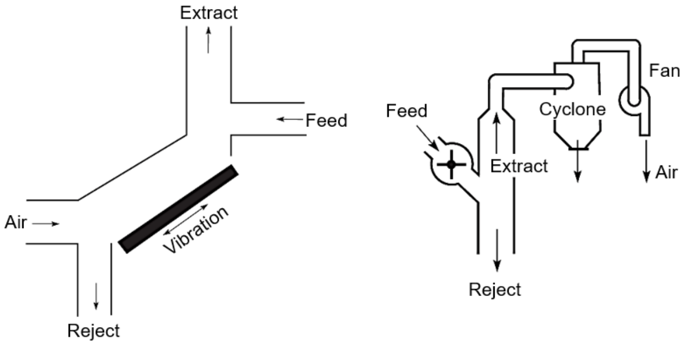

Figure 17 Air classifier (Worrell and Vesilind, 2012, p. 231)

Worrell and Vesilind (2012, p. 226-228) explain that after particles accelerate in fluids, they attain terminal velocity, in which drag force is equal to gravity force equaling net force to zero and making velocity constant. Separation of different materials based on density rather than terminal velocity can be attained if particles are constantly accelerated and decelerated and no such situation can happen where accelerating material particle catches up to other particle moving with terminal velocity. There are different solutions, for example, zig-zag classifier (Figure 18) has turbulent air flow because of corners in the duct, which helps to separate chunks of material stuck together, allowing materials to be sorted based on their density. Heavy particles will slide and drop from edge to edge, be hit with upstream air and be further separated, until the densest materials will eventually leave as reject (Worrell and Vesilind, 2012, p. 236-238). Separation quality of zig-zag classifier gets worse when input has moisture content mainly because of increasing paper density and agglomeration (Velis et al., 2010, p. 1026).

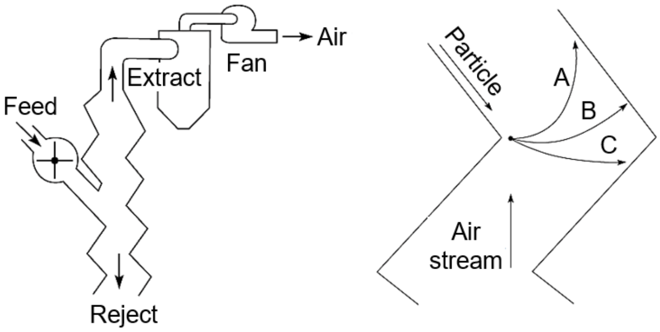

Figure 18. Zig-zag classifier (Worrell and Vesilind, 2012, p. 235-236)

Table 11 shows typical extract results from air classifier with shredded refuse input that has 15% moisture and 8.3% ash content. Worrell and Vesilind suggests that when moisture content doubles there will be drop of 5% in recovery. Also, nominal particle size of materials (paper and cardboard excluded) affects recovery rate, for example with smaller nominal particle size there are more smaller plastic particles that are more likely to leave with air flow as extract (Worrell and Vesilind, 2012, p. 235). Table 12 show air classifier data from several studies. Based on that results air classifiers show great variance in performance and one generic rejection model cannot be applied to all air classifiers.

Table 11. Typical results from air classification (Worrell and Vesilind, 2012, p. 234)

	Shredded refuse	**Extract from air classifier**
Non-combustible	**Percent by weight**	
Rocks and dirt	0.3 %	0 %
Ferrous metal	7.8 %	0.08 %
Nonferrous metal	1.0 %	0.05 %
Glass and other	7.8 %	1.82 %
Total	**16.9 %**	**1.95 %**
Combustible	**Percent by weight**	
Paper	52.2 %	78.8 %
Wet garbage	11.8 %	0.1 %
Yard and garden	6.7 %	8.6 %
Other	12.2 %	10.6 %
Total	**82.9 %**	**98.1 %**

Table 12. Performance of air classifiers from several studies (Velis et al. 2010, p. 1031)

	Low-gravity product		**High-gravity product**	
	Recovery %	**Purity %**	**Recovery %**	**Purity %**
Combustibles		60-99		
Paper	<1-99			
Paper and cardboard	66.6	73.7		27.1
Plastics	85.2/1-65	11.8		1.5
Paper and plastics	85-99	55-80		
Ferrous metals	2-50	0.1-1/1.1	98.0	38.0
Nonferrous metals	45-65	0.2-1/0.1	85-99	
Fines	80-99	15-30		
Ash	45-85	10-35		
Wood	13.1	1.6		7.8
Textiles	32.2	11.6		17.8
Glass		0	100.0	0.7
Vegetable matter		0.1	90	0.5

3.5.4 Magnets

To separate ferrous materials, such as steels, magnets are needed. Ferrous materials captured by a magnet are separated by doctoring blades or are moved out of influence of the magnet by conveyor belt and are dropped off (Figure 19). The amount of ferrous removal is affected by the distance of the magnet to the refuse and by the speed of the conveyor, as with slower speeds magnet has more time to pull ferrous material out. Also, depth of the burden above conveyer belt has effect, as ferrous content at the bottom requires more force to be pulled through all the materials above (Worrell and Vesilind, 2012, p. 242-243). Worrell and Vesilind (2012, p. 244-245) suggest that conveyor belt should have as uniform particle thickness as possible and belt length before the magnet should be as short as possible to prevent particles with different densities piling on top of each other. Increasing the height of the magnet above belt and conveyor belt bury depth decrease recovery percentage, and maximum recovery percentage is about 87% (Worrell and Vesilind, 2012, p. 244). Velis et al. (2010, p. 1038) suggests ferrous metals recovery rate to be up to 95%. Batteries bring challenge to material management because of chemical pollution. About 90% of batteries are magnetic or slightly magnetic, which allows most of them to be removed with magnet separator (Velis et al., 2010, p. 1038).

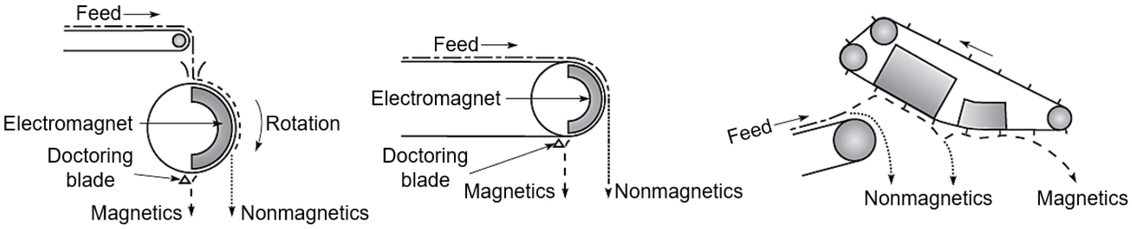

Figure 19. Typical magnet separators (Worrell and Vesilind, 2012, p. 243)

3.5.5 Eddy current separators

Purpose of eddy current separator is to separate nonferrous metals from the feed of which ferrous metals are already removed. Eddy current separators are typically inclined tables where electrical fields are generated with induction motor. Eddy current is produced by magnetic induction in material changing over time. When refuse material goes down the inclined table, nonferrous metals having ability to conduct electrical current are affected by electrical field and pushed away by electromagnetic forces (Worrell and Vesilind, 2012, p. 245-246). Out of the nonferrous metals aluminum is the most important and aluminum usually is combined with other materials (Velis et al., 2010, p. 1038). Table 13 shows extract capacity of ECS. In the example there is optional third category of sorting called middlings. This part consists of mixture of nonferrous content and nonmetallics which do not fly as far as feed material with greater nonferrous purity (Sommer & Kenny, 1978, p. 11). Example of this type of ECS shown in Figure 20. According to

Velis et. al. (2010, p. 61) aluminum yields can be up to 90% with purity of 60-70%, because other materials are removed also alongside. This is contradicting with Table 13, because according to it Aluminum yield is 49%. This can be explained by differences in how waste is pre-treated before ECS, for example how well are the particles shredded and separated (Sommer & Kenny, 1978, p. 3).

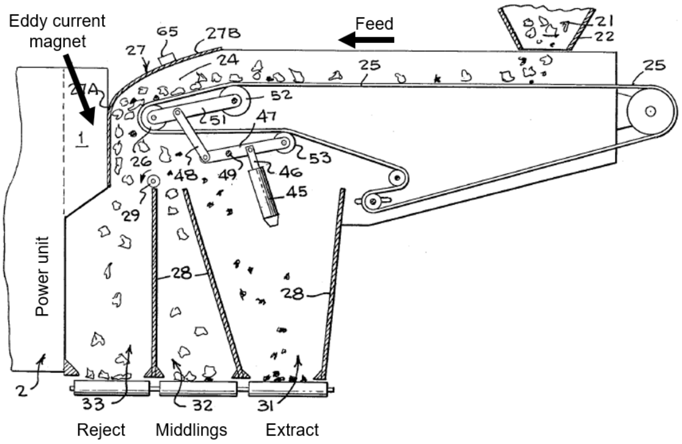

Figure 20. ECS with three output streams (Sommer & Kenny, 1978, p. 3)

Table 13. Separation of different materials by ECS (Worrell and Vesilind, 2012, p. 246)

		Percent by weight			
	Weight (kg)	**Aluminum**	**Aluminum Foil**	**Other inorganics**	**Organics**
Extract	14.5	88.8	0.2	5.5	5.5
Middlings	7.4	60.2	2.1	11.6	25.1
Reject	85.7	7.2	7	3	86.6
Feed	107.5	21.9	2.6	3.9	71.5

3.5.6 Manual sorting

In manual sorting corrugated cardboard, PET plastic bottles, HDPE plastic and aluminum are hand-picked from refuse stream (Worrell and Vesilind, 2012, p. 250). Maximum capacity of pickers is 454 kg/h/person (Worrell and Vesilind, 2012, p. 213).

3.5.7 Optical sorting

In Near-infrared detection (NIR) devices spectrometer identifies molecular structure of the material based on material specific spectra, and fast blast of air stream separates selected materials. Common application in MBT plants is removing plastics containing chlorine, for example PVC. Recovery percentages can be up to 90%. (Velis et al., 2010, p. 1037).

4. EFFECTS OF WASTE PARTICLES ON CFB BOILER

This chapter studies how pre-treated MSW derived waste fuel affects CFB boiler. Input data is affected by matters studied in previous chapters, as is shown in Figure 21.

Figure 21. Waste-to-energy phase studied in this chapter: CFB boiler

4.1 Minimum demands for fuel

After pre-treatment waste fuel enters boiler. Circulating fluidized bed (CFB) boiler (Figure 23) is a steam generating device, where heat is absorbed by heat transferring fluids through surfaces, which are in contact with flue gases generated from burning incoming fuel and bed material circulating in the boiler. Fuel is fed into lower part of the furnace (Basu, 2015, p. 4-7). When waste fuel is incinerated, water contained in the fuel is vapored and leaves with flue gas. Energy content of the water vapor is difference between upper and lower calorific values of the fuel. Waste can be theoretically burned without auxiliary fuel when water content is below 50%, ash content is below 60% and combustible content is over 25% (Haukohl, Rand and Marxen, 1999, p. 11-12). Figure 22 shows Tanner triangle, which is visual representation of these theoretical values. According to Table 7, Malaysian waste has moisture content of ~59% and ash content of ~7%. Tanner triangle shows that untreated Malaysian waste would require auxiliary fuel to be burned.

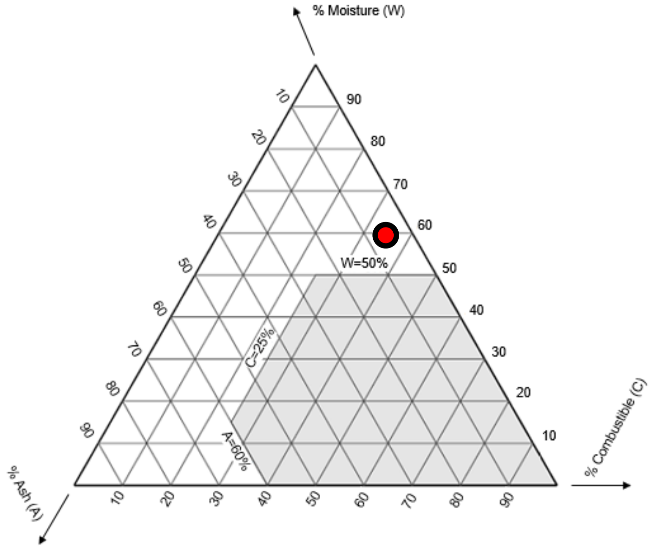

Figure 22. Malaysian waste characteristics shown in Tanner triangle (Haukohl, Rand and Marxen, 1999, p. 12)

4.2 Possible waste combustion issues in CFB boiler

Table 14 shows how different challenges with different fuels will affect boiler design. The higher the number, the more demanding is the challenge and dedicated solution is probably required (Bolhàr-Nordenkampf et al., 2015, p. 170). Risk for corrosion and erosion and increase in bottom ash flow with waste fuel is clearly higher than with other fuel types. Table 15 shows what kind of harmful effects can different SRF properties cause to CFB boiler. Figure 23 shows visual combination of both tables on typical CFB layout.

Table 14 Comparison of CFB issues in different fuel types (Bolhàr-Nordenkampf et al., 2015, p. 170)

Challenge field	Fossil	Wood	Agro	Recycled	SRF
High temp corrosion	0	0...1	1	1	2
Mid temp corrosion	0	0	0	2	2
Cold end corrosion	0	0...1	1	2	2
Superheater fouling	0...2	0...1	2	1	2
Cold end cleaning	0	0	1	1	1
Bed agglomeration	0...2	0...1	2	1	1
Loop agglomeration	0...2	0...1	2	0	1
High bottom ash/debris flow	0...2	0...1	1	1...2	2
High fly ash flow	0...2	0	0	1	1
Back pass erosion	1	0	0	1	2
Emissions	1	1	1	1	1

Table 15. Harmful effects of different SRF properties on CFB boiler (Iacovidou et al., 2018, p. 540)

SRF properties	Harmful effects
1. Moisture content	Lower LHV, ignition and incomplete combustion problems
2. Bulk density	Feeding problems
3. Particle size	Agglomeration of SRF particles
4. Ash content	Particulates emissions, additional ash disposal costs
5. Cl content	Corrosion of heat transfer surfaces
6. Alkali and alkaline content	Slagging, fouling and corrosion
7. Silica content	Ash deposition on heat transfer tubes
8. Potentially toxic elements (e.g. Sb, As, Pb, Cr, Co, Mn, Cu, Ni, V)	Bottom and fly ash utilization and disposal issues, increased heavy metal emissions

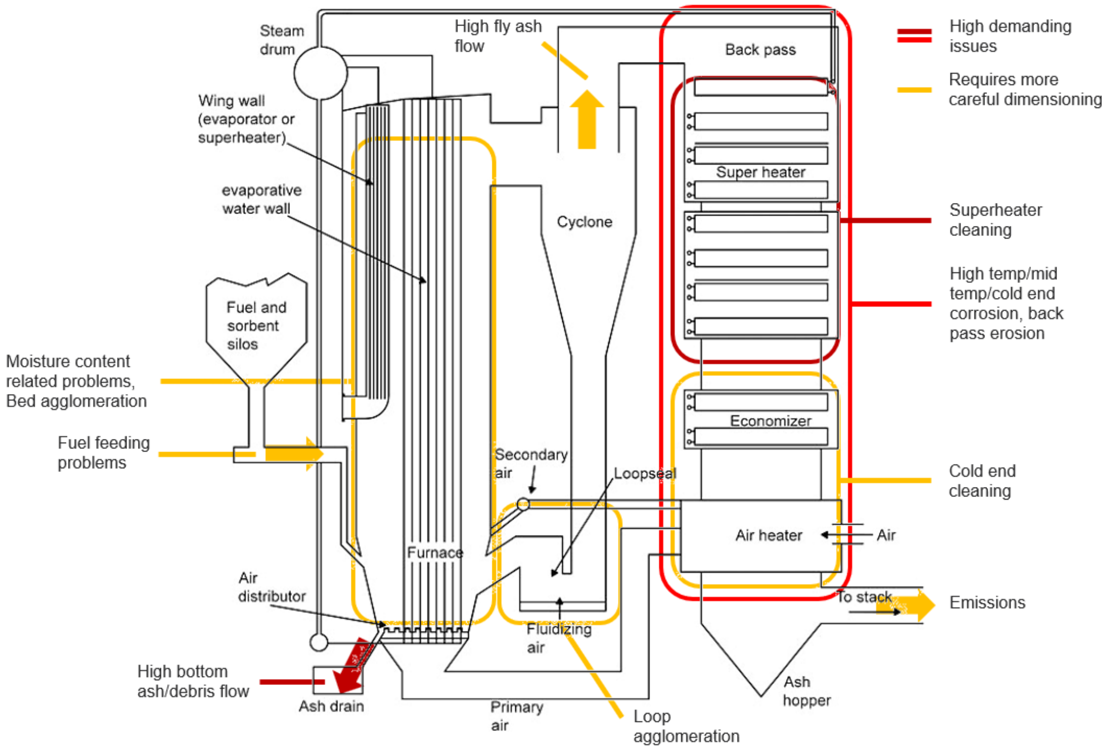

Figure 23. Waste fuel related issues and their locations in CFB (modified from Basu, 2015, p. 179)

4.2.1 Increasing moisture content and decreasing heating value

High moisture content could lead to ignition problems and maximum combustion temperature can decrease. These could lead to increase in harmful emissions such as CO, soot, and polycyclic aromatic hydrocarbons (Iacovidou et al., 2018, p. 539). Moisture content also affects heating value of the fuel. According to VTT (2002, p. 216) CFB boiler can burn fuel with up to 60% moisture content. Higher heating value is the total amount of fuel feeds chemical energy that will release during combustion. Equation (1) shows Dulong's equation for higher heating value (Khuriati et al., 2017, p. 2871), which is converted to kJ/kg unit. C (carbon), H (hydrogen), O (oxygen), S (sulfur), and W (water) are percentages in content as received. According to study comparing different energy content equations to measured data, Dulong's equation shows good accuracy on estimating MSW heat value (Khuriati et al., 2017, p. 2874). Lower heating value could be described as sensible heat content of flue gases, which would be available for heat transfer (Niessen, 2015, p. 11). Equation (2) shows how lower heat value is calculated when latent heat from vaporized water is subtracted from higher heat value (Phyllis, 2021).

$$HHV_{dulong,ar} = 339.1C + 1\,434.0\left(H - \frac{O}{8}\right) + 94.2S(9H - W) \tag{1}$$

$$LHV_{ar} = HHV_{ar} - 2443\left(\frac{8.936H}{100}\left(1 - \frac{W}{100}\right) + \frac{W}{100}\right) \quad (2)$$

To keep thermal output for the fuel constant, increase in moisture content would require increase in fuel input. With increasing moisture content flue gas weight increases. This would require larger furnace and cyclone to keep the superficial gas velocity unchanged (Basu, 2015, p. 168-169).

4.2.2 Bulk density affecting fuel feeding

Changes in bulk density of fuel might affect boiler so that feeding system requires changes (Iacovidou et al., 2018, p. 540). Generally bulk density of fuel is affected by particle density, particle size distribution, moisture content, and impurities (Alakangas et al., 2016, p. 187). Table 16 shows typical densities for different waste materials.

Table 16. Typical densities for different materials (Van Caneghem et al., 2012, p. 559)

Item	Range of Density and typical value (kg/m3)
Food waste (mixed)	130-480 (290)
Paper	40-130 (85)
Cardboard	40-80 (50)
Plastics	40-130 (65)
Rubber	100-200 (130)
Garden trimmings	60-225 (100)
Wood	130-320 (240)
Dirt, ashes, etc.	320-1000 (450)
Textiles	100-200 (180)
Fruit wastes	250-750 (360)

4.2.3 Particle size distribution affecting hydrodynamics

Particle size distribution affects hydrodynamics of CFB boiler. If the amount of coarser material increases in the fuel, lower bed density increases and upper bed density decreases, which decreases heat absorption. Also, too big particles cannot be fluidized (Basu, 2015, p. 113). This could lead to increase in particles falling through the furnace as bottom ash without burning completely (Iacovidou et al., 2018, p. 539). If the amount of finer material increases in the fuel, more fuel will burn in upper parts of the furnace and in cyclone, and finest particles might leave unburnt (Basu, 2015, p. 113). 90% of particles should be less than 90 mm and 100% should be less than 200 mm is one example of RDF particle size requirement for CFB (Kokko, 2020, p. 11).

4.2.4 Bed agglomeration

Sintering happens when particles start to soften and inter-particle bonds are formed if minimum sintering temperature of the particle is exceeded (Van Caneghem et al., 2012, p. 573). Larger agglomerates are formed and temperature around them will rise. If melting temperature of the bed materials is exceeded, clinkers will be formed and bed will be defluidized (Basu, 2015, p. 333). Mostly agglomeration is due to silica (Si) bed materials reacting with alkali particles of the fuel. Main chemical compounds causing agglomeration are alkali metals sodium (Na) and potassium (K) (Van Caneghem et al., 2012, p. 569) but other important components in formation of low-melting compounds (eutectics) are phosphorus (P), iron (Fe), sulfate anions (SO_4^{2}-) and chloride (Cl-) (Niessen, 2015, p. 405). Table 36 shows melting points of common eutectic mixtures. Some mixtures can have lower melting points than their individual eutectic compounds. Also glass or metals such as Pb and Zn have low melting points (Bolhàr-Nordenkampf et al., 2015, p. 172). Ca and Mg are known to prevent agglomeration significantly if concentration of Na or K is low enough. Ratio of Ca/(Na + K) can indicate probability of agglomeration, with increasing ratio decreasing the probability (Van Caneghem et al., 2012, p. 571). Factors boosting agglomeration tendency are temperature which increases stickiness of the particles and particles surface area which increases when particle size gets smaller, while bigger particle momentum caused by bigger particle size and gas velocity decreases the tendency (Van Caneghem et al., 2012, p. 575).

4.2.5 Increasing ash content

According to Tang et al. (2016, p. 170) fly and bottom ash in MSW boilers consists mainly of SiO_2, CaO, Al_2O_3, Fe_2O_3, Na_2O, and MgO. Other ash oxides in RDF with lesser quantities include K_2O, P_2O_5, SO_3 and TiO_3 (Van Caneghem et al., 2012, p. 570). Table 17 shows example on how different heavy metals could be concentrated between bottom and fly ash. Percentages are based on mean values of metal concentrations in several incinerators. Some metals in the source material show higher deviation in values than others and applicability on CFB boilers is not mentioned, so the concentrations might vary a lot in different boilers and with different feed (Niessen, 2010, p. 320-322).

Table 17. Example on how metals distribute between fly and bottom ash (adapted from Niessen, 2010, p. 322)

	Al	As	Ca	Cd	Cr	Cu	Fe	Hg	Ni	Pb	Zn
Fly ash	75 %	14 %	50 %	99 %	23 %	37 %	32 %	95 %	72 %	61 %	78 %
Bottom ash	25 %	86 %	50 %	1 %	77 %	63 %	68 %	5 %	28 %	39 %	22 %

Ash contains particles that are carcinogenic and toxic. This could make finding further use for the residue challenging (Niessen, 2010, p. 320-321). Operation experience from

CFB boiler has shown that high amounts of glass, aluminum and other non-fluidizable materials causes bottom ash chutes to get blocked. This problem has been resolved by increasing bottom ash discharge capacity (Bolhàr-Nordenkampf et al., 2015, p. 177).

4.2.6 Erosion

In CFB erosion happens when either solids by themselves hit the wall with their own momentum or when solids moving along the wall are hit by other solids, causing abrasion. Amount of erosion is affected by mass and velocity of the impacting particles (Basu, 2015, p. 308). Corrosion can promote erosion, for example when protective oxide layer is gone particles can collide with metal surface. This combination of corrosion and erosion is thought to be main reason near the sootblowers for material wastage coming from superheaters (Basu, 2015, p. 321).

4.2.7 Slagging and fouling

Slagging and fouling are ash depositions in different sections of the boiler. In slagging molten alkali metal ashes deposit in the high temperature refractory sections where heat is transferred mainly by radiation (Iacovidou et al., 2018, p. 541) and in fouling dry ash carried by flue gas deposits over convective heat surfaces such as superheaters, reducing their heat transfer rate (Basu, 2015, p. 321; Iacovidou et al., 2018, p. 541). Particles have tendency to become sticky and will start to accumulate on surfaces when their initial deformation temperature is exceeded (Niessen, 2010, p. 196). Amount of sodium (Na) and potassium (K) content in fuel are indications of low-melting compounds such as NaCl and Na_2SO_4 which will affect slag fusion temperature (Niessen, 2010, p. 98). Also, chlorine, aluminum, and glass contents increase ash deposition rates (Van Caneghem et al., 2012, p. 571; Bolhàr-Nordenkampf et al., 2015, p. 177).

4.2.8 Corrosion

Corrosion happens mainly because of oxidation or reduction, sulfidation, and chlorination of outer surfaces of heat transfer tubes (Basu, 2015, p. 315-316). In high temperature corrosion chlorine compounds condensate as sticky deposits on superheater tube surfaces (Bolhàr-Nordenkampf et al., 2015, p. 170; Basu, 2015, p. 321). Low temperature corrosion happens when metal temperature is so low that moisture in the flue gases will concentrate on the surface. This could happen in different zones, such as economizer and combustion air heater (Niessen, 2010, p. 190). Main elements affecting risk of corrosion are K, Na, Ca, Cl, Pb, Zn, and S. Chlorine can appear in the form of alkali chlorides (such as KCl or NaCl), heavy metal chlorides (such as $PbCl_2$ or $ZnCl_2$) or HCl (Kinnunen, 2019, p. 40, 44, 48). Calcium based compounds can capture acid flue gas compounds SO_x and HCl. Sulfur can reduce how much metals are affected by chlorides by making ash less sticky, which reduces high-temperature corrosion in tubes (Niessen 2010, p. 97, 190; Van Caneghem et al., 2012, p. 564, 571). Some other elements involved in corrosion are Si, Mg, Al, and Fe. (Van Caneghem et al., 2012, p. 575).

4.3 Design and span values for waste fuel

Table 18 shows example of design and span values for waste fuel in CFB waste plants. Fuel for CFB 1 consists of mixed household waste and sorted industrial waste with sewage sludge co-fired, and fuel for CFB 2 is RDF (VTT, 2002, p. 224, 227). This example shows that waste fuel values can sometimes exceed design values. To prevent boiler related problems mentioned before, it is important to identify what factors are affecting the quantity of harmful elements.

Table 18. Waste fuel in CFB plants (VTT, 2002, p. 225)

Steam in both boilers 470°C/6.5 MPa	**CFB 1 (2002)**		**CFB 2 (2000)**	
Main elements	**Design**	**Span**	**Design**	**Span**
Carbon (% dry basis)	45.0	35-55	44.8	
Hydrogen (% dry basis)	5.8	4-9	6.28	
Oxygen (% dry basis)	27.3	25-45	29.5	
Nitrogen (% dry basis)	1.0	≤1.0	1.15	≤1.2
Sulphur (% dry basis)	0.4	≤0.5	0.25	≤1
Chlorine (% dry basis)	0.8	≤0.8	0.83	≤1.08
Inert materials (% dry basis)	19.7	12-23	17.1	12-22
Moisture (%)	28.9	15-40	28.0	20-35
Lower heating value (MJ/kg)	12.6	10-16	12.5	9.2-16.7
Heavy metals:				
Al (g/kg dry fuel)		≤10	10	≤+30%
Pb (mg/kg dry fuel)		≤500	200	≤+30%
Cr (mg/kg dry fuel)			50	≤+30%
Cu (mg/kg dry fuel)			150	≤+30%
Mn (mg/kg dry fuel)			150	≤+30%
Ni (mg/kg dry fuel)			20	≤+30%
As (mg/kg dry fuel)			10	≤+30%
Cd+Hg (mg/kg dry fuel)			10	≤+30%
Pb+Cr+Mn+Zn+V+Co+Sn+Ti+Sb (mg/kg dry fuel)			1200	≤+30%
Zn (mg/kg dry fuel)		≤800		
Cd (mg/kg dry fuel)		≤2.0		
Hg (mg/kg dry fuel)		≤0.6		

Fuel source defines the worst-case scenario and pre-treatment defines the steps needed to reduce issues in the boiler. This ties up municipal waste, pre-treatment and CFB boiler systems as an interconnected whole where each step has an effect on the following step.

5. MATERIALS AND METHODS

5.1 Research structure

This thesis is structured so that there is at first literature survey and then modelling work based on literature findings. Figure 24 shows the structure of the thesis. Southeast Asia countries waste management data was searched to find information on how waste is managed in different countries in the region and what is the composition of the waste in landfills. The waste quality data was used as input to pre-treatment system model. Information was searched on how different pre-treatment equipment would affect the quality of the waste refuse mass flow to create a model of the pre-treatment system. The waste pre-treatment system for modelling work was chosen based on a process case that includes main components found in most pre-treatment systems, and is shown in Figure 10 in Chapter 3.4.2. Information was also searched on RDF quality to compare the results made with the model. Information was searched on the demands of CFB boiler for waste fuel quality, and on how different components of the waste fuel affect the boiler. Information found was used as a basis for analyzing results found using the created model.

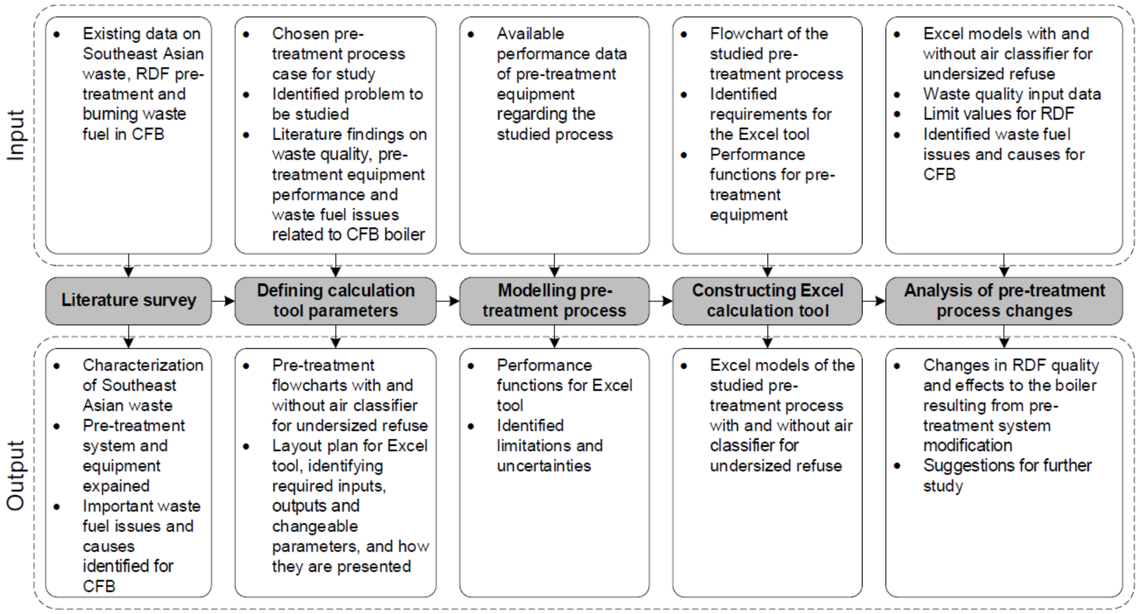

Figure 24. The structure of the thesis

Based on the waste quality and pre-treatment equipment data, the model was made to see quality of RDF entering a CFB boiler with and without air classifier for undersized refuse. Then sensitivity analysis was made on how changing parameters in different pre-treatment equipment will affect the fuel quality in both cases. Model results were compared to actual RDF data and CFB limit values to find out would the fuel be qualified to being burned in the CFB boiler. Error factors were evaluated to estimate uncertainty of the model results and to identify how the accuracy can be improved. Based on the literature findings and model results was evaluated how the boiler is affected by changes made to the pre-treatment system. Suggestions were made on the benefits and risks of the modification in the pre-treatment system and how the new pre-treatment modelling presented in this thesis can be improved.

5.2 Waste data

As the findings in Chapter 2 shows, waste qualities in Southeast Asia differ from one country to another, and even within each country waste quality can vary in different regions. Therefore, waste data from Malaysia, Indonesia and Viet Nam were used for comparison as waste input. Out of the three countries studied, Malaysia had the most comprehensive municipal waste data found from the last decade so the data in the study was used for primary model input in this thesis. The study by Bandar and Tempatan was made in 2011-2012 and considering the ongoing Malaysian waste programs shown in Table 3, such as utilization of organic compounds and the reduction of recyclables in the waste stream, and the trends on how different material flows evolve, for example, increase in plastic and electronic waste, MSW composition might have changed to this day, but the study was assumed to provide data accurate enough for the model study in this thesis.

For this thesis, only household waste was considered, as the Malaysian waste study (Bandar and Tempatan, 2013) had proximate and ultimate analysis made for that type of waste. Studying household waste is also justified by the fact that most of the generated waste in Malaysia is by households rather than ICI sector, as is shown in Figure 5. Required waste data had to be specific enough to take into consideration for example sorting of different types of plastic, because as the analyses in Table 32 and Table 33 in Appendix A shows, different materials from the plastic category have different chemical compositions. These tables were used to define the chemical composition and the metal contents of each waste material. In addition, Cl, K, Na, and Pb quantities for different materials were calculated from Table 34, which is from a MSW study by VTT. Pb quantities for each material were available from Malaysian waste study, but they seemed unrealistically low values compared to other studies, so instead values from VTT study were used. Categories for different materials in Table 34 are shown in Table 19.

Table 19. Waste materials from Malaysian study categorized into VTT study categories

Category	Materials
Paper & cardboard	Mixed paper, newsprint/old newspaper, cardboard
Plastic (hard)	HDPE, PVC, PS
Plastic (soft)	PET, LDPE, PP
Textile	Diapers, textiles
Rubber	Leather
Wood	Garden waste, wood, peel husk
Food waste	Food waste

Data shown in Table 31 in Appendix A was used to calculate percentages of different waste components in the total waste stream entering the pre-treatment system. Household hazardous waste was excluded as their quantity was relatively small compared to other categories and there was not detailed analysis of them on the report. It is also safe to assume that most of them would be picked away before entering the pre-treatment system or would be sorted in the system itself. For example, it was mentioned in Chapter 3 that magnets would remove most of the batteries, so the exclusion of HHW is justified to simplify the model. Also, other plastics, other nonferrous metals and other minor components did not have information detailed enough to make assumptions on their composition and their total fraction was so small that they could be ignored. Table 31 shows original and modified percentages based on these simplifications.

Table 5 in Chapter 2.4 was used to get the waste composition for Indonesia and Viet Nam. For this study relative amounts of different materials in each material category were assumed to be the same as in Malaysian waste study. For example, plastics PET, HDPE, PVC, LDPE, PP, and PS would have the same relative amounts compared to each other but the total amount of plastics is changing. Materials from Table 31 adapted into categories from Table 5 are listed in Table 20. Table 21 shows used waste input values for Indonesia and Viet Nam. Table 5 is missing amounts of textile and other wastes for Viet Nam. The amount of textiles for Viet Nam was chosen to be 3.5% because both Malaysia and Viet Nam have the same amount. That leaves the amount of other wastes for Viet Nam to be 14.5%. The assumptions presented here might be inaccurate, because as Chapter 2 has shown, each country has differences in waste generation and management. More detailed analysis for waste composition and quality in Viet Nam and Indonesia however were not considered to be relevant within the scope of this thesis.

Table 20. Waste materials adapted into Southeast Asian waste composition table by UNEP

Category	Material
Food/organic waste	Food waste, garden waste, wood, peel/husk
Paper	Mixed paper, newsprint/old newspaper, cardboard
Plastic	PET, HDPE, PVC, LDPE, PP, PS
Metal	Ferrous metal, aluminum
Glass	Glass bottle, sheet glass
Textile	Textiles
Rubber	Rubber
Others	Tetra Pak, diapers, leather, porcelain/ceramic/stones

Table 21. Waste input values for Indonesia and Viet Nam

Waste category	Indonesia	Viet Nam
Food/organic waste	59.6%	55.0%
Paper	9.0%	5.0%
Plastic	14.0%	10.0%
Metal	4.3%	5.0%
Glass	1.7%	3.0%
Textile	3.5%	3.5%
Rubber	5.5%	4.0%
Others	2.4%	14.5%

Some simplifications were made to the waste behavior during the pre-treatment process to make modeling possible within the scope of this thesis. It was assumed that none of the metal or other chemical element content included in different materials would leave during the pre-treatment process, for example, by dissolving into the water that is removed during biodrying. Also, moisture content of each material was assumed to remain the same for the rest of the pre-treatment process after biodrying. This would lead to assumptions, for example, particle size remains constant after shredding. This might not be the case in reality, for example, considering nature of parabolic movement of waste inside trommel screen as is shown in Figure 15 in Chapter 3.5.2, waste is being pushed against wall of the drum similarly to laundry in washing machine, resulting some of the moisture in wet oversized soft waste most likely to leave through the apertures. For some materials these might be oversimplified assumptions, but these simplifications allowed creating the pre-treatment model with the available information on the process.

5.3 Excel tool requirements

To study how different steps in studied pre-treatment system affect RDF quality, Excel was chosen as a base for the tool. Required inputs, functionality, and outputs to answer the fourth research question are listed in Table 22. Input waste quantity and elemental analysis values for waste materials remains in this study constant, but waste composition of different materials and pre-treatment unit performance parameters, such as sieving aperture size, were made modifiable to study the effects of different settings. The main purpose of the tool was to study output RDF quality, but information on side streams would be important also to understand where different materials end up at, how different side streams could be utilized and how different parameter values will change mass flows.

Table 22. Basic requirements of the Excel calculation tool for the study

Inputs	Functionality	Outputs
• Waste quantity • Waste composition • Elementary analysis for each waste material • Pre-treatment unit performance functions and parameters	• Calculates the waste quantity and composition in each step of the modeled pre-treatment process based on the input and unit performance parameters • Displays outputs numerically and visually	• Primary and side stream mass flows and compositions • Analysis of the output RDF, including relevant parameters to evaluate combustibility and harmful effects on the boiler

Two different Excel models were required: one with air classifier separating heavy particles from the extract flow coming from the screen after shredder (shown in Figure 9 in Chapter 3.4.2), and one without it (Figure 25, in which the process has air classifier removed from the bottom right corner). The processes are otherwise same but taking the air classifier away will make the previously sieved heavy fraction enter the boiler. To study the effects of this change in the system it was required that each pre-treatment process unit behavior would be modeled.

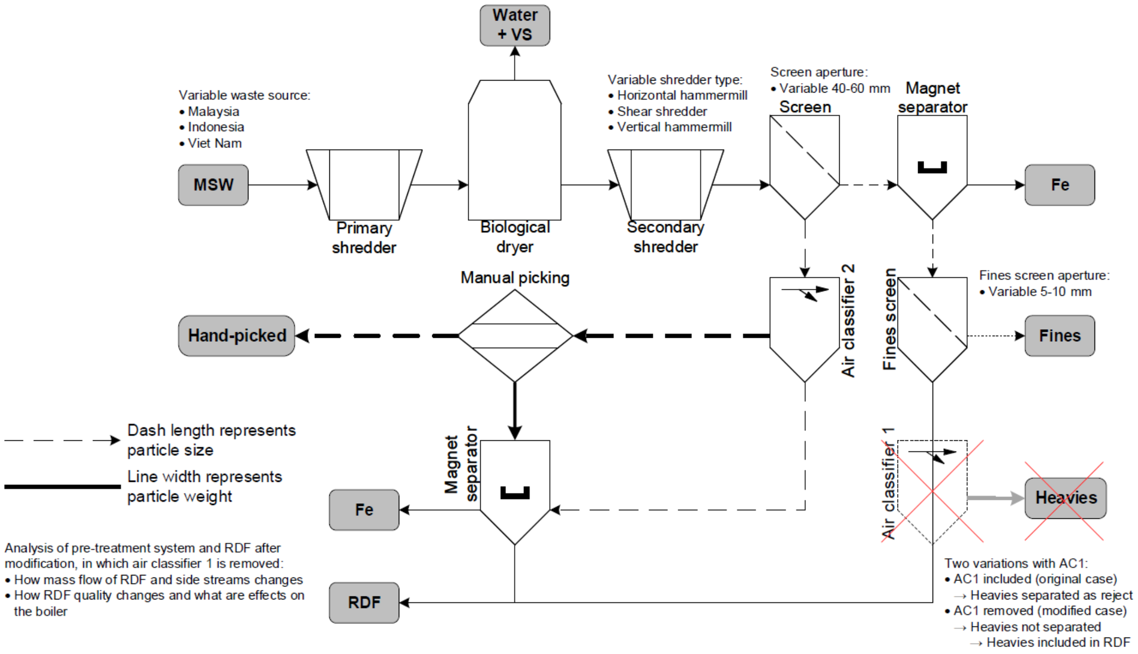

Figure 25. Pre-treatment system flowchart with air-classifier for undersized removed

5.4 Pre-treatment system unit process modelling

To create a model of the pre-treatment system, functions had to be defined for how waste quality changes in each unit of the pre-treatment process. This was done based on the information found in Chapter 3. Primary shredder did not require modeling because it was considered only to be for bag opening purposes and to limit maximum particle size to 200 mm, which was mentioned in Chapter 4.2.3 as being required maximum particle size in CFB boiler. Making model for the ferrous separator was simple, as the only ferrous metal material was assumed to be recovered and with a recovery rate in the scope mentioned in Chapter 3.5.4. Rest of the process required more careful consideration.

Table 32 in Appendix A shows moisture content of each material. These were used to calculate the masses of water in each material category, and the sum of them divided by the total mass of the waste stream gives total moisture content. In the biodrying model target moisture content after drying is defined. The assumption was that reduction of moisture content for each material would be relatively equal. This might not actually be true, for example, some sealed bottles or plastic bags might have still liquids inside if pre-shredder has not opened them. After selecting target moisture content, each material's moisture mass would then be multiplied by the same factor to acquire chosen moisture content after drying. This factor was defined iteratively for selected target moisture content by using goal seek function of Excel. After moisture content of biodried refuse was calculated, the amount of evaporated water was the water content difference between input and output refuse in biodrying. As was mentioned in Chapter 3.4.1, ~15% of the mass loss during biodrying is due to volatile solids (VS) degradation of organic matter, with theoretical 1:5.5 degraded VS to evaporated water mass ratio. When the amount of evaporated water is known, the amount of degraded VS can be calculated dividing it by 5.5. Organics category in Table 31 consists of materials food waste, garden waste, wood, and peel husk. For this thesis modeling was simplified so that for each material their own relative ratios of VS elements C, H, O, N, and S would remain the same, but their total amount would be multiplied by factor, which would make the total VS amount of the organics category drop by the amount required for water evaporation. VS content of all the materials in organics category would be multiplied by the same factor. This is also simplification, because for example, food waste and peel husk might degrade with different speeds. Amount of fixed carbon and ash would remain unchanged. Data from Table 32 was used for calculations.

For modelling the secondary shredder, three different data groups were used to model three different shredders for comparison. These three different shredders are horizontal hammermill, vertical hammermill, and shear shredder. As was mentioned in Chapter 3.5.1, rotary shears are recently preferred over hammermill shredders and their size distribution data might be different because of different mechanics. This gives reason to study how different shredder type affects RDF quality. Horizontal hammermill shredder size distribution data from Figure 14 in Chapter 3.5.1 was used as data group 1. Because the shredder size distribution data has a smaller number of categories than the amount of materials in Table 31, different types of waste had to be categorized based on those labels in Figure 14. This categorization is shown in Table 23. Categorization posed some problems: rubber category contains shoes, which also contain materials that could be categorized to textiles, diapers could contain plastic fibers and peel husk could be from fruits that have grown in a garden. Categorization was made based on what was considered to be the best fit. Data groups 2 and 3 were used for shear shredder (data in Table 37) and vertical hammermill (data in Table 38). Table 24 shows slight differences in categories, but similar considerations were required as in Table 23.

Table 23. Shredder waste categories for particle size distribution data group 1

Category	Materials
Cardboard	Cardboard, Tetra Pak
Ferrous	Ferrous metal
Food	Food waste
Garden	Garden waste
Glass	Glass bottle, sheet glass
Miscallaneous	Rubber, leather
Nonferrous	Aluminium
Paper	Mixed paper, newsprint & old newspaper
Plastic, rubber & leather	PET, HDPE, PVC, LDPE, PP, PS, rubber, leather
Sand & rock	Porcelain/ceramic/stones
Textiles	Diapers, textiles
Wood	Wood, peel husk

Table 24. Shredder waste categories for particle size distribution data groups 2 and 3 (Bond, Temple & Grubbs, 1986)

Category	Materials
Paper	Mixed paper, newsprint & old newspaper
Plastic	PET, HDPE, PVC, LDPE, PP, PS
Cardboard	Cardboard, Tetra Pak
Textiles	Diapers, textiles
Wood	Wood, peel husk
Other organics	Food waste, garden waste, rubber, leather
Glass	Glass bottle, sheet glass
Inerts	Porcelain/ceramic/stones
Ferrous	Ferrous metal
Nonferrous	Aluminum

The data for horizontal hammermill shredder (Figure 14) is used in an educational book published in 2012 but the original research on the size distribution dates to 1974. It could be argued that the data might be different nowadays because of shredding equipment upgrades or quality of materials changing, but considering the fact that the size distribution figure was used 40 years later in a solid waste engineering book written by two authors with a long career in the fields of waste management research indicates that the data is still valid enough. The original study had common probability distributions fitted to particle size data for each material and equations were given (Ruf, 1974, p. 323-339), however different method was used for this thesis. A cumulative distribution chart in Figure 14 was scanned with image processing software, and functions for each material was created from acquired data. Using probability distributions from the original study would have been easier, but by comparing them to functions created with the image processing their accuracy was much worse. Then again, this raises questions about accuracy of the hand drawn particle size distribution image in Figure 14. For this thesis it was assumed, that Figure 14 shows accurate results. Figure 26 shows comparison of polynomial fitting from scanned data to the original normal distribution fitting.

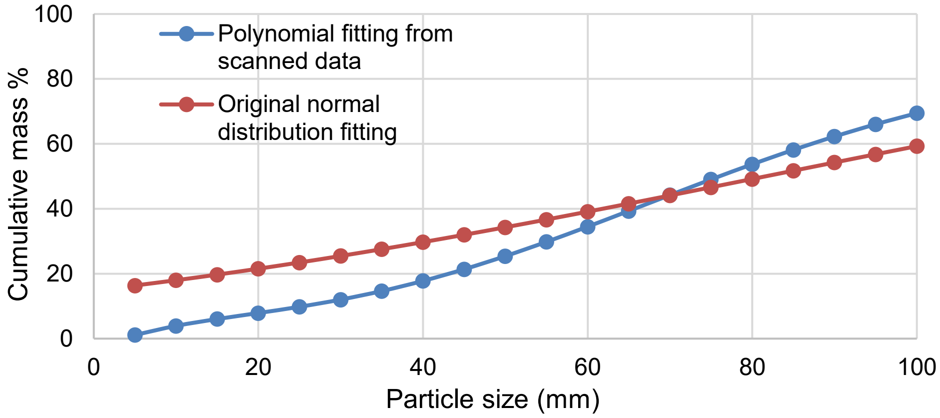

Figure 26 Comparison of the cumulative particle size distribution between scanned data and normal distribution fitting from the original size distribution study

Cumulative graphs in the hammermill size distribution figure (Figure 14, Chapter 3.5.1) were converted to data with software called ‘im2graph’. Software uses image processing algorithms to identify graphs from pictures and allows exporting point data as .csv files with defined resolution. Data in the table was in logarithmic scale, but defining axes logarithmically was available in the software. The issue with the software is that it identifies overlapping lines as one dataset. This was overcome for each graph by exporting only parts that do not overlap others. Amount of overlapping data left out would not make any significant difference in defining the functions as those parts were relatively small, and the outlines of the graphs were clearly visible from the exported datasets. Trendline was made for the data points converted from the original table. The equation of the trendline was shown with four decimal precision. This equation was then used in VBA function, where input is particle size in mm and output is a fraction of how much of the total mass of the material goes below input particle size. For some data sets single polynomial trendline was not accurate. In these cases, data set was divided into multiple parts for which each was made own suitable trendlines that had different equations. These were then implemented to VBA function with IF statements for the particle size range of each trend line function. Also, IF statement was made to prevent mass percentage going over 100%. Excel functions were made for each material listed in Table 23. Figure 27 shows an example of a particle size distribution trendline made for the scanned data points.

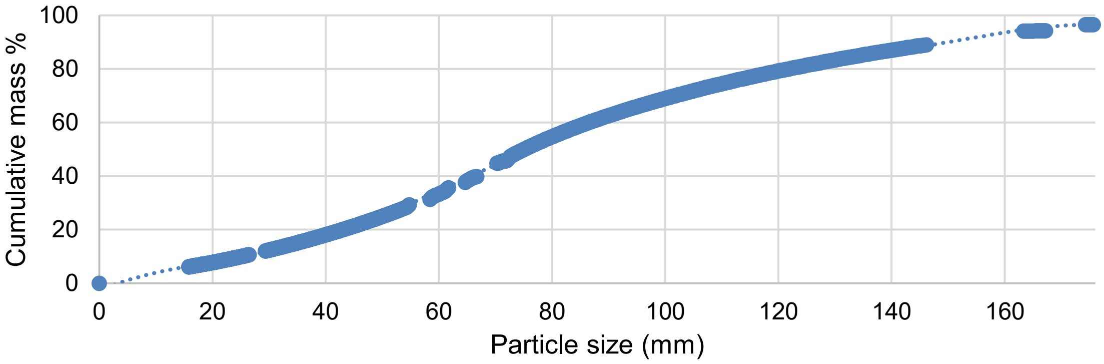

Figure 27. Data points and trendline of particle size distribution of cardboard after shredding

Data from Table 37 and Table 38 in Appendix B were used for modelling shear shredder and vertical hammermill shredder. Data was from a study published in 1986. Particle size distribution data was presented in table format instead of figure. This required different kind of approach for modelling. Table 37 and Table 38 show masses for different size ranges for each material category. Size ranges are based on sieving aperture sizes used in the study. For each material total mass of particles was calculated, and then was calculated percentages on how mass of each material is distributed between different size ranges. Then was calculated cumulative percentages starting from the smallest size range. Excel VBA function was made, which requires input attributes of selected particle size and cumulative mass percentages for each size range category. Function calculates first degree polynomial slopes and additive constants for each size range, and IF sentences were used to model each size range as different first-degree polynomials, which create a uniform size distribution graph. This same function was used to model particle size distributions of each material for both shredders. Figure 28, Figure 29 and Figure 30, show particle size distributions for all three shredders made with created VBA functions in the range of 5-100 mm. All three size distribution figures show differences in line shapes. This indicates that type of hammermill affects greatly how material is sorted in screening and what will be the particle size distribution of the RDF fuel after pre-treatment. Therefore, all three shredder models were used in analysis for comparison.

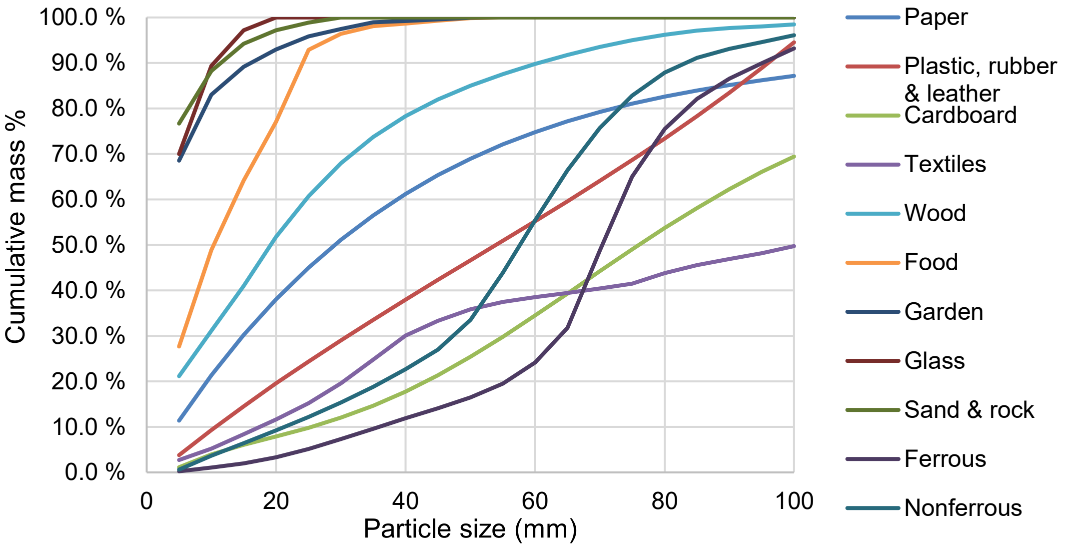

Figure 28. Particle size distribution of horizontal hammermill shredder

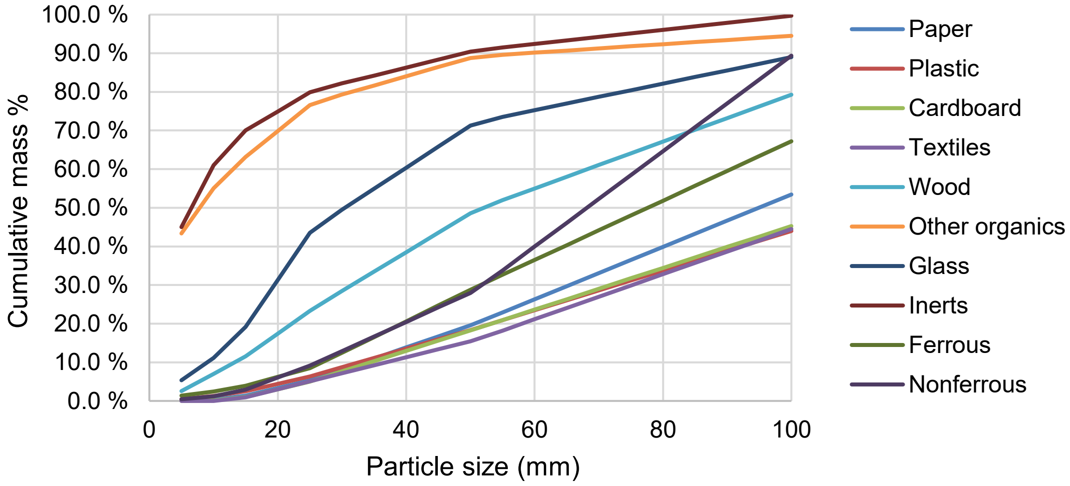

Figure 29. Particle size distribution of shear shredder

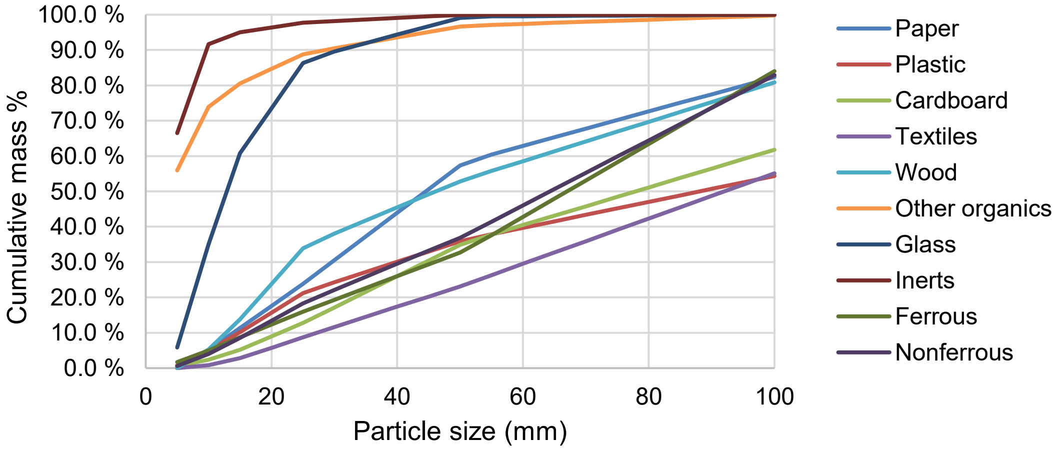

Figure 30. Particle size distribution of vertical hammermill shredder

Particle size distribution tables for each material were made for each new equipment after screen. The range was between 0-100 mm with 10 mm increments in size range, and the amount of particles over 100 mm was calculated by subtracting the sum of particles below 100 mm from the total amount of each material. For other equipment than screens it was assumed that particle amounts in each size range would be multiplied by the same recovery rate factor, thus simplifying modelling so that the particle size is an unaffecting factor for example in performance of air classifier.

In Chapter 3.5.2 it was mentioned that 85% to 95% of extract would be recovered in screening. A 90% recovery rate was chosen for this study. An assumption was made that the recovery rate would be the same for all materials. This might not be true because, for example, wet paper tends to stick into larger materials more likely than stones. With the insufficient information available on the matter this simplification was considered to have a relatively small impact on the end results. The mass of materials with size under the chosen aperture size multiplied by extraction rate was to be categorized as extract and rest of the materials as reject. This same method was used to model both screen and fines screen.

Data on Table 11 in Chapter 3.5.3 was used to make calculations for the air classifier. An assumption was made according to Table 12 comparing air classifier performance from different studies that paper extraction rate of 95% would be reasonably realistic. With this assumption it was possible to calculate extraction rates of other materials according to Table 11. First mass was calculated for each material in the table with an arbitrary total mass of 1000 tpd. Table 11 shows amount of extracted materials as percentage of total extract, therefore first the total mass of the extract had to be solved by dividing extracted 95% of input mass of paper by its fraction 0.788 of the total extract from Table 11. Then the masses for other materials in the extract were calculated by multiplying total mass with each material's extract fraction, and extraction rates for the air classifier model were calculated by dividing each material's extract mass with input mass. Table 25 shows these calculations made with input total mass 1000 tpd. In the table the sum of input mass is less than 1000 tpd because of inaccuracies from rounding in Table 11, but this error was considered irrelevant in defining the extraction rates for this thesis. Because the material categories were different from the categories in shredder models, new categorization was needed. This is shown in Table 26.

Table 25. Extraction rates of different materials for air classifier model

Material	Fraction of input	Input mass (tpd)	Fraction of extract	Extract mass (tpd)	Extract rate (%)
Rocks and dirt	0.3%	3.0	0%	0.0	**0.0%**
Ferrous metal	7.8%	78.0	0.08%	0.5	**0.6%**
Nonferrous metal	1.0%	10.0	0.05%	0.3	**3.1%**
Glass and other non-combustible	7.8%	78.0	1.82%	11.5	**14.7%**
Paper	52.2%	522.0	78.8%	495.9	**95.0%**
Wet garbage	11.8%	118.0	0.1%	0.6	**0.5%**
Yard and garden	6.7%	67.0	8.6%	54.1	**80.8%**
Other combustible	12.2%	122.0	10.6%	66.7	**54.7%**

Table 26. Air classifier waste categories

Category	Materials
Rocks and dirt	Porcelain/ceramics/stones
Ferrous metal	Ferrous metal
Nonferrous metal	Aluminum
Glass and other non-combustible	Glass bottle, sheet glass
Paper	Mixed paper, newsprint & old newspaper
Wet garbage	Food waste
Yard and garden	Garden waste, wood, peel husk
Other combustible	Cardboard, polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), Tetra Pak, diapers, rubber, textiles, leather

In manual picking, corrugated cardboard, PET plastic bottles, HDPE plastic and aluminum are picked from the refuse stream (Chapter 3.5.6). Considering that Tetra Pak contains significant amounts of aluminum, they were chosen to be manually picked in the model as well. The maximum capacity of the pickers was found to be 454 kg/h/person in Chapter 3.5.6. By assuming that manual picking would be in operation 24 h/day, the daily picking capacity for one person can be calculated. Then by multiplying the daily picking capacity by the number of manual pickers, and dividing the product by the sum of all hand-picked materials (PET, HDPE, aluminum, cardboard and Tetra Pak) coming to the manual picking process, recovery percentage of manual picking is calculated. The assumption was that the recovery percentage would be the same for each material.

5.5 Excel tool parameters for the study

The Excel tool was built on requirements and functions defined in the previous Chapters 5.3 and 5.4. Each process unit changes waste quality based on the defined functions. Output of the previous part is taken as input for each module. For screens, ferrous separators, air classifiers and manual picking output was divided into extract and reject based on the purpose of separation. Each pre-treatment sub-process except shredding and air classifier had user-defined parameters controlling separating rates. The parameters of the Excel tool are listed in Table 27.

Table 27. Excel model parameters in the thesis

Part of the process	Parameters
Input waste composition	Input total mass (constant) Relative amounts of each material (variable) Elementary analysis of each material (constant)
Drying	Total moisture after drying (constant) Loss of organic volatile matter (constant)
Shredding	Shredder PSD (variable)
Screen and fines screen	Screen aperture size (variable) Screen recovery rate (constant)
Air classifiers	Recovery rates for different materials (constant)
Ferrous separators	Magnet recovery rate (constant)
Manual picking	Amount of pickers (constant)

Table 28 shows the constant parameter values used in the analysis. Table 31 shows the variable parameters used in the analysis and outputs for analyzing, and what should be noted here is that change in each variable affects outputs. This many variables make sensitivity analysis tricky, but it was considered that in addition to the two process variations variable input waste composition, variable PSD of the shredder and variable aperture of both screens would make too much difference to the output RDF to be ignored.

Table 28. Constant parameters in the study

Parameter	Constant value
Elementary analysis of each material	Initial values from Table 32, Table 33, and Table 34
Input total mass	1000 tpd
Moisture after biodrying	35 %
Loss of organic volatile matter in biodrying	1:5.5 ratio in relation to mass of evaporated water
Screen and fines screen recovery rate	90 %
Air classifier recovery rates	From Table 25
Magnet recovery rate	90 %
Amount of pickers	3

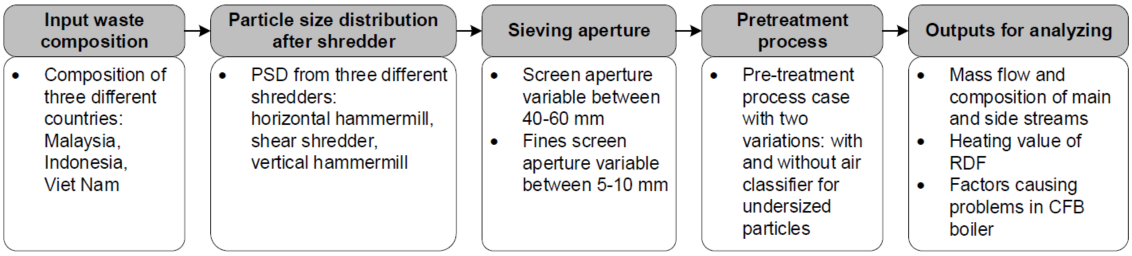

Figure 31. Variable parameters in the study

5.6 Analysis of the results

The analysis was divided into two parts: mass flow analysis and detailed analysis. In the mass flow analysis it was analyzed how the mass flows of main and side stream outputs change when the air classifier 1 is removed, what is the composition of the heavies and what is the composition of the RDF before and after the air classifier 1 is removed. Constant values for screen (40 mm) and fines screen (10 mm) were used, but waste input composition was varied between Malaysia, Indonesia, and Viet Nam. In the detailed analysis yield, moisture content, lower heating value, amount of corrosion specific elements, amount of elements affecting to ash melting, amount of ash and particle size distribution of the RDF were compared with different variables mentioned in Figure 31, because these factors were identified as being crucial to the boiler performance. Figure 32 shows the basic layout for how all variables will be presented in a compressed way. Each analyzed result has two data sets: first set has a variable screen aperture between 40-60 mm with 5 mm steps and constant fines screen aperture of 10 mm, and second set has a constant screen aperture of 40 mm and variable fines screen aperture between 5-10 mm with 1 mm steps. Both sets have three charts horizontally, each representing different type of shredder. Each chart has graphs showing data for Malaysia, Indonesia, and Viet Nam, and for each country solid lines mean the original process and dashed lines mean that air classifier 1 is removed. The purpose of the variable screen apertures and variable shredder types was to validate the results so that even if these specified variable parameters were to change, same conclusions could be made.

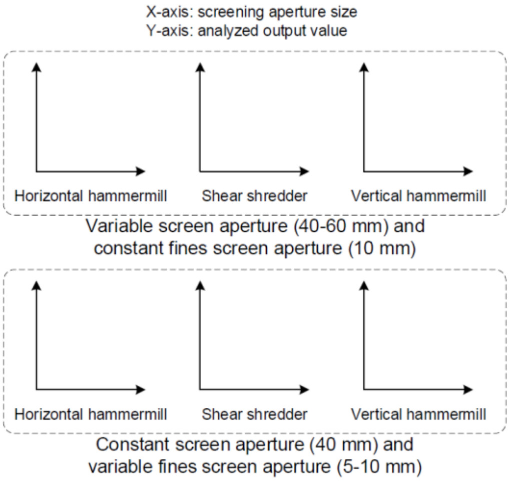

Figure 32. Basic layout of detailed analysis results

Table 29 shows the RDF results that were analyzed, what are their effects to the boiler and what are the main sources. LHV was calculated with equations from Chapter 4.2.1. The effects of CFB boiler were estimated based on findings made in Chapters 4.1 and 4.2, and sources were identified from Table 32 and Table 34 in Appendix A. Results were compared to CFB design values shown in Table 18 (Chapter 4.3) and SRF quality standard limit values shown in Table 35 in Appendix A.

Table 29. Results that were analyzed in detailed analysis

Analyzed result	Main effects to the boiler	Main sources
Moisture	Lower LHV, ignition and incomplete combustion problems	Food waste, diapers, mixed paper, LDPE
Particle size distribution	Affects hydrodynamics of the boiler	Depends on shredder type and RDF composition
S	Involved in corrosion, agglomeration, slagging and fouling. Can reduce high-temperature corrosion	Rubber, PVC, cardboard
Ash	Disposal issues, particulates emissions	In addition to inert materials: garden waste, mixed paper, food waste (in dry basis)
LHV	Heat content available for heat transfer	C, H, O, S and moisture content of RDF
Cl	Causes corrosion. Involved in agglomeration, slagging and fouling	Rubber, hard plastics, food waste, textiles
K	Causes agglomeration, slagging and fouling. Involved in corrosion	Food waste, textiles, soft plastics
Na	Causes agglomeration, slagging and fouling. Involved in corrosion	Food waste, textiles, paper, soft plastics
Al	Bottom ash disposal problems and increases ash deposition. Could be involved in corrosion	In addition to pure aluminium waste: Tetra Pak, textiles, rubber, leather, wood
Pb	Involved in agglomeration, heavy metal corrosion, slagging and fouling	Hard plastics, rubber, food waste
Zn	Involved in agglomeration, heavy metal corrosion, slagging and fouling	Rubber, textiles, plastics

The results were collected into a summary table showing analysis values before and after the modification, positive, neutral, or negative direction of effect on the boiler, and if the limit values were exceeded. Applicability of the removal of air classifier 1 was discussed based on the results of the analysis, and error factors of this study were identified.

6. RESULTS AND DISCUSSION

6.1 Pre-treatment system mass flow analysis results

Figure 33 to Figure 37 show results with screen aperture of 40 mm and fines screen aperture of 10 mm. Figure 33 and Figure 34 show RDF output and side stream fractions of total mass flow. Water and volatile solids leaving from biodrying take up significant amount of the total mass flow. This is already above typical pre-treatment process total rejection rate of 20-35% mentioned in Chapter 3.1, which leaves RDF yield to be rather small. Heavies rejected from air classifier 1 are about 10-15% of total mass flow. When the air classifier 1 is removed, the whole heavies fraction then goes to RDF out flow. Other side streams are unaffected since there are not any pre-treatment process units after air classifier 1.

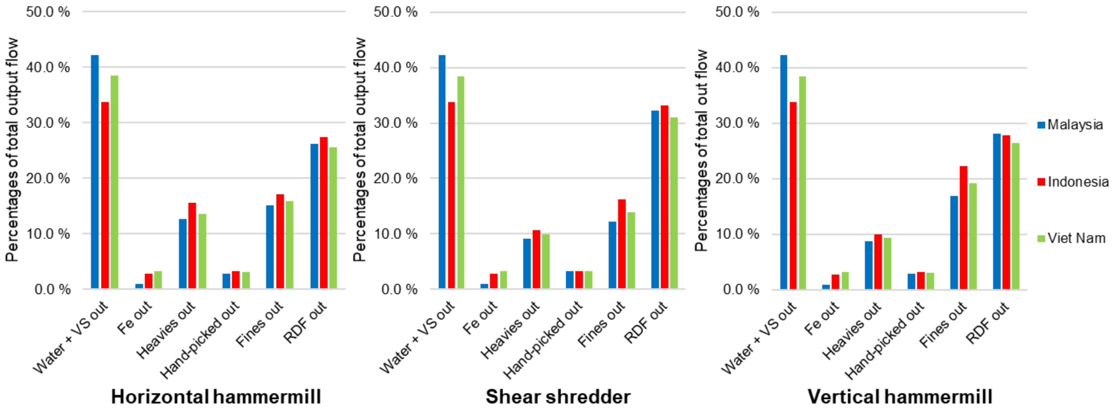

Figure 33. Output flows of pre-treatment process with air classifier 1

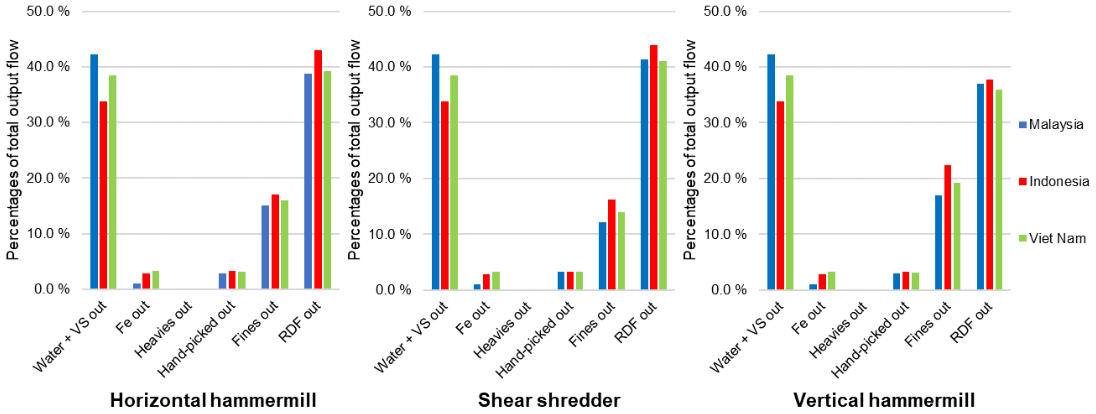

Figure 34. Output flows of pre-treatment process without air classifier 1

Figure 35 shows the composition of heavies. The heavies mostly consist of food waste. Southeast Asian waste contains so much food, that even after the fines screen takes away significant amounts there still remains much for air classifier 1. According to the air classifier performance values shown in Table 25, 99.5% of the wet waste goes to heavies as reject. When air classifier 1 is removed, all of this goes to RDF. Looking at the shredder PSD figures Figure 28, Figure 29, and Figure 30, a fraction of food waste in heavies could be greatly reduced by increasing the fines screen aperture size. After food the next largest quantities present in heavies are glass, plastics, textiles, and leather/rubber. Amount of all individual materials compared to food are relatively smaller, but their sum in addition to potentially harmful substances found in food has some effects on the boiler when heavies are added to the RDF.

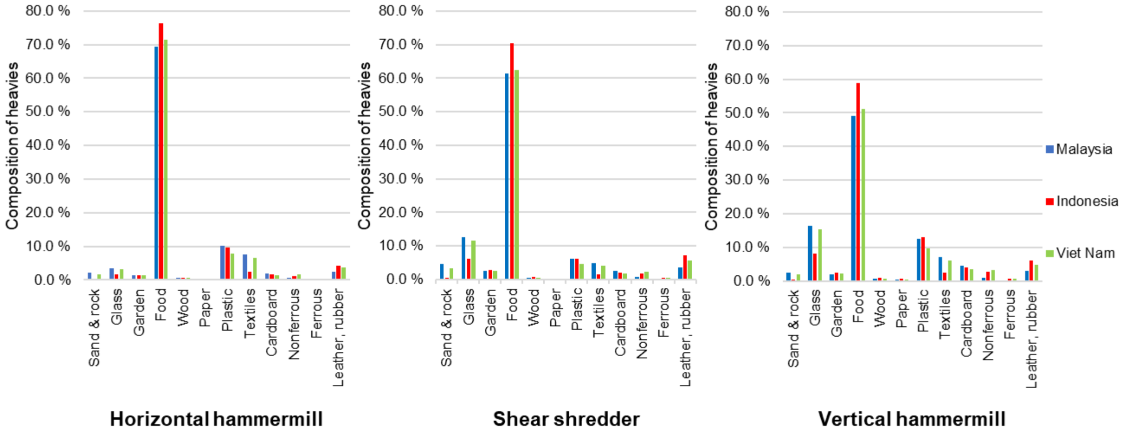

Figure 35. Composition of heavies

Figure 36 and Figure 37 show how composition of the RDF changes when air classifier 1 is removed and heavies are added to the RDF. Initially, most of the RDF is plastics and textiles. In this categorization diapers were included in textiles. The amount of nonferrous and ferrous materials is small, since two magnets and a manual picking unit are taking out most of them. When heavies are added to the RDF, food is increased to relatively same amounts as plastics and textiles, and in horizontal hammermill and shear shredder models food quantity even exceeds them. Materials with lesser quantities in heavies also increase relatively much, since the RDF yield is only 2 to 3 times the amount of heavies. Out of those materials, the amount of glass even doubles in vertical hammermill model. This could increase the risk of agglomeration. When considering bulk density of the RDF after the modification, according to material densities shown in Table 16 in Chapter 4.2.2 food and inert materials have higher density than textiles and plastics. Judging from the fact that relative amounts of plastics and textiles decrease while food and inert materials increase, bulk density will likely become higher and changes to the feeding system might be required, but as mentioned, bulk density is affected by many other variables and this assumption cannot be said for certain. The RDF will be analyzed in more detailed level later in this chapter to evaluate other effects on the boiler.

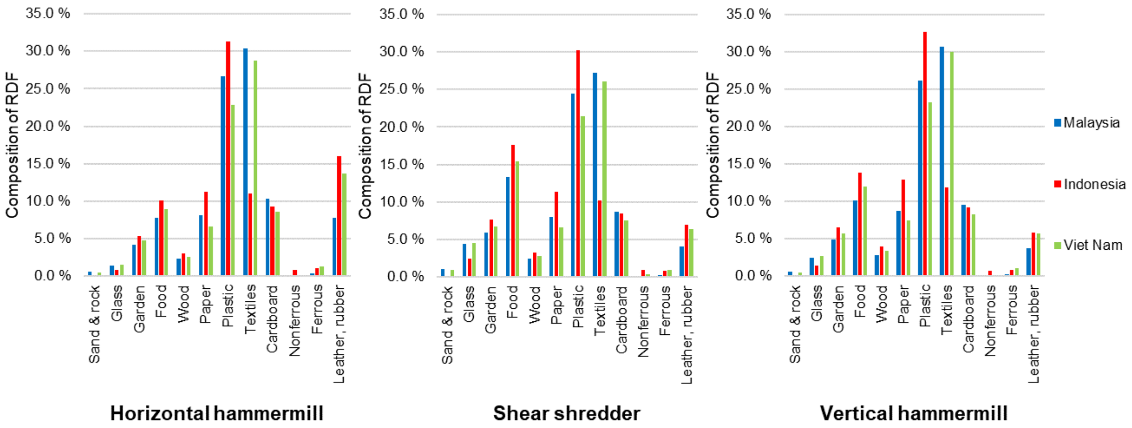

Figure 36. Composition of RDF in pre-treatment process with air classifier 1

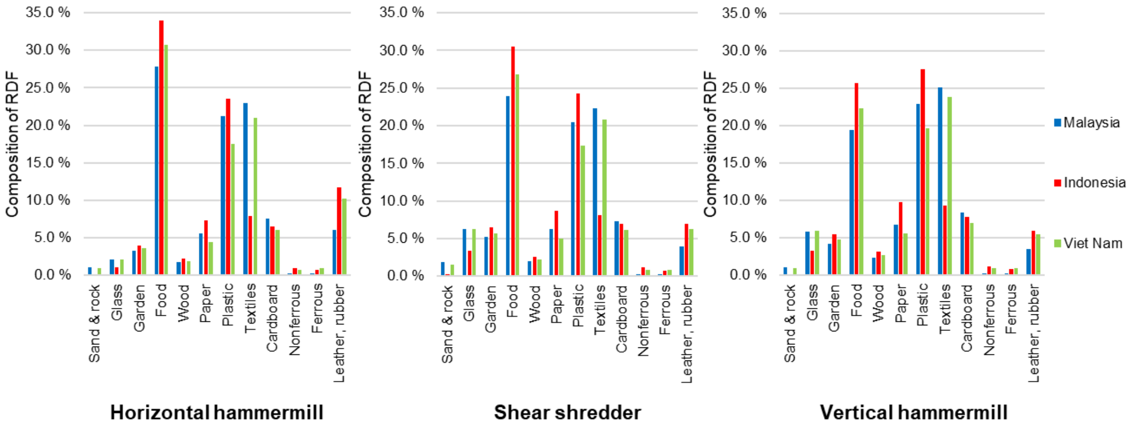

Figure 37. Composition of RDF in pre-treatment process without air-classifier 1

6.2 Detailed analysis results

For each result ‘with AC’ means the original case with air classifier 1, and ‘without AC’ means that the air classifier 1 is removed and heavies fraction is added to RDF. Figure 38 and Figure 39 show how screen and fines screen affect the yield of RDF. In the original case, changing screen aperture size affects RDF yield more, while when air classifier 1 is removed changing fines screen aperture makes bigger difference. Making fines screen aperture smaller could make RDF yield bigger, but it would increase the amount of inert and food materials. If the RDF yield was to be increased, the most efficient way would be to make the target moisture content of refuse higher after biodrying, which would then consequently decrease LHV of the RDF. In any case, since changes to both screens will affect the RDF quantity and therefore quality because of resulting changes in reject output streams, these figures justify studying further changes with variable screen and fines screen apertures to make more certain conclusions.

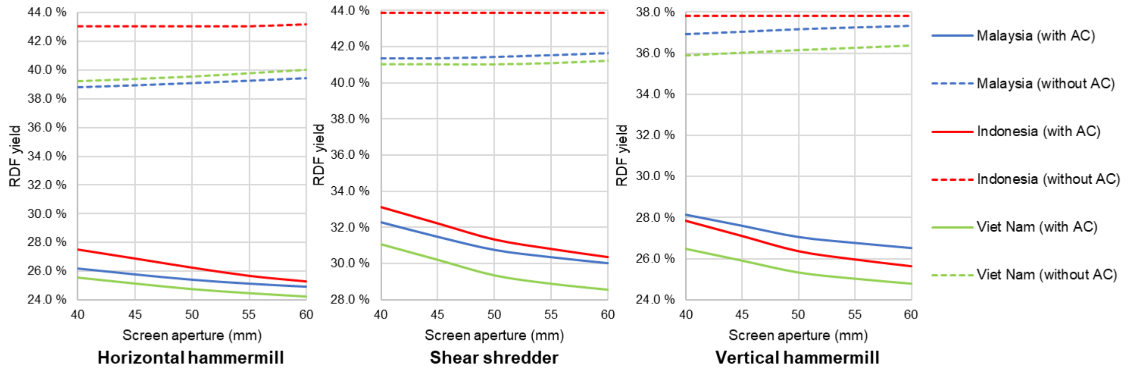

Figure 38. RDF yield with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

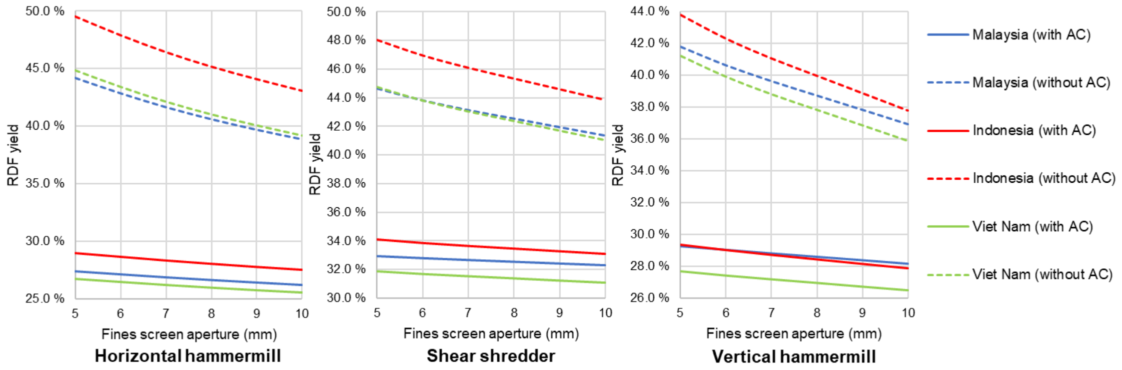

Figure 39. RDF yield with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.1 Moisture content of RDF

Figure 40 and Figure 41 show how moisture content of RDF changes. Moisture content increases greatly, which is mainly because of great amount of food in heavies. When compared to moisture content design values of 28.9% and 28% shown in Table 18 in Chapter 4.3, moisture content in RDF with heavies added goes above these design values. It also exceeds the SRF standard limits shown in Table 35. This much increase in moisture content lowers the LHV noticeably and compared to the CFB boiler design values and the SRF standard limits might introduce ignition and incomplete combustion problems. Still, moisture content is way below theoretical combustion limit of 50% shown in the tanner diagram in Chapter 6.1.

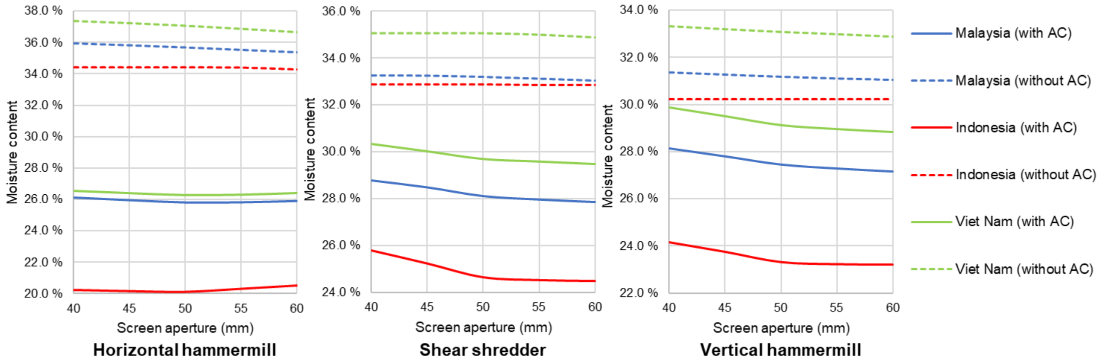

Figure 40. Moisture content of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

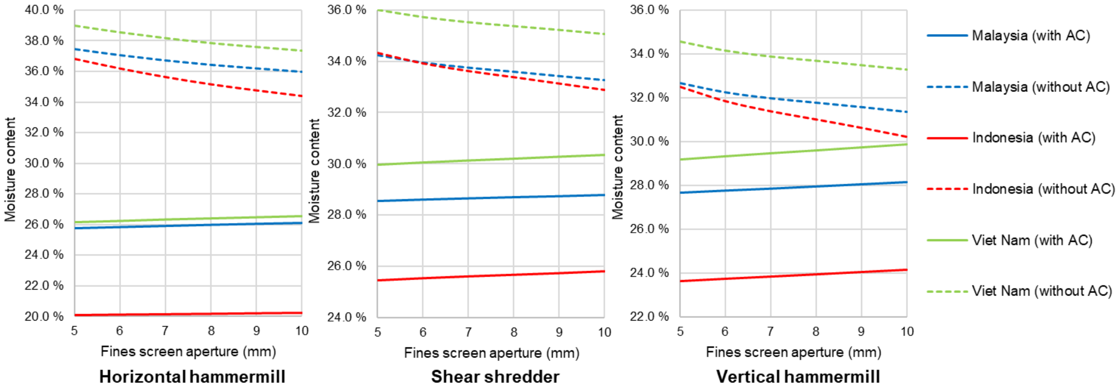

Figure 41. Moisture content of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.2 Particles below 90 mm

Figure 42 and Figure 43 show the amount of particles in RDF that are below 90 mm size. In Chapter 4.2.3 it was mentioned that 90% of particles should be under 90 mm. These results do not meet the requirement. Model with horizontal hammermill shredder and Indonesian waste input gets closest to the requirement. Even so, each model result shows that the amount of finer particles increase greatly, which changes the hydrodynamics of the boiler so that the heat absorption might increase. In the model the biggest increase in particles below 90 mm is because of food waste in the range of 10-30 mm. Materials with highest quantities of particles with size over 90 mm in RDF are textiles, diapers, and cardboard.

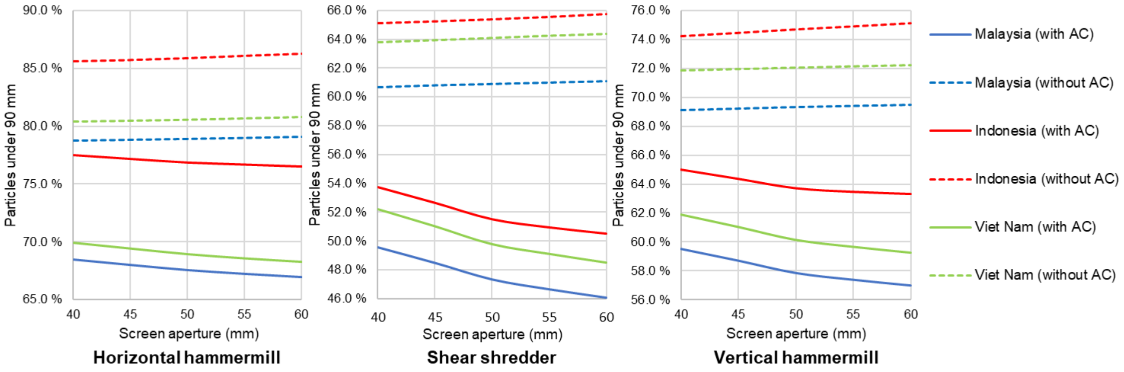

Figure 42. The amount of particles under 90 mm in RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

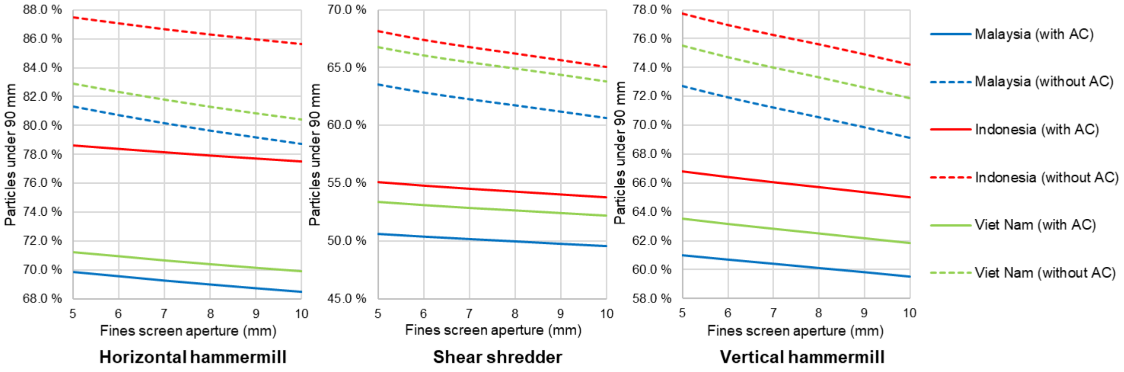

Figure 43. The amount of particles under 90 mm in RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.3 Sulfur content of RDF

Figure 44 and Figure 45 show how the sulfur content in dry basis of RDF changes. With air classifier 1 removed sulfur content mostly reduces. Abrupt changes in the figures are due to two decimal range. According to the model rubber is the biggest source of sulfur, and reduction happens because of added materials which have lower sulfur contents. Still, the sulfur content in every case remains higher than the design values in Table 18 and at best can be qualified as class III SRF according to Table 35. Based on the findings in Chapter 4.2, the amount of sulfur based low-melting compounds causing agglomeration and acid flue gases causing corrosion can reduce, but the high-temperature corrosion in tubes caused by chlorides can increase because sulfur reduces ash stickiness.

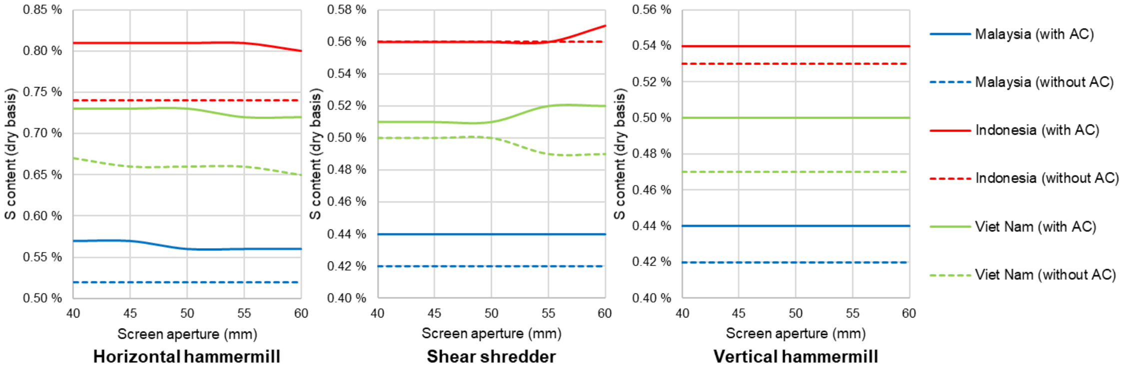

Figure 44. Sulfur content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

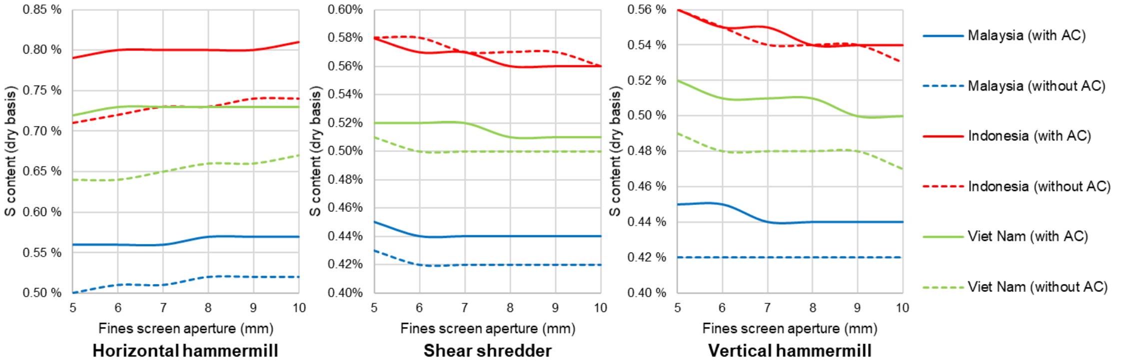

Figure 45. Sulfur content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.4 Ash content of RDF

Figure 46 and Figure 47 show how the ash content in dry basis of RDF changes. Ash increases significantly in each model variation. In this study the moisture reduction in biodrying was relatively same for each material, with Malaysian waste input as an example moisture content of food after biodrying is 73.92% and ash content in wet basis is 5.39%. Therefore, ash content in dry basis of food is 26.08%. This in addition to pure ash material categories in the heavies (sand and rock, glass, nonferrous, and ferrous) explains the big increase, with the biggest increase caused by food, glass, sand, and rock categories. In the horizontal hammermill model ash content remains below design values of 19.7% and 17.1% shown in Table 18 in Chapter 4.3, but in shear shredder and vertical hammermill models data from Malaysia and Viet Nam goes above them. Also, some of the ash results go below CDR (2006) SRF standard limit 15%, some below UNI 9903 SRF standard limit 20%, and some would not be qualified to SRF standards. Ash content is below Tanner diagram maximum amount of 60%, and because moisture content is also below limit values fuel would still be combustible without auxiliary fuels. A big increase in ash content leads to higher ash discharge capacity requirement, it could increase particulates emissions, and higher glass content in RDF increases risk of bottom ash chutes blockage.

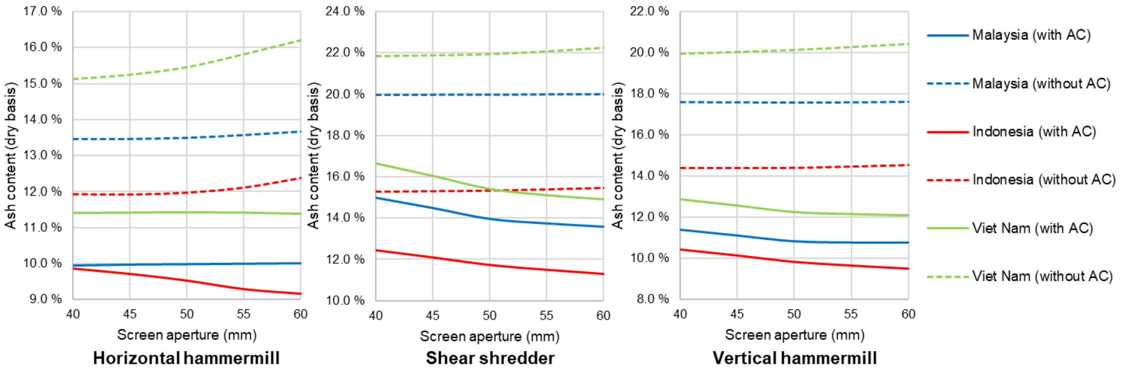

Figure 46. Ash content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

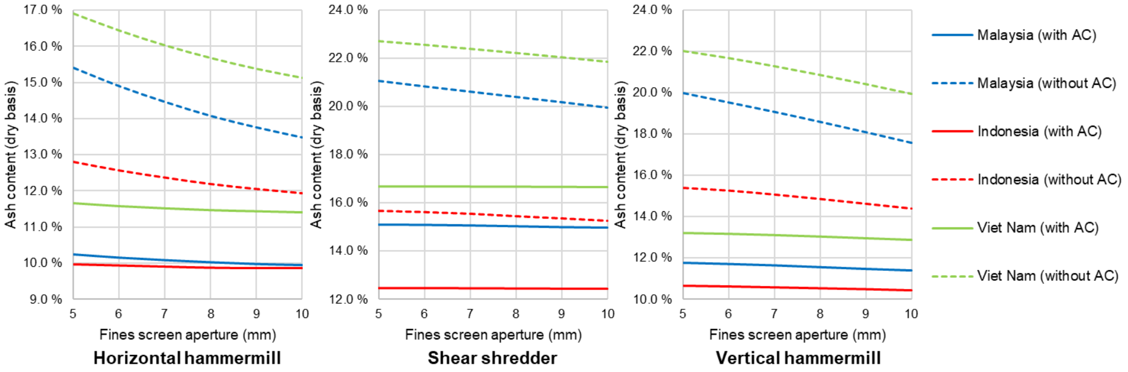

Figure 47. Ash content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.5 Lower heating value of RDF

Figure 48 and Figure 49 show how the lower heating value of RDF changes. In each model variation the LHV decreases greatly. This is due to the increasing moisture content coming from the food waste in the heavies. The LHV stays above the CFB boiler design value of 12.5 MJ/kg shown in Table 18 in Chapter 4.3 even though the moisture content goes above the design values. This is because of the high content of plastics in RDF, as is shown in Figure 34. According to Table 32 plastics have the highest LHV values of the waste materials. Only the Indonesian waste input manages to pass the minimum SRF standard limit of 15 MJ/kg shown in Table 35. When LHV decreases, the heat content available for heat transfer decreases and a constant thermal output would require higher feed rate of the fuel.

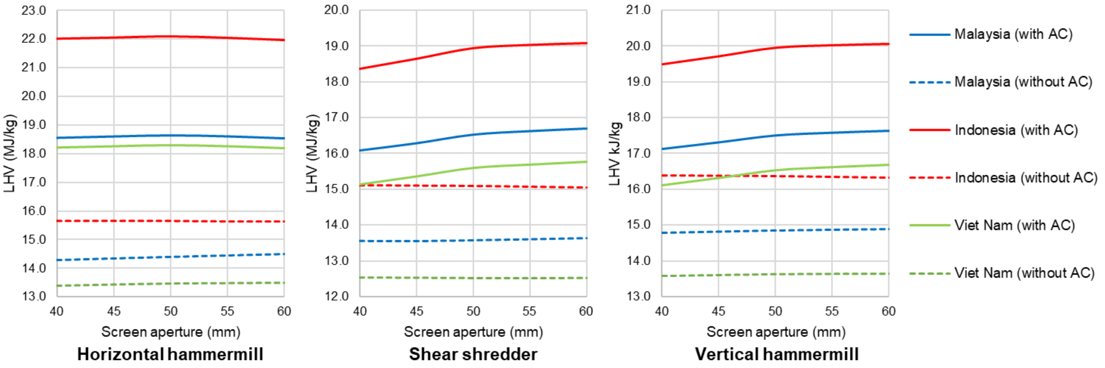

Figure 48. LHV of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

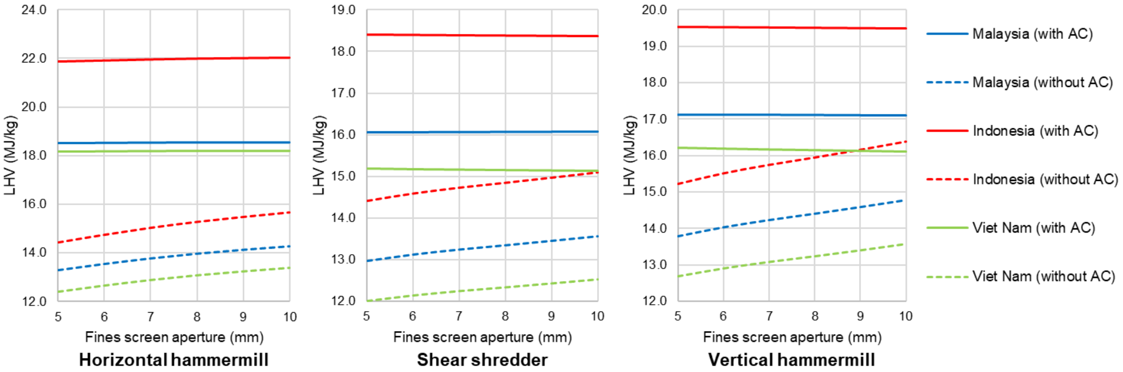

Figure 49. LHV of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.6 Chlorine content of RDF

Figure 50 and Figure 51 show how the chlorine content of RDF changes. In all the cases, except in horizontal hammermill variation with waste from Indonesia and Viet Nam, the chlorine content increases slightly. Material adding the most chlorine from the heavies is food waste, followed by rubber and plastics. For the horizontal hammermill model with the waste input from Indonesia and Viet Nam can be identified from Figure 36 and Figure 37 that those variations have much greater content of rubber/leather category, which explains the higher chlorine content than in the other model variations. Also, relative amount of rubber/leather also decreases greatly with the air classifier 1 removal, while in the other model variations relative amount does not change much. Table 34 shows that rubber has the biggest chlorine content out of the MSW materials and is 8 times more in a dry content than with food or plastics, which explains why the chlorine content decreases in those variations where rubber decreases. Even in all the unmodified cases the chlorine content is above the biggest design value of 0.83% shown in Table 18 in Chapter 4.3 and SRF standard value of 0.9% in Table 35. The single biggest source of chlorine in each model is rubber, followed by food and diapers. Since the chlorine content does not change much except in the shear shredder and vertical hammermill variations with waste from Indonesia, this chlorine increment might increase the corrosion risk only slightly. However, even with this slight increase in the chlorine content when considering that the decrease in the sulfur content increases the high temperature corrosion risk, their combined effect might increase the high temperature corrosion risk even more greatly.

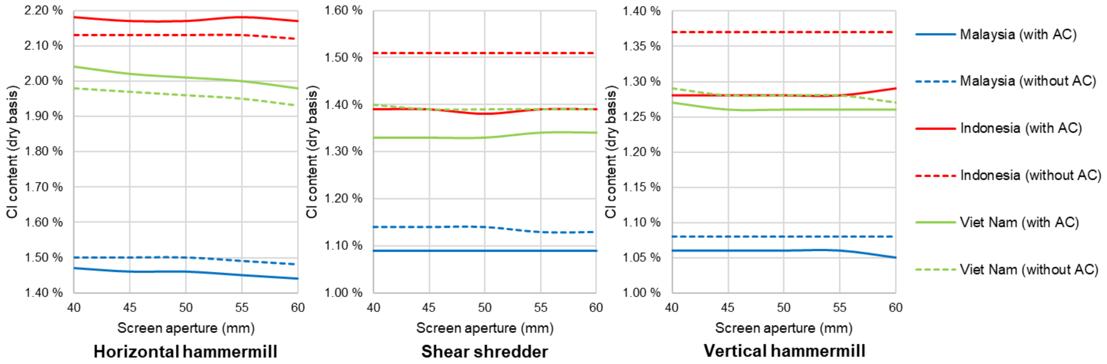

Figure 50. Chlorine content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

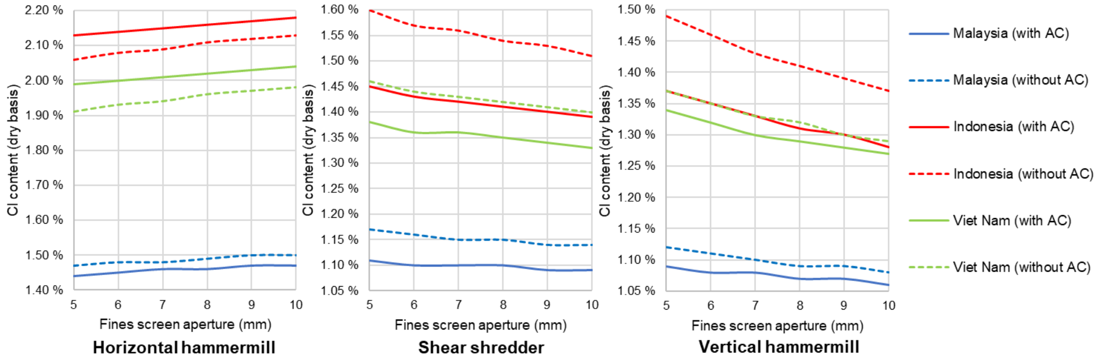

Figure 51. Chlorine content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.7 Potassium and sodium content of RDF

Figure 52 and Figure 53 show how the sum of potassium and sodium content of RDF changes. In the shear shredder variations in Figure 52 Viet Nam and Indonesia graphs for the process with air classifier 1 are overlapping, and so are the graphs of the same countries without the air classifier 1 in Figure 53. The sum increases greatly in all the variations. The biggest source of potassium and sodium in these models are food waste, followed by diapers and textiles. The heavies include big amounts of food waste, which is the main reason for huge increase of potassium and sodium content. Potassium and sodium are not included in the CFB boiler design values table shown in Table 18 in Chapter 4.3. According to the SRF quality standards shown in Table 35, RDF in the original case would be qualified to class II because the potassium and sodium content is below 0.4%, but with the air classifier 1 removed only half of the variations would go below class III limit of 0.5%. This much increase in the potassium and sodium content can increase the risk of agglomeration, slagging, and fouling.

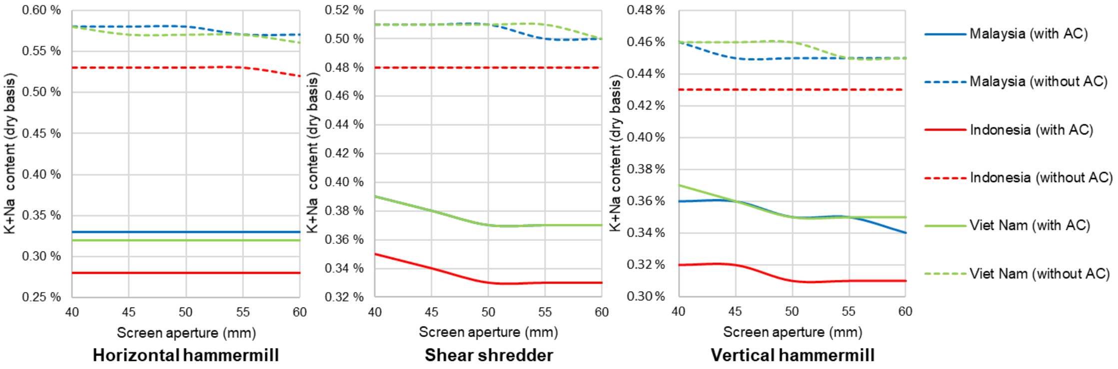

Figure 52. Potassium and sodium content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

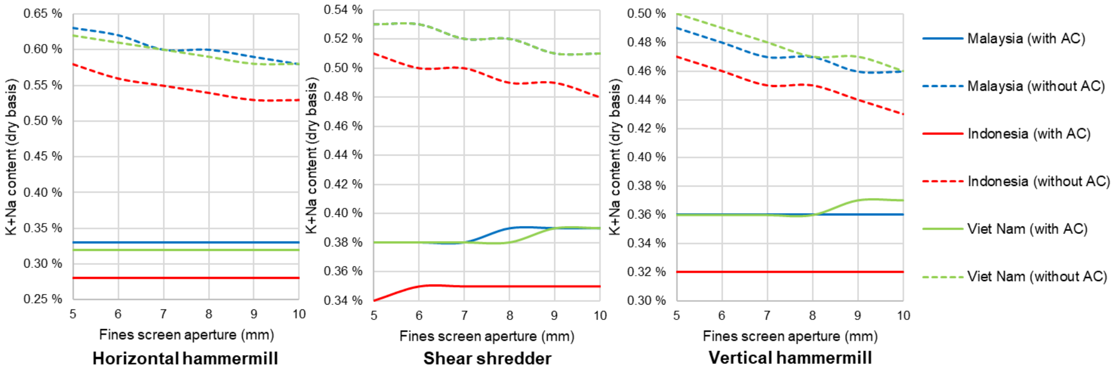

Figure 53. Potassium and sodium content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.8 Aluminum content of RDF

Figure 54 and Figure 55 show how the aluminum content of RDF changes. In each variation aluminum content increases greatly. This is due to the nonferrous content of the heavies shown in Figure 35. After the process modification, with all the shredder variations the aluminum content of RDF with the waste input from Malaysia stays below the design value of 1% shown in Table 18 in Chapter 4.3, but with the other countries the design value is exceeded. Even though in this study the waste from Indonesia and Viet Nam have almost the same metal content as is shown in Table 21 in Chapter 5.2, their resulting aluminum content in RDF differ greatly. This is because in the manual picking unit the recovery rate calculation is based on the total amount of hand-picked materials, which includes PET, HDPE, aluminum, cardboard, and Tetra Pak, and their total amounts are different for both countries. The manual picking unit also explains why the aluminum content is highly dependent on the screen aperture size. With a higher aperture size, less waste will go to the manual picking unit, which means less aluminum removed by the manual picking unit and more removed by the air classifier 1. In the modified version all the aluminum that would normally be removed by the air classifier 1 are fed into RDF. Increase in the aluminum content in the variations where the design value is exceeded could increase bottom ash disposal problems and ash deposition on the heat transfer surfaces.

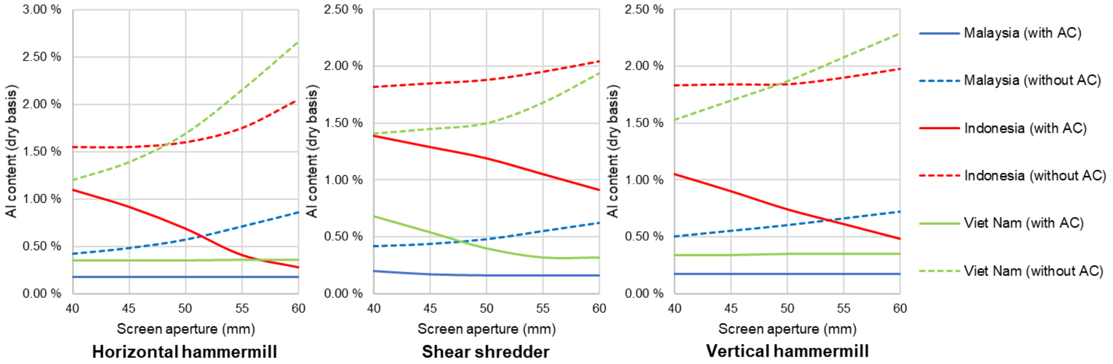

Figure 54. Aluminum content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

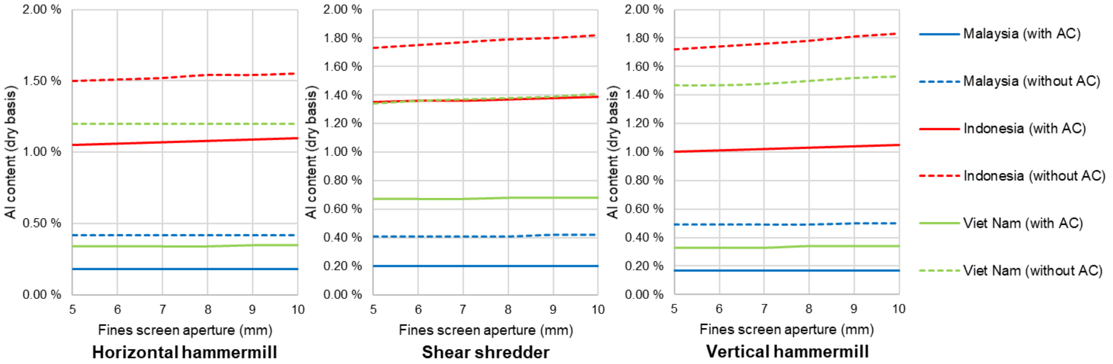

Figure 55. Aluminum content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.9 Lead content of RDF

Figure 56 and Figure 57 show how the lead content of RDF changes. In each variation, except with the waste from Viet Nam in the vertical hammermill variation, the lead content increases slightly when the air classifier 1 is removed. Lead is mainly coming from rubber, HDPE, PS, and food, and the order of them as lead source varies between the waste from different countries. The lead content values before and after the modification are below the design value of 200 ppm shown in Table 18 in Chapter 4.3 and below the second highest SRF quality limit value of 190 ppm shown in Table 35. This indicates that the lead content stays within suitable limits for CFB boiler, however there might be some slight increase in the risk for agglomeration, heavy metal corrosion, slagging, and fouling.

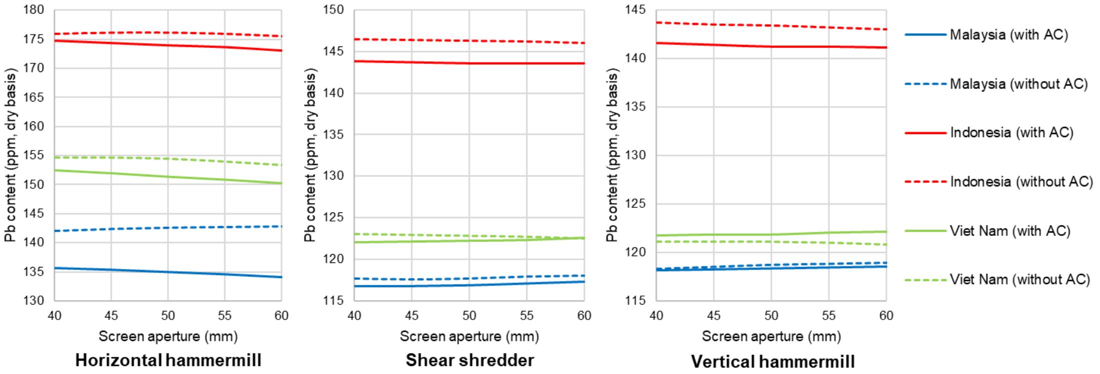

Figure 56. Lead content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

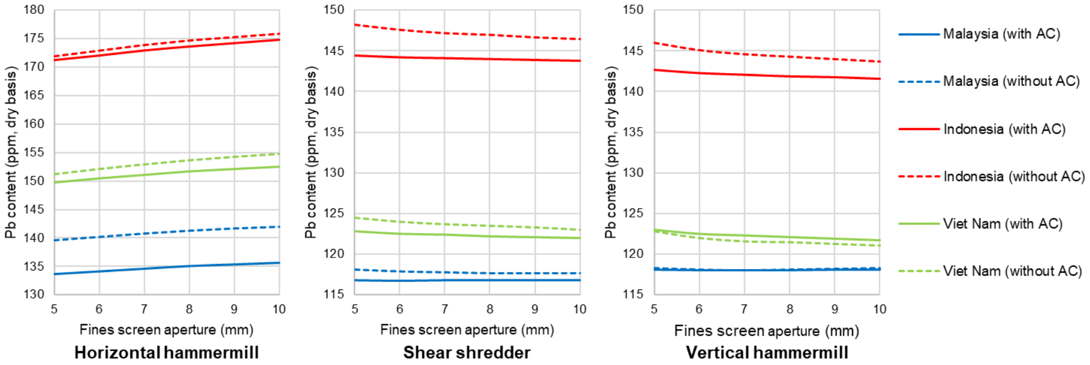

Figure 57. Lead content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.2.10 Zinc content of RDF

Figure 58 and Figure 59 show how the zinc content of RDF changes. In each case, except for the shear shedder and vertical hammermill variations with the waste from Indonesia, the zinc content decreases slightly. Zinc comes mainly from rubber. The decrease could be explained by a huge increase in food waste, which contains according to Table 34 relatively small amount of zinc compared to other materials such as rubber. According to Figure 35, the heavies in the shear shredder and vertical hammermill models with the waste from Indonesia have bigger leather and rubber content than the other countries, which explains the increasing zinc content. According to Table 34, rubber has 3800 ppm zinc content whereas food for example has only 110 ppm zinc content, which means that even small increments in the amount of rubber can increase the zinc content of RDF more than food waste content decreases. In all variations the zinc content stays below the CFB boiler design value of 800 ppm shown in Table 18 in Chapter 4.3 and the SRF quality limit value of 500 ppm shown in Table 35. This indicates that the zinc content is before and after the pre-treatment modification within suitable limits for CFB boiler and decrease in zinc content might decrease the risk for agglomeration, heavy metal corrosion, slagging, and fouling.

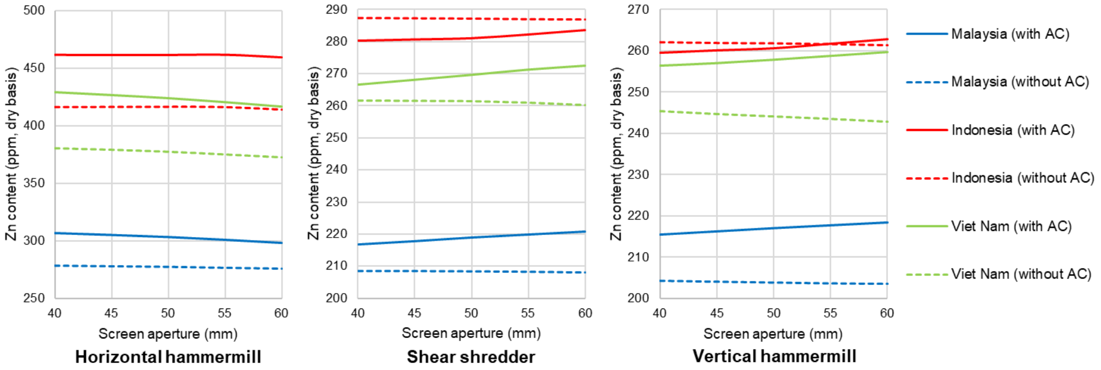

Figure 58. Zinc content (dry basis) of RDF with variable screen aperture (40-60 mm) and constant fines screen aperture (10 mm)

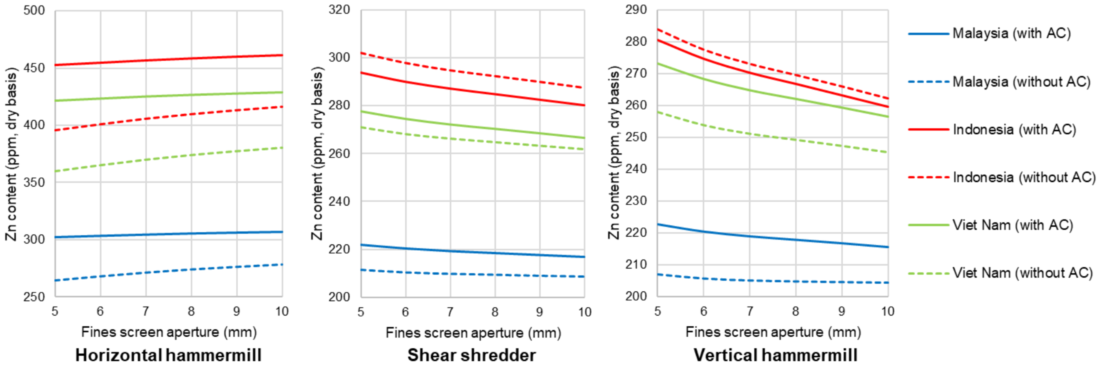

Figure 59. Zinc content (dry basis) of RDF with constant screen aperture (40 mm) and variable fines screen aperture (5-10 mm)

6.3 Summary of the analysis results

Table 30 shows a summary of the analysis results. At first, results before and after the removal of air classifier 1 for all shredder and input variations with 40 mm screen aperture and 10 mm fines screen aperture are shown. Blue color is for Malaysia, red for Indonesia and green for Viet Nam. ‘HH’ is horizontal hammermill, ‘SS’ is shear shredder and ‘VH’ is vertical hammermill. Then trend arrows are shown, which indicate how changes in each analyzed result affects the boiler performance. These are subjective estimations based on how much each parameter changes and what are the effects based on the analysis of each result. Last column shows if the design and quality limit values of each parameter were exceeded. 0 indicates that the results stay within the design and quality limits, 1 indicates that in some variations the limit values are not met and 2 indicates that most or all of the variations do not meet the requirements. RDF yield was excluded from the table as it was not considered relevant to the boiler performance.

Changes in the moisture content, ash content, lower heating value, potassium and sodium content and aluminum contents in RDF have a negative impact on the boiler performance. Out of these, the moisture content does not meet neither design nor quality limit values. This might not however be a critical issue. Considering that the waste fuel can be burned without auxiliary fuel when the moisture content is below 50% (chapter 6.2.1) and the CFB design values shown in Table 18 are from two decades ago, which almost certainly makes a difference in technologies handling the high moisture content issues such as emissions coming from incomplete combustion, this moisture content could be acceptable. Food waste is identified as being the biggest cause of the problems. By looking at the particle size distribution graphs in Figure 28, Figure 29 and Figure 30, increasing the fines screen aperture size up to for example 30 mm could make a significant reduction in the food waste content of RDF, but in this process it would reduce the RDF yield greatly. As the aluminum content increase is mainly due to the nonferrous materials, one solution would be to add an eddy current separator (Chapter 3.5.5) before the RDF bunker if the aluminum content of RDF was to be considered problematic. Increase in the fines screen aperture size would also make a slight difference if adding new equipment was not an option.

Changes in the sulfur content, chlorine content and lead content in RDF does not make much difference to the boiler performance. The chlorine content before and after the modification is above both the design and the quality limit values. An increase in the fines screen aperture in the shear shredder and vertical hammermill models could slightly reduce the amount of rubber, which has the biggest chlorine content in dry basis. Also, an optical sorting unit (Chapter 3.5.7) could be considered for reducing plastics, which are another relevant source of chlorine.

Changes in the amount of particles under 90 mm and the zinc content in RDF makes a positive impact on the boiler performance. Even so, the particle size distribution still does not meet the design value limit. Textiles and diapers are making the biggest impact on lowering the content of particles under 90 mm. They could be removed in the manual picking line alongside with plastics, cardboard, and aluminum since they are mainly problematic for the boiler.

Removing the air classifier for undersized refuse would lower the quality of RDF and introduce some problems for the boiler, but the fuel would be still combustible and might require some changes in the boiler, but studying those required changes is not in the scope of this thesis.

Table 30 Summary of the analysis results with 40 mm screen aperture and 10 mm fines screen aperture

Analyzed result	Results with AC1	Results without AC1	Boiler performance trend arrow	Design and quality limit values exceeded
Moisture	HH: 26.1%/20.2%/26.6% SS: 28.8%/25.8%/30.3% VH: 28.2%/24.2%/29.9%	HH: 35.9%/34.4%/37.4% SS: 33.3%/32.9%/35.1% VH: 31.4%/30.2%/33.3%	↘	2
Particles under 90 mm	HH: 68.5%/77.5%/69.9% SS: 49.6%/53.8%/52.2% VH: 59.5%/65.0%/61.9%	HH: 78.8%/85.6%/80.4% SS: 60.7%/65.1%/63.8% VH: 69.1%/74.2%/71.9%	↗	2
S (dry basis)	HH: 0.57%/0.81%/0.73% SS: 0.44%/0.56%/0.51% VH: 0.44%/0.54%/0.50%	HH: 0.52%/0.74%/0.67% SS: 0.42%/0.56%/0.50% VH: 0.42%/0.53%/0.47%	→	1
Ash (dry basis)	HH: 10.0%/9.9%/11.4% SS: 15.0%/12.4%/16.7% VH: 11.4%/10.4%/12.9%	HH: 13.5%/11.9%/15.1% SS: 20.0%/15.3%/21.9% VH: 17.6%/14.4%/20.0%	↘	1
LHV	HH: 18.6/22.0/18.2 MJ/kg SS: 16.1/18.4/15.1 MJ/kg VH: 17.1/19.5/16.1 MJ/kg	HH: 14.3/15.7/13.4 MJ/kg SS: 13.6/15.1/12.5 MJ/kg VH: 14.8/16.4/13.6 MJ/kg	↘	1
Cl (dry basis)	HH: 1.47%/2.18%/2.04% SS: 1.09%/1.39%/1.33% VH: 1.06%/1.28%/1.27%	HH: 1.50%/2.13%/1.98% SS: 1.14%/1.51%/1.40% VH: 1.08%/1.37%/1.29%	→	2
K+Na (dry basis)	HH: 0.33%/0.28%/0.32% SS: 0.39%/0.35%/0.39% VH: 0.36%/0.32%/0.37%	HH: 0.58%/0.53%/0.58% SS: 0.51%/0.48%/0.51% VH: 0.46%/0.43%/0.46%	↘	1
Al (dry basis)	HH: 0.18%/1.10%/0.35% SS: 0.20%/1.39%/0.68% VH: 0.17%/1.05%/0.34%	HH: 0.42%/1.55%/1.20% SS: 0.42%/1.82%/1.41% VH: 0.50%/1.83%/1.53%	↘	1
Pb (dry basis)	HH: 136/175/153 ppm SS: 117/144/122 ppm VH: 118/142/122 ppm	HH: 142/176/155 ppm SS: 118/147/123 ppm VH: 118/144/121 ppm	→	0
Zn (dry basis)	HH: 307/462/429 ppm SS: 217/280/267 ppm VH: 216/260/257 ppm	HH: 279/416/381 ppm SS: 209/287/262 ppm VH: 204/262/245 ppm	↗	0

The results indicate that by evaluating the effects on the boiler at this detailed level when cost saving modifications are made to the waste fuel pre-treatment system gives better input data for evaluating combustibility of the waste fuel and the resulting changes in the boiler. When costs for an air classifier unit and heavies handling are reduced, based on the results, for example, bottom ash handling costs will increase. Estimating cost efficiency of the modification is not within the scope of this thesis. The results also indicate that the waste in Southeast Asia from different countries and with different shredder equipment would make a difference in the resulting RDF quality. This would suggest that the waste from different parts of Southeast Asia would require dedicated solutions to both pre-treatment and boiler processes depending on the location and there is need for more detailed study on particle size distributions of shredders, because for example, as is shown in Table 30 different shredder types make big differences in the amount of particles under 90 mm, ash content, and chlorine content. In Chapter 3.5.1 was mentioned that making accurate models of shredders have been difficult because of many variables affecting the particle size distribution, thus the particle size distributions for horizontal hammermill, shear shredder, and vertical hammermill presented in this thesis might be accurate for only certain conditions. Even having some range of variation for the PSD of each material would give better estimates on the worst-case RDF quality coming from the pre-treatment system, if size-based separation units are included in the pre-treatment process after shredding. Overall, the analysis results show that in each variation output parameters mostly change into the same direction and regardless of the variations in input parameters approximate conclusions can be made on how the boiler performance would be affected.

As was discussed in Chapter 5, many simplifications and assumptions were made in the pre-treatment process modelling. As the only detailed information of waste composition was from Malaysia, composition of the waste from Indonesia and Viet Nam was estimated based on those findings. Also, only household municipal solid waste with hazardous waste and electronic waste excluded was presented as the input waste to the pre-treatment system. Waste coming from different sources within each country with different compositions could make a significant difference in the end results, but the chosen waste data was considered to represent the average composition well enough for this study. It should be noted that waste coming to the pre-treatment process could also include aggregates, construction debris, or other materials not included in the municipal waste composition study used as a reference for input composition. This could make a difference in estimating the problems caused by the removal of air classifier, for example if the heavies would contain lots of materials that would block feeding conveyors or bottom ash chutes of the boiler.

The pre-treatment unit models were based on literary findings, which could be inaccurate with modern equipment, and the parameter values were chosen so that they would represent the case as realistically as possible with the available information. Each unit also has more variables than those used in this thesis, such as the effect of moisture content on the separation rate in air classifiers or the effect of particle size on the separation rates in a manual picking unit. Change in the elementary composition of each material after the biodrying might bring inaccuracies in this study, for example if the moisture removed with the extract in the fines screen is higher than in the model or if in the biodrying the amount of elements such as chlorine is reduced from the process by dissolving into the evaporating water. Judging from all the variables that would lead to inaccuracies, the output parameters would have some error compared to values gained from an actual case process, but even so this modelling allows the RDF quality changes resulting from modifications in a pre-treatment system to be studied. The accuracy could be improved by a more detailed study on the performance of each process unit, but due to the scope of this thesis this level of detail used in this study was considered to be accurate enough to make conclusions in this case study.

Validation data for the results from an existing plant was not available. Also, considering that waste is highly heterogeneous, samples for a validation would have to be taken within wide time frame to show average values more accurately. When considering each individual unit in a pre-treatment system, the performance results from for example an air classifier could vary based on the composition of incoming refuse to the unit and different unit designs from different manufacturers might make a difference, and even performance results from different studies (Table 12 in Chapter 3.5.3) show wide variation. By comparing the heavies content shown in Figure 35 to the air classifier example extract composition in Table 12, ferrous metal, paper and cardboard contents are highest in Table 12, while their amount is less significant in the studied model in all the variations and the content of food and plastics is higher. This is because in the study by Velis (2010, p. 1031) details of the process and the waste composition before the waste comes to the air classifier are not explained for paper, cardboard, and plastics, and the rest of the purity values are from an air classified oversized product coming from a 25 mm screen in a non-MBT plant. This is a good example on the difficulty of comparing different theoretical data on the performance of pre-treatment units to each other. Validating the results of this thesis would require comparison of exactly the same process with the model, and even then waste feed might show variations to the used input waste composition depending for example on the time of the year and on how many samples were taken. When comparing the RDF output of the model in this thesis to RDF from different countries shown in Table 8, Table 8 itself shows wide variation in the RDF quality between different countries, in the original source is not specified whether the ash and chlorine content are on wet or dry basis, the waste input composition changes between each country (Di Lonardo, Lombardi and Gavasci, 2012, p. 363), and most likely each of the RDF in the table is produced with a different pre-treatment process. This indicates that estimating the deviation from existing results is difficult.

The results were calculated with different parameter variations to make more reliable conclusions. The modelling was based on literature findings available on the subject and the modelling of each unit in the process was made with the highest consideration on being as detailed and accurate as possible with the information available on the performance of each process unit and the time available to finish the thesis. The RDF quality analysis accuracy of this pre-treatment modelling is questionable without further validation, but the results would still indicate that even with varying parameters consistent conclusions can be made on the direction of changes to the different RDF quality parameters when a pre-treatment system is modified. The reliability of this methodology is dependent on the level of detail of the performance modelling of each process unit. This type of pre-treatment process modelling would however point to the right direction in finding an optimal combination of waste fuel pre-treatment and boiler technology solutions for different kinds of waste input.

7. SUMMARY AND CONCLUSIONS

Since the municipal solid waste, waste fuel pre-treatment process, and waste fuel boiler are interconnected whole it is important to understand the causalities between them. The goal of this thesis was to gain an understanding on the waste fuel pre-treatment process from the CFB boiler point of view. The secondary goal was to understand how different variables in the waste source and the pre-treatment process will affect RDF quality and therefore affect the boiler performance. Waste source variation was studied within Southeast Asia region for three different countries representing different development tiers. A typical pre-treatment process case suitable for treating waste with high organic and moisture content was studied. Then was identified how different properties of RDF will affect the boiler performance. The pre-treatment case process was modelled based on the information found on the waste composition in Southeast Asia and performance of each pre-treatment process unit, and the model was used to study how RDF quality changes when the air-classifier for undersized refuse is removed from pre-treatment system to reduce the amount of reject flows. Different waste input and process variables were used to validate the conclusions on the effects of the pre-treatment process modification.

Study on the waste generation and management in Southeast Asia showed that because of rapid urbanization waste generation in the region is expected to rise significantly and each country in the region has its own waste management programs. Municipal solid waste composition varies a lot with different countries, and even within one country waste can be highly heterogeneous since waste management legislations and directives are not yet well utilized in the region. Also, Southeast Asian countries tackle with plastic and electronic waste dumped there from around the world. Therefore, one conclusive profile on the Southeast Asian waste cannot be made. Common in the waste composition is that it has a high content of food and organic waste which makes the moisture content high. Political interest in ecological waste management in Southeast Asia is increasing, and after the waste-sorting issues are solved emerging waste-to-energy technologies will be more efficient.

As Southeast Asian waste by itself requires pre-treatment to be burned as a fuel in CFB boiler, a biological-mechanical treatment process was studied, because it is suitable for treating waste with high moisture content. Many different mechanical equipment and process variations exist for pre-treatment, but this study focused on a single case process. In the studied process was shown that reject is separated based on particle size, density, magneticity, and visual inspection. Because the waste in Southeast Asia has high organic content, the moisture lost in biodrying makes this type of pre-treatment process have higher rejection rates than typical pre-treatment processes. It was shown that the performance of each pre-treatment unit is affected by many variables in how the unit is operated, what is the mechanical design, and what are the characteristics of the waste coming to the unit. Literature based findings on the performance of each process unit were used on modelling an Excel calculation tool for the analysis.

Study on the effects of waste particles on CFB boiler showed that combustion issues are caused by many different components. Some of the most significant issues were shown to be corrosion, fouling, and high bottom ash flow. For this study the most relevant components causing issues and materials in which they are included were identified. Food waste was shown to be the cause for many different issues, and other relevant materials included rubber, textiles, and plastics. These findings were used in the analysis of how the pre-treatment process modification affects the boiler and what are the causes.

The analysis results of the pre-treatment process modification show that the overall RDF quality gets worse when air classifier for undersized refuse is removed. Lower heating value decreases, the amount of ash to be disposed increases, and the risk of agglomeration, slagging, and fouling increases. The only relevant performance improvement is that the particle size distribution of the fuel becomes finer. Still, the results would indicate that only the moisture content, amount of particles under 90 mm size, and chlorine content would not meet the design and quality limit values used in this thesis with all the different variables, while the other analyzed results would be within the limits in some or all of the variations. It should be noted that the design values used for comparison might be dated and show only one general example of CFB boilers, so more careful judging of the results is required.

The results from the Excel calculation tool used in this thesis have not been validated and errors are most likely to occur due to assumptions and simplifications made in the modelling. This methodology used in this thesis should be considered as an example to improve waste fuel pre-treatment process modelling so that the relevant RDF characteristics from the CFB boiler point of view are considered in the modelling and shown as the output results. This amount of detail without validation is enough to show estimations on the directions of how different RDF properties changes when modifications are made to the model. Suggestions to improve the model accuracy and reliability is to take more variables into account and to use performance data of the modern pre-treatment equipment that are currently used. As the amount of waste generated increases in Southeast Asia and there is increasing awareness on the environmental impact of waste disposal, it is indication that rejects from waste-to-energy processes should be minimized in the future. This will increase the importance of understanding better how a waste-to-energy process consisting of waste fuel pre-treatment and CFB boiler can be optimized to meet the demands of modern times and improving the pre-treatment process modelling is a step towards that goal.

The main contributions of this thesis are:

- Showing estimations on the combustibility of RDF, which is derived from Southeast Asian waste pre-treated in a biological-mechanical pre-treatment case process
- Suggesting a modelling method for the waste fuel pre-treatment process, which would allow estimating the process modification effects on the fuel entering CFB boiler
- Providing information on the waste generation and management in Southeast Asia, equipment used in biological-mechanical pre-treatment process, and how different waste fuel properties and particles affect the CFB boiler
- Suggesting how accuracy of the waste pre-treatment process modelling could be improved

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APPENDIX A: WASTE CHARACTERIZATION TABLES

Table 31. Waste generated, discarded and disposed by Malaysian households (Bandar and Tempatan 2013, p. 70)

	Waste Components	**As Generated MT/day**	**As Discarded MT/day**	**As Disposed MT/day**	**As disposed Percentages (original)**	**As disposed percentages (modified for thesis)**
Organics	Food Waste	9 685	8 563	8 492	43.8%	44.7%
	Garden Waste	1 252	1 240	1 445	7.5%	7.6%
	Wood	88	88	92	0.5%	0.5%
	Peel Husk	206	217	248	1.3%	1.3%
Paper	Mixed Paper	310	286	273	1.4%	1.4%
	Newsprint Old Newspaper	677	475	380	2.0%	2.0%
	Cardboard	841	697	567	2.9%	3.0%
Plastics	Polyethylene Terephthalate (PET)	538	463	374	1.9%	2.0%
	High-Density Polyethylene (HDPE)	774	610	604	3.1%	3.2%
	Polyvinyl Chloride (PVC)	107	92	90	0.5%	0.5%
	Low-Density Polyethylene (LDPE)	832	782	717	3.7%	3.8%
	Polypropylene (PP)	290	263	188	1.0%	1.0%
	Polystyrene (PS)	293	293	299	1.5%	1.6%
	Other Plastics	16	16	33	0.2%	0%
Glass	Glass Bottle	707	528	521	2.7%	2.7%
	Sheet Glass	12	30	59	0.3%	0.3%
Metals	Ferrous Metal	383	336	211	1.1%	1.1%
	Aluminium	197	160	85	0.4%	0.4%
	Other Nonerrous Metals	15	15	16	0.1%	0%
Household Hazardous Waste	Batteries	23	22	22	0.1%	0%
	Fluorescent Tube	56	48	48	0.2%	0%
	E-Waste	30	52	52	0.3%	0%
	Aerosol Cans	155	140	140	0.7%	0%
	Paint Container	20	20	20	0.1%	0%
Others	Tetra Pak	343	308	282	1.5%	1.5%
	Diapers	2 625	2 625	2 625	13.5%	13.8%
	Rubber	309	309	399	2.1%	2.1%
	Textiles	661	660	660	3.4%	3.5%
	Leather	84	85	99	0.5%	0.5%
	Porcelain / Ceramic/Stones	93	95	289	1.5%	1.5%
	Other Minor components	5	8	48	0.2%	0%

Table 32. Proximate analysis, ultimate analysis and calorific values of different materials in Malaysian household waste (Bandar and Tempatan 2013, p. 94)

	Proximate Analysis				Ultimate Analysis					Calorific Value	
	Moisture content %	**Volatile Matter, wet basis %**	**Fixed Carbon, wet basis %**	**Ash Content, wet basis %**	**C, wet basis %**	**H, wet basis %**	**O, wet basis %**	**N, wet basis %**	**S, wet basis %**	**Higher Heating Value dry, kJ/kg**	**Lower Calorific Value wet, kJ/kg**
Food	82.00	14.30	1.54	2.16	7.88	1.2	5.6	1.09	0.05	12 427	229
Garden	30.85	50.46	11.14	7.55	30.7	3.01	26.88	0.81	0.2	17 522	11 356
Mixed Paper	54.57	34.51	3.70	7.22	21.63	3.2	12.39	0.79	0.2	20 536	7 988
Newsprint	22.73	74.33	1.03	1.90	37.78	6.5	29.5	1.35	0.23	16 209	11 953
Cardboard	12.17	72.53	7.36	7.94	37.39	7.15	33.18	1.61	0.56	16 466	14 148
Tetra Pak	14.70	71.20	7.33	6.78	38.41	6.39	32.21	1.2	0.32	14 884	12 323
PET	5.69	92.46	0.93	0.92	79.37	8.06	4.95	0.88	0.12	33 755	31 678
HDPE	5.65	91.64	1.30	1.41	76.24	9.26	6.4	0.74	0.3	34 706	32 584
PVC	7.29	79.78	3.77	9.17	69.58	7.3	4.17	1.17	1.33	32 143	29 607
LDPE	44.69	50.40	0.96	3.95	40.62	6.14	3.72	0.74	0.14	29 924	15 443
PP	24.52	61.93	6.45	7.10	49.46	7.14	9.99	1.65	0.14	30 620	22 498
PS	10.32	88.19	0.29	1.20	67.79	8.37	10.33	1.42	0.58	31 725	28 180
Diapers	76.69	19.91	1.72	1.68	9.93	2.26	9.1	0.26	0.08	25 434	4 049
Textile	53.80	37.86	7.31	1.03	25.39	3.19	15.83	0.56	0.21	18 185	7 079
Rubber	2.96	87.76	0.92	8.36	66.58	5.14	13.51	0.99	2.47	23 092	22 323
Leather	4.66	81.54	4.86	8.95	58.74	8.64	16.56	1.53	0.93	26 337	24 977
Wood	15.92	72.07	10.89	1.11	43.65	6.52	31.34	1.21	0.25	20 092	16 488

Table 33. Metal analysis (ppm) of the individual components (Bandar and Tempatan 2013, p. 95)

	Mercury	Vanadium	Chromium	Manganese	Iron	Cobalt	Copper	Zinc	Arsenic	Silver	Cadmium	Lead	Aluminium	Magnesium	Nickel
Food	0.005	0.081	5.46	13.91	31	0.07	0.63	2.95	0.067	0.100	0.010	0.077	-	9.20	2.88
Garden	0.018	0.837	4.68	92.71	226	0.20	3.69	17.15	1.218	0.188	0.030	0.851	-	35.89	0.22
Mixed Paper	-	0.796	59.22	19.20	137	0.62	7.38	109.69	0.760	0.205	0.177	0.245	-	23.59	1.14
Newsprint	0.022	1.412	57.89	35.99	535	0.32	9.68	16.93	0.524	0.349	0.082	2.108	-	39.41	1.18
Cardboard	0.033	1.447	12.55	44.23	174	0.57	15.71	14.78	0.566	0.848	0.051	0.263	-	45.32	0.64
Tetra Pak	0.036	0.616	18.52	29.25	4 597	1.07	2.57	75.87	0.679	0.587	0.206	0.092	3 262	45.12	19.20
PET	0.034	0.986	134.06	6.21	2 706	0.34	6.19	200.20	1.173	0.504	0.106	2.490	-	51.17	2.90
HDPE	0.023	1.347	90.00	1.23	148	5.03	2.84	368.04	0.351	0.504	4.057	0.900	-	50.33	2.96
PVC	0.022	1.396	87.49	1.82	141	7.32	1.94	358.41	0.295	0.536	3.197	0.510	-	51.43	3.75
LDPE	0.029	0.698	108.88	4.14	1 019	0.52	2.44	149.89	1.034	0.878	0.046	3.094	-	30.31	1.77
PP	0.027	1.632	75.16	1.59	122	2.82	3.30	271.74	0.257	0.456	1.096	0.507	-	42.89	0.59
PS	-	1.322	6.78	37.56	231	1.05	3.12	33.88	1.343	0.500	0.084	0.737	-	49.12	1.45
Diapers	-	0.358	1.76	0.46	32	0.10	0.43	9.74	0.093	0.135	0.070	0.669	-	12.14	0.13
Textile	0.017	0.235	69.49	2.52	89	0.08	0.96	11.66	0.455	0.222	0.030	0.877	3 225	24.61	0.23
Rubber	0.037	6.121	-	30.89	841	1.43	227.44	1 714.35	1.432	0.398	0.670	1.461	2 069	41.79	2.68
Leather	0.048	8.345	-	35.71	1 139	2.79	278.44	2 188.07	2.059	0.473	0.040	1.770	2 541	51.19	3.04
Wood	0.044	0.281	50.84	3.13	78	0.37	3.95	13.48	0.309	0.264	0.045	1.130	3 455	44.31	0.84

Table 34. Elemental analysis of components of household MSW (Nasrullah et al., 2016, p. 41)

Element	Unit	Paper	Plastic (hard)	Plastic (soft)	Textile	Rubber	Foam	Wood	Food Waste
Cl	wt %, d	0.15	1.6	0.83	1.1	8.0	0.75	0.05	1.2
F	wt %, d	0.002	0.003	0.004	0.004	0.001	<0.001	<0.001	0.002
Br	wt %, d	0.001	0.001	0.001	0.008	0.001	0.001	0.001	0.001
Na	mg/kg, d	1 400	570	1 300	3 700	980	800	220	11 200
K	mg/kg, d	940	440	1 200	1500	420	670	710	7 600
Mn	mg/kg, d	32.0	25.0	37.0	42.0	30.0	25.0	49.0	58.0
Cr	mg/kg, d	15.0	67.0	41.0	5300	87.0	37.0	7.0	37.0
Cu	mg/kg, d	31.0	24.0	37.0	77.0	1400	40.0	4.7	140
Ni	mg/kg, d	6.0	26.0	18.0	31.0	32.0	17.0	3.3	14.0
Zn	mg/kg, d	47.0	170	160	310	3 800	3 800	20	110
Sb	mg/kg, d	3.0	56.0	5.0	62.0	170	2.8	1.8	3.4
As	mg/kg, d	0.43	0.61	1.0	2.4	0.6	0.5	0.1	0.8
Cd	mg/kg, d	1.2	9.0	0.50	3.1	1.5	0.5	0.12	0.1
Co	mg/kg, d	1.0	2.0	1.4	2.4	4.8	1.6	<0.5	1.4
Pb	mg/kg, d	12.0	500	19.0	63.0	370	38.0	3.0	120
Mo	mg/kg, d	0.9	1.6	21.0	4.0	2.2	1.3	0.5	1.8
Se	mg/kg, d	0.84	1.2	0.8	1.0	1.0	1.6	<0.53	1.1
Tl	mg/kg, d	<0.5	<0.5	<0.5	0.5	0.5	<0.5	<0.5	-
V	mg/kg, d	4.1	2.2	6.5	6.2	4.3	5.0	0.98	4.3
Hg	mg/kg, d	0.05	0.05	0.1	0.2	0.2	0.1	0.05	0.05

Table 35. Limit values for existing SRF quality standards (Velis et al., 2010, p. 1047-1048)

		Italy		Germany		Finland			EURITS
Parameter	**Units**	**CDR (2006)**	**UNI 9903**	**Median**	**80th percentile**	**Class I**	**Class II**	**Class III**	**Cement kilns**
Moisture content	% ar	<18	<25						
Ash content	% d	<15	<20						5
Nitrogen (N) content	% ar/d					<1.00	<1.50	<2.50	0.7
Sulfur (S) content	% ar/d	<0.3 d	<0.6 ar			<0.20	<0.30	<0.50	
Chlorine (Cl) content	% d	<0.7	<0.9% ar			<0.15	<0.5	<1.5	<0.5
Lower calorific value	kJ/kg ar	>20 000	>15 000						>15 000
Cd + Hg	mg/kg d		<7						
Sb	mg/kg d			50	120				
As	mg/kg d		9	5	13				
Cd	mg/kg d	<3		4	9	<1.0	<4.0	<5.0	
Cr	mg/kg d	<70	<100	125	250				
Co	mg/kg d			6	12				
Cu	mg/kg d	<50 soluble	<300 soluble	350					
Pb	mg/kg d	<100 volatile	<200 volatile	190					
Mn	mg/kg d	<200	<400	250	500				
Hg	mg/kg d	<1		0.6	1.2	<0.1	<0.2	<0.5	<2
Ni	mg/kg d	<30	<40	80	160				
K+Na	% d					<0.20	<0.40	<0.50	
Tl	mg/kg d			1	2				<2
V	mg/kg d			10	25				
Zn	mg/kg								500

Table 36. Melting points of common eutectic mixtures (Niessen, 2010, p. 108)

Eutetic mixture	Melting point (°C)
NaCl (100%)	800
NaSO4 (100%)	884
Na2CO3 (100%)	851
Na2O-SiO2 (100%)	800
MgSO4 (100 %)	1 185
MgSO4 (41%), Na2SO4 (59%)	660
Na2O-SiO2 (55%), Na2SO4 (45%)	635
NaCl (35%), Na2SO4 (65%)	623
NaCl (38%), Na2CO3 (62%)	633
Na2SO4 (53%), Na2CO3 (47%)	828

APPENDIX B: SHREDDER PARTICLE SIZE DISTRIBUTION TABLES

Table 37. Shear shredder particle size distribution (Bond, Temple and Grubbs, 1986, section 2 p. 13)

	Percentages of total mass									
Particle size range (mm)	**>304.8**	**203.2-304.8**	**152.4-203.2**	**101.6-152.4**	**50.8-101.6**	**25.4-50.8**	**12.7-25.4**	**6.35-12.7**	**3.175-6.35**	**<3.175**
Paper	0.00%	0.13%	0.89%	7.83%	6.71%	2.83%	0.99%	0.23%	0.04%	0.00%
Plastic	0.00%	0.24%	3.69%	2.98%	3.26%	1.54%	0.61%	0.28%	0.10%	0.00%
Cardboard	0.00%	1.51%	1.50%	5.48%	4.33%	2.12%	0.80%	0.19%	0.01%	0.00%
Textiles	0.00%	0.83%	0.47%	1.09%	1.30%	0.46%	0.23%	0.07%	0.00%	0.00%
Wood	0.00%	0.00%	0.41%	0.57%	1.53%	1.27%	0.74%	0.45%	0.22%	0.00%
Other Organics	0.00%	0.00%	0.18%	0.62%	0.83%	1.81%	2.57%	2.20%	1.75%	5.51%
Glass	0.00%	0.00%	0.00%	1.03%	1.72%	2.72%	3.05%	2.18%	0.57%	0.20%
Inerts	0.00%	0.00%	0.00%	0.00%	0.57%	0.64%	0.77%	0.66%	0.98%	2.20%
Ferrous	0.00%	0.00%	1.04%	1.03%	2.56%	1.36%	0.38%	0.14%	0.07%	0.05%
Nonferrous	0.00%	0.00%	0.00%	0.23%	1.67%	0.51%	0.21%	0.02%	0.02%	0.00%

Table 38. Vertical hammermill shredder particle size distribution (Bond, Temple and Grubbs, 1986, section 2 p. 14)

	Average size of the particle (mm)									
Particle size range (mm)	**>304.8**	**203.2-304.8**	**152.4-203.2**	**101.6-152.4**	**50.8-101.6**	**25.4-50.8**	**12.7-25.4**	**6.35-12.7**	**3.175-6.35**	**<3.175**
Paper	0.00%	0.00%	0.77%	7.83%	6.71%	2.83%	0.99%	0.23%	0.04%	0.00%
Plastic	0.53%	1.05%	1.34%	2.98%	3.26%	1.54%	0.61%	0.28%	0.10%	0.00%
Cardboard	0.00%	0.25%	1.20%	5.48%	4.33%	2.12%	0.80%	0.19%	0.01%	0.00%
Textiles	0.71%	1.31%	0.07%	1.09%	1.30%	0.46%	0.23%	0.07%	0.00%	0.00%
Wood	0.00%	0.00%	0.00%	0.57%	1.53%	1.27%	0.74%	0.45%	0.22%	0.00%
Other Organics	0.00%	0.00%	0.00%	0.62%	0.83%	1.81%	2.57%	2.20%	1.75%	5.51%
Glass	0.00%	0.00%	0.00%	1.03%	1.72%	2.72%	3.05%	2.18%	0.57%	0.20%
Inerts	0.00%	0.00%	0.00%	0.00%	0.57%	0.64%	0.77%	0.66%	0.98%	2.20%
Ferrous	0.00%	0.00%	0.00%	1.03%	2.56%	1.36%	0.38%	0.14%	0.07%	0.05%
Nonferrous	0.00%	0.00%	0.00%	0.23%	1.67%	0.51%	0.21%	0.02%	0.02%	0.00%