Critical Reviews in Environmental Science and Technology, Volume 40, Issue 12, 2010, Pages 979-1105

Production and quality assurance of solid recovered fuels using mechanical-biological treatment (MBT) of waste: a comprehensive assessment

C.A. Velis, P.J. Longhurst, G.H. Drew, R. Smith and S.J.T. Pollard*

Centre for Resource Management and Efficiency, Sustainable Systems Department, School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK

*Corresponding author: s.pollard@cranfield.ac.uk, Tel: + 44 (0)1234 754101, Fax: + 44 (0)1234 751671

ABSTRACT

The move from disposal-led waste management to resource management demands an ability to map flows of the properties of waste. Here, we provide a comprehensive review of how mechanical-biological treatment (MBT) plants, and the unit processes that comprise them, perform in relation to management of material flows, whilst transforming inputs into output fractions. Focus is placed on the properties relating to the quality of MBT-derived fuels. Quality management initiatives for solid recovered fuels (SRF) are reviewed and SRF quality from MBT plants assessed through a statistical analysis of published data. This can provide a basis for a targeted reduction in pollution load from solid MBT outputs and subsequent end-user emissions. Our analysis, among else (i) verifies the difficulty of chemical separation solely by mechanical means; (ii) illustrates the trade-off between achieving a high quality of recoverable outputs and the quantity/properties of reject material; and (iii) indicates that SRF quality could respond to legislative requirements and market needs, if specific improvements (reduction of Cl, Cu and Pb content) are achieved. Further research could enhance the confidence in the ability of MBT plants to produce a quality

assured SRF suitable for specific end-users, without contradicting the wider requirement for an overall sustainable management of resources.

Keywords: residual waste, mechanical-biological treatment, solid recovered fuel, material flow analysis

Running header inside manuscript: SRF production by MBT: a review

Contents

List of Figures

example, a screening unit with 25 mm openings could theoretically concentrate all of the paper card and plastic in the overflow fraction. Redrawn from Ruf[83], cited in Hasselriis[61]

FIGURE 4 Particle-size distribution (PSD) of components of single-shredded MSW, in semi-logarithmic diagram. After shredding each waste component (e.g. paper) tend to occupy a wider range of sizes, compared with before size reduction (see FIGURE 3). This could restrict the potential for selective screening of certain waste components after shredding. Redrawn from Ruf[83], cited in Hasselriis[61]

FIGURE 5 Schematic diagrams and operation principles for certain typical comminution equipment in MSW: (a) hammermill; (b) rotary shear. Adapted from Tchobanoglous et al.[63]

FIGURE 6 Schematic diagram of a vertical section of a ball mill, demonstrating its operating principle: as the drum rotates at a low speed around its horizontal axis the grinding balls in contact with the drum walls are lifted by the centrifugal force. At a certain point they lose contact and fall (cascade), impacting on the materials. Adapted from Faculty of chemical technology. University of Split[104] and Suryanarayana [105]

FIGURE 7 Secondary comminution of SRF, before pelletising, by different types of size reduction equipment; comparative results for the mass distribution of the shredded output. Data from Jackson[111], cited in Porteous[67]

FIGURE 8 Simplified flow-chart and mass balance of the Nehlsen bio-drying MBT plant in Stralsund, Germany. Adapted from Breuer[89]

FIGURE 9 Effect of comminution and screening on the relationship of net calorific value $O_{p,net}$ and the energy based yield to the screen overflow, for different aperture sizes. Data points within each series from top to bottom correspond to the screen overflow product using 40, 80 and 150 mm apertures. Data form the MBT plant at Quarzbilchl, Germany. Redrawn from Soyez and Plickert[59]

FIGURE 10 Cumulative mass fractions reporting at the screen undersize for various types of pre-treated domestic waste. Curves: (1) feed material; (2) comminution and drum screen at 100 mm; (4) and (5): ball-mill and 40 mm trommel underscreen; (6) ball mill-trommel and separation <5 mm organic-rich fraction. Characteristic particle size $d_{63.2}$ values are provided (63.2% ^{w}/w total mass smaller in size). From Koch et al.[145], with permission

FIGURE 11 Histogram of cumulative mass of the organic fraction of German residual domestic waste after comminution in a Loesche-Hese cascade mill. Data from Koch et al.[106]

FIGURE 12 Mass balance for MBT process using Hese ball mill with flanged trommel. SWB: stabilised bio-waste. For legend refer to FIGURE 8. Data form Koch[109]

FIGURE 13 Mass balance data from the Brandenburg Recycling Park, using a Hese ball mill. SWB: stabilised bio-waste. For legend refer to FIGURE 8. Data from Schade-Dannewitz[108]

FIGURE 14 Schematic diagram showing the operating principle of a cross-flow air separator with pneumatic transport of the low-gravity material. Redrawn from Timmel[65]

FIGURE 15 Schematic diagram showing the operating principle of a ballistic separator: (1) waste objects drop onto conveyor; (2) rotating metal conveyors follow an eccentric circular movement; (3) light fraction is carried upwards: e.g. paper, corrugated cardboard, plastic sheets and bags (4) heavy fraction rolls down: e.g. bottles, metals, hard plastics; (5) screen fraction falls through: e.g. sand, discarded food. Adapted from Mitsubishi Rayon Engineering[161]

FIGURE 16 Simplified flow-chart and indicative mass balance of the Herhof biodrying MBT plant at the Rennerod and Asslar sites. RTO: regenerative thermal oxidation. For legend refer to FIGURE 8**.** Adapted from Diaz et al.[232]

FIGURE 17 Particle-size distribution by sieve analysis of Herhof SRF (Stabilat®). Fractions with particle size lower than 60 mm exhibit high biomass content. Redrawn from Wengenroth[168]

FIGURE 18 Composition of Herhof SRF (Stabilat®). Data from Herhof Environmental[218]

FIGURE 19 Energy-based concentrations of trace elements in RDF produced in early MBT plants, presented on logarithmic scale. Comparison with the 1998 limit guidance concentrations of the Swiss Agency for the Environment, Forrest and Landscape (BUWAL). A $Q_{p,net}$ of 18 MJ kg^{-1} has been assumed to convert values from mass basis to energy basis. Redrawn from Rotter et al.[49]

FIGURE 20 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of the of location values of net calorific value $Q_{p,net}$, expressed on an as received (ar) and dry (d) basis. Box-plot conventions: (1): lower and upper lines of the boxes denote the 25^{th} and 75^{th} percentiles; (2) lower outlier limit and upper outlier denoted by whiskers define the non-outlier range, i.e. range of values that defined as is the range of values that do not differ form the median more than the 25^{th} or 75^{th} percentile plus 1.5 times the interquartile range (height of box) (3) extreme values, presented as asterisks, exceed the 75^{th} percentile plus 3 times the interquartile range.

FIGURE 21 Results of descriptive statistical analysis on MBT-derived SRF data: 1. Location values of moisture content MC expressed on an as received basis (ar); and 2. Location values of ash content expressed on a dry basis (d). For box-plot conventions see FIGURE 20.

FIGURE 22 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location and 80^{th} percentile values of chlorine concentration [Cl], expressed on a dry basis (d). For box-plot conventions see FIGURE 20.

FIGURE 23 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location of concentration of trace elements, expressed on a dry basis (d). The As, Cd and Hg are further compared in FIGURE 24 using a suitable axis scale. For box-plot conventions see FIGURE 20.

FIGURE 24 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location of concentration of certain trace elements, expressed on a dry basis (d). See FIGURE 23 for comparison with more elements. For box-plot conventions see FIGURE 20.

FIGURE 25 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location and 80^{th} percentile values of mass-based mercury concentration [Hg], expressed on a dry basis (d). For box-plot conventions see FIGURE 20.

FIGURE 26 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location and 80th percentile values of energy-based mercury concentration [Hg], expressed on an as received basis (ar). For box-plot conventions see FIGURE 20.

List of Tables

TABLE 10 Results on material flow management performance of ballistic separation; low-gravity product stream intended to concentrate components suitable for RDF/SRF production in MBT plants

TABLE 11 Existing and provisional national and trade quality assurance/quality control systems and standards for RDF/SRF in Europe

TABLE 12 Overview of limit values for existing European SRF quality standards

TABLE 13 CEN classification codes for SRF

TABLE 14 Properties for sufficient characterisation of WDFs according to end-use specifications

TABLE 15 Quality parameters for SRF according to end-use

TABLE 16 Quality standards for SRF use in cement kilns

TABLE 17 Comparison of CO_2 emissions of various fossil fuels and Herhof SRF (Stabilat®)

TABLE 18 Background information on data-series used for the statistical evaluation of the MBT-derived European RDF/SRF

TABLE 19 Results on statistical analysis of MBT-derived RDF/SRF data-series

Abbreviations

AC	Air classifier
AD	Anaerobic digestion
APC	Air pollution control
AR	Aspect ratio
BCPP	Brown coal power plant
BMT	Biological-mechanical treatment
CEN	European Committee for Standardisation
CEN/TC	Technical Committee of CEN
CHP	Combined heat and power
CLO	Compost-like output
CV	Calorific value
DBB	Dry bottom boilers
DIN	Deutsches Institut für Normung
DTI	Department of Trade and Industry
EC	Energy content
EN	European standard
EfW	Energy from waste
EU	European Union
FBC	Fluidised bed combustion
HCPP	Hard coal power plant

IR	Infrared
LHV	Lower heating value
MBT	Mechanical biological treatment
MEC	Material enrichment coefficient
MFA	Material flow analysis
MP	Melting point temperature
MSW	Municipal solid waste
NCV	Net calorific value
NIR	Near-infrared
OFMSW	Organic fraction of municipal solid waste
PAS	Publicly available standard
PCDD/Fs	Polychlorinated dibenzodioxins/polychlorinated dibenzofurans
PCBs	Polychlorinated biphenyls
PFA	Pulverised fly ash
PM	Particulate matter
POP	Persistent organic pollutants
PSD	Particle size distribution
QA	Quality assurance
QMS	Quality management systems
QC	Quality control
RDF	Refuse-derived fuel
ROCs	Renewables obligation certificates
RRSB	Rosin Rammler Sperling Bennet function

SBW	Stabilised biowaste
SCR	Selective catalytic reduction
SP	Lower softening point temperature
SRF	Solid recovered fuel
SWM	Solid waste management
TC	Transfer coefficients
TCC	Total chlorine content
TGA	Thermo-gravimetric analysis
VS	Volatile solids
WBB	Wet bottom boiler
WDF	Waste-derived fuel
WID	Waste incineration directive

1. INTRODUCTION

Modern waste management, whilst advocating avoidance and minimisation of waste production, has strong focus on recycling and recovery. However, even with the most successful source separation schemes, there remains a significant quantity of residual waste. Internationally, mechanical biological treatment (MBT) technologies are being adopted for treating this residual waste[1-7]. Interest has been strongest in Germany[8, 9], Austria[10, 11], Italy and Spain, with other countries starting to follow; for example, the UK[12-14], France[15], Greece[16] and Portugal[17]. MBT is also a potential option for environmentally developing countries[18, 19]: e.g. Brazil[20], south-east Asia[21] and China[22].

This review provides an account of MBT plants that produce RDF/SRF from municipal solid waste (MSW), focusing on material flow and performance. The review complements a recently published assessment of the generic aspects of MBT[5], and is timely because MBT plants are increasingly adopted in Europe to help meet landfill diversion targets. We provide an assessment of the science and process technology of MBT, including the performance of unit processes within MBT plants, so that waste managers, regulators and policy makers can assess the strategic contribution that MBT can make to sustainable waste management. The use of terminology in this field, especially pertaining to fuels, is clarified. An assessment of the policy-related aspects of MBT and SRF adoption is made elsewhere[23].

MBT technologies were developed in Germany and Italy, with the first plants established *ca*. 1995. Similar systems exist, to a lesser extent, in Australia and the US. Over the last 15 years, a considerable capacity of MBT has been installed within Europe[6, 7]. In Germany, more than 6.35 million tonnes of residual waste are treated through MBT plants per year[9]. This is largely a response to the European Union (EU) Landfill Directive (LFD) (99/31/EC)[24]. The LFD requires a phased reduction in the amount of biodegradable waste disposed of to landfill, because of its potential to produce landfill gas and leachate.

A fundamental question is: how does MBT serve the need for the effective management of material flows, as an integral part of sustainable resource management? Elemental and biological composition is the critical factor for extracting value from waste, rather than its origin [25]. The EU thematic strategy[26] has re-orientated efforts at recovery according to waste properties, and the challenge in exploiting value is now in extracting homogeneous fractions of known composition from heterogeneous matrices harbouring potentially harmful biological and chemical constituents[27]. Using process technology to secure relatively homogenous output materials of specified composition should enable: (1) the concentration of contaminants for onward disposal or treatment and (2) production of recyclate to a desired quality, prolonging their utility[28]. MBT plants are designed for effective materials flow management. They use integrated mechanical processing and biological reactors to convert and separate residual waste into output streams of suitable quality. Typical outputs include biostabilised material, dry recyclate, waste-derived fuels (WDFs), contaminated solid reject fractions, and controlled releases to liquid media and air.

The thermal recovery of waste through production of WDFs (termed refuse-derived fuel (RDF) or solid recovered fuel (SRF)) has also gained significant impetus[29-40]. A significant option for MBT plants is to produce a waste-derived fuel (WDF)[5, 14, 23, 41-44]. Alternative process configurations, such as MBT plants optimised for the production of a compost-like output (CLO) to be applied on land, have been reviewed elsewhere[4]. The MBT-derived RDF/SRF concentrates the combustible, high calorific value (CV) fraction, enabling thermal recovery in a series of potential end uses, such as cement kilns and power plants[23] as an alternative to fossil fuels.

We seek to address a number of key questions in this review. What is the desired quality of such fuels and how can this be monitored through quality management schemes? RDF/SRF marketability is increasingly dependent on compliance with existing and emerging quality standards[45, 46]. Different end-uses pose different challenges for the desired quality. Quality management initiatives in Europe are discussed. This review also addresses how choices over mechanical processing operations (such as air classifiers and ballistic separators) and their arrangement in the process flow sheet affect final RDF/SRF quality. The design of waste processing plants largely remains semi-empirical[47, 48] and limited modelling has been attempted. Published information is collated for the material management performance of typical mechanical processing equipment.

What descriptors and tools are suitable for evaluating the material flow performance of MBT plants? Established approaches such as yield and purity are covered along with the application of material flow analysis (MFA) to MBT[49, 50].

Can the desired RDF/SRF quality be achieved by MBT plants? Previous experience in the mechanical processing of waste identified a limited ability to generate outputs of the desired chemical composition[49, 51]. First generation RDF production plants that operated on mixed municipal solid waste (MSW) failed in both the US and Europe because of high levels of contaminants and a high degree of variability in RDF quality[49, 52]. This failure is also attributable to the prevailing economics that were driven by widespread availability of low-cost landfill. The quality and yield of RDF/SRF also impacts on the residual (reject) fraction, which will determine the overall economic success of MBT plants producing RDF/SRF. Here, data available in the literature for MBT-derived RDF/SRF properties are statistically analysed to reflect the currently achievable quality.

Biodrying is a form of composting that can be used for drying waste before subsequent mechanical separation. Biodrying MBT plants are optimised for RDF/SRF production. A significant quantity of readily biodegradable substances is contained within residual waste (*ca.* 68% $^{w}/_{w}$ in England)[53]. In biodrying MBT plants, most of the biomass content from the input can be incorporated into the RDF/SRF, reducing the biodegradable material for landfill and producing a partly renewable fuel. However, biodrying is a relatively new technology and, despite having been subject to research and development[54, 55], is neither fully understood nor optimised[56]. A separate evaluation of biodrying for RDF/SRF production is in preparation.

In order to understand the science and engineering of MBT processes adequately, it is necessary to make reference to commercially available technologies. These are described according to the manufacturer or trade name. The authors have no interest in promoting or endorsing specific technologies.

1.1. Terminology for MBT-derived fuels

MBT output fractions intended as secondary fuels fall into the category of WDFs, also referred to as solid waste fuels, secondary fuels, substitute fuels, or alternative fuels. In the absence of a legal definition or universally accepted term, the two most established terms relevant to thermally recoverable waste fractions are RDF and SRF. Many other partially overlapping terms exist and are discussed elsewhere[5, 32, 57]. Conventionally, RDF refers to a combustible, high CV waste fraction (e.g. paper, card, wood and plastic) produced by the mechanical treatment of municipal or similar commercial/industrial waste.

SRF is a recently introduced term that denotes a WDF prepared to a quality specification. A technical committee of the European Committee for Standardisation (CEN) (CEN/TC 343) works to unify the various approaches to WDF, providing quality management guidance. According to CEN/TC 343, SRF should be[30]: "*solid fuel prepared from non-hazardous waste* [as defined in Directive on hazardous waste (91/689/EEC); the input waste can be specific waste streams, municipal solid waste, industrial waste, commercial waste, construction and demolition waste, sewage sludge, etc.[58]] *to be utilised for energy recovery in incineration or* *co-incineration plants, and meeting the classification and specification requirements laid down in CEN/TS WI00343003'* [now available as DD CEN/TS 15359:2006].

RDF or SRF may originate from sources other than MBT, such as source-segregated paper/card/plastic fractions. However, in this review these terms will refer to fuel produced by MBT plants, and for clarity a distinction is made between MBT-derived RDF and SRF. FIGURE 1 shows the relationship between different terminologies.

<<Figure 1>>

"SRF" is any MBT-derived WDF that follows (or can be reasonably anticipated to follow) the CEN quality management procedures. The WDF produced by biodrying is typically SRF. These processes are optimised to produce a partially stabilised fuel of consistent and high-quality composition as their primary output. Such MBT configurations could achieve CEN certification when trading the WDF in third party markets. "RDF" is any MBT-derived WDF that was not, or could be reasonably anticipated to meet, the CEN quality management procedures in the immediate future. This might be any WDF produced as a co-product of MBT optimised for different primary products, such as biogas from anaerobic digestion (AD) or biostabilised output for landfill storage. Hence, we interpret SRF as a WDF following a quality management; but not necessarily exhibiting better quality compared with an RDF. However, because the quality management procedures relate to SRF production, much higher reliabilities for SRF can be anticipated when compared to RDF. In the US, the term RDF has been applied to WDFs of standardised quality, according to ASTM standards [57]. The term "RDF/SRF" is used within this review.

1.2. MBT characteristics, classification and design objectives

MBT is a generic term that encompasses a range of waste technologies. Most MBT unit operations have been employed in predecessor treatment plants operated on mixed waste, such as highly-mechanised in-vessel composting (“dirty” composting) and RDF production plants. In its most advanced role, MBT is a material flow management facility that uses a flowsheet of unit operations to split and bio-convert waste; processing the substances present in waste into suitable outputs, and preferably, marketable products[59]. In this sense, MBT plants are at the forefront of sustainable resource management, enabling a re-direction of substances contained in the waste to the most appropriate intermediate or final sinks.

Overviews of the current state-of-the-art regarding geographical expansion, roles and perspectives of MBT technologies are available[5-7, 9, 41]. Key distinguishing features of MBT plants are[5, 13]: (1) the input (mixed or residual MSW) includes a biodegradable fraction; (2) each plant integrates biological (e.g. aerobic composting, biodrying, anaerobic digestion (AD)) and mechanical unit operations (e.g. size reduction, separation); (3) plants are configured and optimised to produce an array of marketable outputs (secondary products) or at least a stabilised biowaste (SBW) fraction, suitable for disposal in a final storage quality landfill; and (4) plants are enclosed and equipped with air emission control systems *e.g.* operating under negative pressure and biofilters.

The key objectives of biological waste treatment processes vary significantly. A distinction exists between processes configured for pre-treatment before landfill, and those attempting to add value to the waste stream by producing marketable outputs, such as SRF, biogas, or a CLO[27]. When MBT processes are used as a pre-treatment to landfill, the objectives should relate to minimising the adverse consequences of disposal, including volume reduction, biodegradability reduction to minimise landfill gas and odour emissions, and immobilisation of leachate pollutants. According to Juniper[5] one of the most important differentiating features of MBT processes is the type of main bioconversion reactor (TABLE 1).

<<Table 1>>

Other approaches take into account the possible differentiations in the series of mechanical and biological unit operations, diversifying between the terms MBT and biological-mechanical treatment (BMT)[13]. FIGURE 2 provides a schematic for different flow line approaches to MBT plants. Distinction is made regarding the positioning of core biological treatment in the overall flow chart of MBT plants and the stage of RDF/SRF production. Alternatively, MBT processes can be classified according to their primary outputs[5].

<<Figure 2>>

MBT processes may be designed and optimised for the production of one or more primary outputs: (1) biostabilised output, to be disposed of in landfill; (2) WDFs, such as RDF or SRF; (3) biogas, for energy and heat production; and (4) CLO for application on land. Dry recyclates (ferrous and non-ferrous metals, aggregates, glass) are co-products found in most process configurations. Products may be marketable subject to creating and securing viable market outlets. If not, as is predominantly the case, they may render zero or negative value or end up in landfill. Biostabilised output is intended for landfill disposal: despite not being a product, it has to meet quality criteria. Juniper[5] provide an extensive list of potential end-uses for MBT process outputs (TABLE 2**)**. Most of them still have to overcome significant technical, legal, and market barriers, if they are to be successfully adopted.

<<Table 2 >>

2. MECHANICAL PROCESSING FOR MBT

A variety of mechanical equipment is used in MBT plants. Most unit operations were developed in the mining industry (e.g. coal and ore processing) and adapted for waste stream inputs. Process units, such as hammermills and trommel screens, have been used for treating mixed MSW e.g. for size reduction before disposal in landfill, recovery of a high CV fraction for RDF production and recycling of materials such as metals and aggregates. There is significant experience of RDF production plants in the US[61] and Europe[62] from the 1980s. However, in the case of MBT plants, these unit operations are fed with new inputs (residual rather than mixed or source separated waste). In this section an introduction to mechanical unit operations for MBT plants is provided with a review of the main waste characterisation properties necessary to evaluate the performance of mechanical processing. Emphasis is on performance relating to material flow management. Other aspects, such as energy efficiency, or processing that does not change the final chemical composition of the fuel, such as pelletisation, are not covered. The main equipment used for size reduction in MBT plants is presented, including operating principles and performance results where available.

2.1. The role and objectives of mechanical unit operations

Mechanical unit processes change the physical characteristics of waste, so as to facilitate removal of constituents, specific components and contaminants from waste streams[63]. Functions served by mechanical unit operations in MSW include size reduction (comminution), mixing and homogenisation, classification and separation (sorting), densification (compaction), and materials handling, including transport, loading and storage[61, 63, 64]. As-received, residual waste usually undergoes an initial mechanical preparation stage (typically bulky item removal, bag splitting or comminution, size separation) before further mechanical or biological treatment steps. Additional mechanical handling and processing steps can be placed both before (pre-treatment) and after (post-treatment) the core biological unit. The throughput rate of individual processing lines of MBT plants is in the range of 20-30 t h^{-1}[65]. In some instances, mechanical units form part of the core biological step e.g. bucket wheels used for turning at in-vessel composting systems.

The key objectives for mechanical unit operations are to[5, 13]: (1) prepare the input waste for the core biological treatment unit (pre-conditioning); (2) maximise resource recovery by separating out recyclable/recoverable fractions; (3) remove input waste constituents that may inhibit the effectiveness of further processing steps (contraries), or are inappropriate for the outputs; (4) serve specific process control purposes as part of the core biological unit; and (5) refine the outputs so they are fit for the intended use. The processing objectives for each facility are site-specific and influenced by legislative and market demands for outputs. Juniper[5] provide an overview of the policy, legal, and market issues affecting mechanical processing in an EU and UK context. TABLE 3 lists typical mechanical operation units employed in MBT plants.

<<Table 3>>

2.2. Waste characterisation for mechanical processing

Waste characterisation refers to the quantities, composition and physical and biochemical properties of waste. A thorough understanding of these properties for input and output streams is vital for effective design and operation of MBT plants[48]. Important descriptors of the physical-mechanical state and behaviour of waste include, but are not limited to[63, 66]: waste material composition; moisture content (MC); density descriptors (e.g. bulk density, particle density, etc); elastic properties (material stress and strain descriptors); granulometric descriptors (particle shape, size and particle size distribution (PSD)); electromagnetic behaviour; CV descriptors; and optical properties (colour, texture). These aspects of mechanical processing have been partially reviewed elsewhere[48, 61, 67, 68]. Barton[69] provides a qualitative review of selected properties for recyclable municipal waste components. Our focus is on the elastic and granulometric properties of waste.

2.2.1. Elastic properties of waste and comminution

Comminution (size reduction/shredding) behaviour of waste depends largely on its elastic properties[70]. Schubert and Bernotat[70] investigated the basic distinction between brittle and non-brittle (i.e. more ductile) materials during shredding. Brittle waste materials include rubble, glass, cast iron and cast non-ferrous metal scraps. Non-brittle materials show little deformation and high stresses in their stress-strain characteristics. These materials include "rubber-elastic" materials, elastic-plastic materials, and elastic-viscous materials. Mixed MSW, residual waste and the organics fraction tend to exhibit predominantly non-brittle behaviour. Our current understanding of the micro-processing behaviour of non-brittle materials does not allow these processes to be effectively modelled.

2.2.2. Granulometric waste properties

Granulometric properties, such as waste particle size and distribution of waste components or fractions, are conventionally the most significant descriptors[47]. These properties are used to describe the performance of comminution and separation equipment, to model and simulate their operation, for process control of biological treatment units, and for developing sampling protocols for waste characterisation and quality control. There is no universally accepted approach to defining waste particle size, due to the irregularity and variability of waste particles. An overview of the possible types of particle shape, morphology, texture and angularity descriptors, and measuring techniques applicable to the mining industry is provided by Pourghahramani and Forssberg[71]. Tchobanoglous et al.[63] proposed formulas that attempt to account for the three-dimensional, non-isotropic forms of waste particles by estimating an effective particle size (d_e). Material-specific shape categories and characteristic size indicators have been proposed for waste materials, such as metallic scraps and shredded plastics[47]. Hogg et al.[72] discuss the role of particle shape in size analysis and evaluation of mining comminution processes, through the measurement of an equivalent sphere diameter.

There is a good understanding of particle size measurement methods. Extensive information on application to fine materials such as powders is available[73]. A standard method for sieving waste methods has been developed by ASTM since 1985[74]. Detailed guidance on particle size measurement pertaining to SRF has recently been released by CEN, covering both manual and automated sieving for particles >25 mm[75]. Nakamura et al.[76] applied optical determination and image analysis to enable accurate determination of the waste particle size, as well as shape factors such as aspect ratio (AR), roundness (circularity) and sphericity[76, 77]. This method is potentially useful for modelling combustion behaviour of WDFs and evaluating comminution performance. Nevertheless, the practical determination of waste particle size through screening has encountered many restrictions[47]. For example, ductile materials (about 75% of MSW) can exhibit a significantly lower "projected" particle area, depending on the forces acting on them (e.g. a 1 m x 1 m piece of textile can be forced through a 10 cm opening). The operating mode and performance of the screening apparatus can affect the results. Waste items may not move along the sieving surfaces as expected, resulting in the maximum particle size passing through an opening that is less than the actual size of the screen. Furthermore, the wide range of sizes can cause fragmentation of the measurement process[78], producing results that are not directly comparable. For instance, separate size identification for items above and below a certain size, e.g. 40 mm, is not uncommon[47]. Measurement apparatus and software is commercially available for the fines range, with the CEN SRF standard suggesting machine sorting for samples <25 mm, and more specialised methods, such as laser detection, for samples <1 mm[75]. However, certain sieving standards do not cover oversized items, for example, the German mining standard DIN 22019 (part 1) only covers up to 80 mm[79]. In addition, the particle equivalent diameter can be geometric or hydrodynamic/aerodynamic, depending on the measurement method[80]. Furthermore, the heterogeneity and high water content of waste can result in fines adhering to coarse fractions and thus being measured as coarser fractions[78]. The CEN guidance addresses this by proposing air drying of SRF samples with moisture contents greater than 20% $^{w}/_{w}$[75]. As a result of lack of standardisation and the technical challenges outlined above, a certain degree of improvisation on methods for determining particle size has occurred.

PSDs *Y*(d) (equation 1) have been extensively used in minerals processing, but have had limited application in solid waste management. The cumulative weight percent of oversize or undersize, in relation to the size of the particles, is most frequently used[47]. Appropriate graphical representation of PSD data can disclose valuable information about the performance of mechanical processing and enable informed decisions on the configuration of downstream unit operations.

$$Y(d) = 1 - \exp\left[-\left(\frac{d}{d_{63.2}}\right)^{n}\right] \qquad \text{Equation 1}$$

There is evidence that PSDs for both raw mixed and shredded waste may be fitted, at least partially, to a Rosin Rammler Sperling Bennet function (RRSB function)[47, 81]. RRSB is suitable for materials that do not exhibit a well defined upper size limit, but that can describe with accuracy the cumulative weight fraction above a certain sieve size. RRSB distributions plot as a straight line in RRSB grid diagrams (or Weibull diagrams).

Trezek and Savage[82] discussed the effect of size reduction, air classification and screening on PSDs of ferrous metal, aluminium, glass, paper and plastic. Ruf[83] studied PSDs of the main components of MSW (unprocessed and comminuted) and provided a general indication of the size ranges of comminuted waste constituents. Hasselriis[61] described how with mixtures of materials, such as mixed MSW, the RRSB graphs are determined by the relative amounts of the materials and the degree to which their PSDs overlap.

Another approach for graphical representation is the proposed method for analysis of waste deposited in landfills, stemming from geological applications[84]. According to Pfannkuch and Paulson[85], logarithmic-phi units could be used, enabling the calculation of common statistical measures, such as arithmetic and geometrical mean, median, standard deviation, skewness and kurtosis of the distributions.

Typically defined quantities in PSD determination are:

1. cumulative fraction finer than d_x, where x is the percentage (undersize fraction, underflow) passing through the screen/sieve with aperture size d;
2. characteristic particle size $d_{63.2}$ corresponding to Y(d) = 0.632, in other words, the particle size that 63.2% of the cumulative fraction is smaller than (63.2% cumulative passing);
3. nominal product size d_{90} (i.e., aperture/particle size with 90 % cumulative passing) or nominal top size d_{95}, which can be used to define the product size of comminution process or the upper size of a fraction retained between two consecutive sieves; and
4. measure of uniformity (breadth) of PSD n, calculated as the slope of the linear fit trend in a RRSB grid diagram. The steeper the slope of the line, the tighter the size range of the particles. A narrow size range indicates finer shredding and grinding than coarser cutting, leading to a larger proportion of fine material[61].

PSDs have been criticised as not producing meaningful results for solid waste management, because of the problems in size determination and measuring. Instead, particle mass distributions have been proposed, which initial evidence suggests can adequately describe the distribution of unit masses (weight fractions of different materials)[47].

The size reduction ratio η_{dmesh} (Equation 2) is a performance descriptor for comminution unit processes. It is defined as the ratio of the mass of the comminuted product to the mass of the input material, given that the particle size of the comminuted product is lower than the size of the mesh and that of the input material is larger than mesh size[86].

$$\eta_{d_{mesh}} = \frac{m_{P<d_{mesh}}}{m_{I>d_{mesh}}} \qquad \text{Equation 2}$$

Where:

$m_{P<dmesh}$ is the mass of the comminuted product

$m_{I>dmesh}$ is the mass of the input material

3. COMMINUTION PROCESSES

Comminution is a unit operation used to reduce the size of materials. Within the waste field, equipment is generally refered to as as “shredders” or “granulators.” Primary size reduction refers to comminution of as-received waste; whereas secondary shredding refers to further comminution of a waste stream that has undergone primary shredding[66].

Objectives met by comminution include[61, 63, 70, 87]: (1) meeting (commercial) product specifications in terms of particle size and shape, e.g. compost standards or RDF particle specifications to suit the intended method of thermal recovery; (2) fracturing and reducing the size of particles to increase their biochemical reactivity, e.g. lignocellulosic material in anaerobic digestion processes; (3) dismantling assemblies of items into their subcomponents, or cutting them into pieces, enabling separation of desirable and undesirable constituents by downstream mechanical treatment, e.g. closed cans; (4) reduce the bulk of materials for better handling or disposal; (5) disaggregating materials to enable effective separation, e.g. magnets cannot effectively remove metals from a mixture of other large objects; and (6) partially homogenising heterogeneous mixtures. For RDF/SRF production purposes, the combustible fraction should be comminuted finely enough to be easy to convey, store, retrieve, feed and air-classify[61].

3.1. Size reduction in MBT plants

Size reduction is commonly one of the first unit operations in MBT processes. Secondary shredding is employed during RDF/SRF processing or to adjust final product size. Typical mechanical unit operations that serve as the initial treatment step for the input waste, along with their operating principles are reviewed by Enviros[13]. Shredding has conventionally been the first unit operation in most separation systems designed to produce RDF, but in the 1980s some systems that employed trommels as the first processing step appeared[88]. The first biodrying MBT plants resorted to primary shredding of the as-received input, possibly after removal of bulky/unsuitable items. The shredded discharge (e.g. Eco-deco: 200-300 mm; Herhof: < 200 mm or 150 mm) was directly fed into the biodrying stage. At the Nehlsen plant in Stalsund, Germany, after pre-shredding and ferrous material separation, only the underflow of a 65 mm disk sieve is fed into biodrying cells[89]. However, other recent approaches that avoid initial comminution exist. Eco-deco and Nehlsen use secondary shredding in the post-treatment stage, with Eco-deco using comminution as the final refining stage to produce an SRF with the appropriate PSD, and Nehlsen as part of the material separation process of the biodried output.

In MBT plants that do not use biodrying, but are able to produce a WDF fraction, comminution is also important. MBT processes that use aerobic composting as the core biological unit usually have shredding as their first unit operation, followed by trommel separation (e.g. commercial reference sites of Biodegma, Horstmann, Linde, or New Earth)[5]. Different size reduction solutions may be employed by other technology providers. For example, Hese uses a cascade-ball mill merged with a trommel; Sutco uses a crasher to feed a sieve drum; Wright Environmental uses a pulveriser, followed by a magnetic separator and then a trommel; and Wastec uses a bag splitter to feed their proprietary kinetic streamer.

Some MBT processes that use AD or percolation as the core biological unit use size reduction equipment for primary shredding (e.g. Hese uses a cascade ball mill, and OWS uses a shredder) or at the material recovery/pre-conditioning stage that precedes the AD/percolation unit(s). For example, shredding is used by BTA and Grontmij. Shredders are also used in wet pre-treatment processes such as Arrowbio and STB.

3.2. Process control and performance of comminution processes

Comminution operations for the mining and food industries have been widely modelled[87] and the PSDs from various types of shredding equipment can be predicted by computer simulation of the comminution process[90]. Mathematical modelling and simulation of comminution processes in minerals processing and in general have been summarised elsewhere[91, 92]. However, modelling of size reduction in waste management processes is still under-developed. Van Schaik et al.[93] attempted to model the recycling rate of secondary metals during shredding of end-of-life vehicles, drawing from minerals processing theory, using particle size reduction distributions and liberation as key model parameters.

Size reduction performance in MBT plants should be measured against their ability to deliver the desired output characteristics, which depend on the unit position in the overall process flow and the plant configuration. For example, primary shredding will have different goals from shredding for up-grading a final output, and different waste particles size ranges are optimal for composting, fermentation, and RDF/SRF thermal recovery purposes. Selective comminution can be beneficial for material flow management in MBT plants, particularly when different categories of materials, contained in the size reduced output, concentrate in different size ranges. Each type of material tends to occupy a characteristic range of sizes in the as-received waste[61, 83], (FIGURE 3) and comminuted materials with different properties also tend to concentrate in certain size ranges. This could be useful for separation unit operations, such as screens, to separate out fractions rich in certain materials[63].

<<Figure 3>>

Shredding can also cause problems, and trade-offs are inevitable in downstream processing[61, 62]. Comminuted output PSDs and liberation/concentration of certain substances, or set of components within defined size ranges, could be used as characteristic performance indicators for comminution machinery. However, there is evidence that the spread of waste component PSDs generally increases after comminution (FIGURE 4) making classification on an item basis by particle size (screening) increasingly difficult.

<<Figure 4>>

The most important options for (primary) comminution are hammermill shredders, rotary shears, flail mills and cascade-ball mills. Their operating principles, performance in relation to material flow management, and results from MBT plants are discussed below. TABLE 4 summarises their main features.

<<Table 4>>

3.3. Hammermill shredder

Hammermill shredders are commonly used for MSW comminution (FIGURE 5) and are highly varied in energy requirements, and specific configuration (TABLE 4). Hammermill shredders, initially developed for crushing of minerals, are versatile in processing different materials: from sticky clay to tough fibrous solids like leather or steel[87]. Their performance is specific to the input material composition and machinery configuration. The important input properties are ductility, moisture content, temperature, bulk density, and shear strength[63, 64].

<<Figure 5>>

Hammermills can be designed either in horizontal-shaft or vertical-shaft configurations. Horizontal-shaft hammermills have a bottom discharge grate with specific sized openings. Shredded waste remains within the chamber and comminution continues until it reaches the appropriate size to pass through the openings. Vertical-shaft hammermills have a cone-shaped housing that narrows down to a throat section[66].

Vertical-shaft hammermills can be beneficially fed with very-low density materials due to associated windage[64]. The swinging hammers create a vortex/fan effect ("windage" towards product flow) that complements gravity in pulling the waste down into the unit chamber. Grinding occurs more in the lower part beneath the neck section. The ground product is usually comminuted to such a degree that no screening discharge grate is needed.

Vertical-shaft hammermills were specifically designed for MSW processing, but the majority of hammermills in place use the horizontal-shaft configuration. A hammermill shredder is a heavy duty cylindrical or tapered casing, equipped with a number of hammers extended radially to form a rapidly rotating central shaft or disc. Size reduction is achieved by the combined actions of impaction and tearing by the swinging steel hammers. To avoid damage to equipment, hammers can be mounted flexibly on the shaft, allowing for rotation over bulky or very dense waste components. Input waste components enter the mill from the top and move downwards under gravity. A component entering the shredding zone will inevitably be struck by the hammers, imposing sufficient force to crush items. Size reduction is continued by waste being struck against stationery breaker plates or cutting bars fixed around the inner housing wall of the grinding chamber.

Hammermills are versatile, suitable for production of specific PSDs and for the liberation of assemblies of parts[70]. Comminution of mixed waste by a hammermill shredder significantly changes the PSD of input constituents, enabling subsequent screening of selective fractions. Despite the spreading effect for some component PSDs, it can be beneficial for others. For instance, brittle materials such as glass, sand and rock form a higher proportion of the fine particles range, compared with ductile materials, such as ferrous and non-ferrous metals. Barton et al.[62] provide data on selective shredding for UK RDF production at the former Byker plant, showing the concentration of the non-combustible and putrescibles in the <10 mm fraction (with the exception of metals).

However, a higher degree of size reduction is not always desirable. High-speed rotation and impaction within hammermills pulverises materials, which may compromise RDF/SRF quality by cross-contamination[62]. Fine particles can become embedded in softer materials, such as paper and textiles, contaminating these with unwanted substances. Despite the beneficial use of shredders for selective reduction, the shredding of highly polluted waste components, such as electronic equipment, batteries and composite materials, should be avoided, as it results in contamination of the less polluted items[5, 49]. If glass is contained within the input waste, paper items may become laden with shards of glass that contribute to the ash content[62]. Additionally, fine glass particulates can fly in a subsequent air classifier and become incorporated into the RDF stream, increasing its ash content[61]. The organic fraction of MSW can also be contaminated with minerals[63, 66]. In addition, over-pulverisation is not desirable in the case of material intended for biostabilisation through composting.

The modelling of impact crushers for mining applications is long-established and satisfactory simulation has been achieved (e.g. Nikolov[95]). Modelling aspects of primary comminution of MSW has been attempted[96, 97]. The single most important parameter affecting the shredded output PSD is the mean residence time (τ), defined as the time a feed particle remains within the shredder. Testing results imply that a longer residence time could lead to a smaller characteristic particle size. A smaller output product size can be achieved by operating the hammermill fully loaded (choked). Selection of the size of discharge grate openings in horizontal-shaft hammermills allows for more accurate control over the upper limit of the ground-waste overall PSD. However, tests on MSW commercial scale shredding showed a consistently unpredictable PSD for the output[97, 98]. Validation of the hammermill unit operation of the GRAB[99, 100] computer model of 1985 by data from UK RDF plants showed unsatisfactory results[101]. Parameters used were residence time, residence time distribution, selection function and breakage function, with the last two exhibiting problematic behaviour.

3.4. Rotary shear

Rotary shears or shear shredders are commonly used in waste management operations, including RDF/SRF production plants[65] (TABLE 4). Rotating knives or hooks rotate at a slow speed with high torque. The shearing action tears or cuts most materials.

Multi-rotor types are the most common[63, 66], with two or four parallel counter-rotating shafts each equipped with a series of perpendicularly mounted disks with comminution tools. Shafts are arranged alternately so that the rotors overlap and the cutting tools act as scissors. Different types of tool geometry may be used, to allow for different feedstock and shredding objectives. In radial-gap rotary shears comminution occurs in the radial gap between the rotor knifes and the appropriately adapted stator, resulting from shearing stress[102]. The cutting tools are usually indexable knives of rectangular, triangular or circular shape. In axial-gap machines the comminution process takes place both in the axial and radial gaps. The shredded output of radial-gap shear rotors typically consists of smaller fragments than the multi-rotor axial-gap, due to the greater number of rotor knives, defined comminution geometry and the use of discharge grates in the radial-gap rotary shears[102]. Particles that exhibit elastic-plastic deformation behaviour can be advantageously stressed at low temperatures[70].

Feeding devices (force feeders) can be employed, especially for oversized bulky waste and for radial-gap machinery, usually pushers, swivel arms, feed rollers, and feed conveyors. The shredded output drops or can be pulled through the unit. In most cases the rotating shafts can be automatically reversed in the event of obstruction, resulting in reduced down time due to blockage.

Shear shredders tend to produce a more uniformly sized output and lower contamination than hammermills[63], because of the lower rotation speed and absence of impact as a comminution mechanism. Hence, they are preferred over hammermill in RDF/SRF production lines[65]. The cutter spacing between the shafts can be adjusted, ranging from several mm to cm. This may allow glass and other items to fall through the rotors without being shredded[66]. Qualitative data concerning rotary shear fed with mixed MSW, including tyres and oversized materials, showed that a *ca*. 5 cm cutter spacing reduced the size of glass without pulverising it; and a *ca*. 10 cm spacing allowed several bottles and cans to pass through the rotors and report to the output unbroken[88].

Limitations of rotary shears include the production of a coarsely shredded output and the need to remove large steel and other durable items prior to shredding, as they may cause excessive wear and tear. Mathematical modelling of rotary shears performance is thought by some authors to be virtually impossible, due to the large number of variables involved[64].

3.5. Flail mill

The flail mill is similar to the hammermill, providing coarse shredding as input passes only once through the comminution chamber. There are some important differences[63]. Instead of hammers, comparatively thin flail arms, spaced farther apart, are mounted on the rotating shaft, with their thickness ranging from *ca.* 1 cm to *ca.* 2.5 cm[64]. They are usually single-pass machines, with the input material being shredded only during the passage from the rotor area, as they have no discharge grate. Input material is stricken by the flails and smashed against the anvil plates on the inner side of the comminution chamber. Sufficiently small input particles can pass through the mill without undergoing size reduction. Comminution of paper and card rich fractions is thought to be better achieved by flail mills than by hammermills[64]. Another design variation operates with two counter-rotating shafts. Flail mills have increasingly being used for shredding of the combustible fraction in RDF production plants and as bag openers[63, 64].

3.6. Cascade/ball mill

A cascade mill equipped with grinding balls (or ball mill) is a type of tumbling mill, which has been widely used for mechano-chemical processing operations, from minerals processing to advanced materials production (FIGURE 6)[103].

<<Figure 6>>

Rotating drums use heavy balls to break up or pulverise waste. Tumbling mills have been widely used for intermediate and fine reduction of abrasive materials[87]. In a typical tumbling mill, a continuously or batch-fed cylindrical or conical steel chamber with tampered ends, appropriately lined in the inner side, rotates slowly around a horizontal axis, with about half its volume filled with a solid grinding medium[87]. In ball mills metallic balls cascade within the shell and centrifugal forces lift the balls, in contact with the shell walls and each other, up to where they lose contact and fall. Falling balls and other hard substances contained within the input waste impact on waste feedstock, mainly whilst striking the bottom of the milling chamber. Pressure and shear stresses imposed on the waste constituents result in differentiated comminution, according to their physical-mechanical properties.

In MBT processes they have been used for primary shredding. An early European example of a ball mill use is the Loesche GmbH case, operated from the mid-1980s by the Waste Management Association of Kaiserslautern (ZAK), Germany. Another ball mill based process operates on residual waste in Brandenburg. In 2005 a plant was under construction at the Nentzelsrode landfill to treat the residual waste from Norhtren Thuringia, Germany (140,000 Mg a^{-1}). In the UK, an 180,000 Mg a^{-1} nominal capacity plant that accepts residual waste began operating in Leicester in 2005[106].

Performance data have been published for the Loesche-Hese cascade mill[106-108] and for an Outukumpu-Hese cascade mill, similar to the Harding type, operated in cataract mode[109]. The attached trommel separates two output size ranges, namely underscreen (fine and intermediate fraction, 5-40/35 mm) and overscreen (coarse fraction, 35/40-80 mm). For the Loesche-Hese mill, the degree of size reduction is in the order of organic portion < paper/cardboard < plastics/glass/batteries < wood/stones/metals[106]. For the Outukumpu-Hese mill, the order is organic portion < sand < paper/cardboard < plastic films/glass < stones < visco-plastic/tenaciously plastic/shoes/rubber[109].

Cascade mill action has been found to have a selective effect on different waste constituents. Organic material is crushed or torn and disaggregated, whilst for wood and textiles the action primarily concentrates the coarser fraction (40-80 mm). Ferrous (Fe) material and batteries mostly deform, compress and become rounded at the edges, but do not reduce in size, whilst non-Fe materials deform slightly. This observation is in agreement with the wider experience of the behaviour of ductile, laminated materials in ball mills[72].

In terms of suitability of the output for further treatment, the two-dimensional deformation of non-ferrous material is beneficial for effective separation in eddy-current separators. Operators claim that metallic material is cleaned, enhancing its saleability after separation. Mechanical energy input transformed into heat flow after collisions in-shell leads to temperature rise up to an average of 50-60 °C, resulting in grinding having a drying effect on waste[108]. Drying particularly takes place with respect to coarser, hydrophobic plastics, facilitating downstream separation[106].

3.7. Other comminution processes

With rotating drums, material is lifted up the sides of a rotating drum and then dropped back into the centre. This method uses gravity to tumble, mix, and homogenize waste. Dense, abrasive items such as glass or metal help break down the softer materials, resulting in considerable size reduction of paper and other biodegradable materials. In wet rotating mills with knives, waste is wetted, forming heavy lumps that break against the knives when tumbled in the drum. In bag splitters, such as flail mill or shear shredders, a more gentle shredder is used to split plastic bags whilst leaving the majority of the waste intact.

3.8. Comparison of PSDs of comminution processes

Preliminary results on the PSDs of various comminution methods[110] allow ranking of the processes. More intensive comminution (i.e. higher cumulative mass passing, d_{20}) was found for ball mills *ca.* 68%; mixing drum; hammermill *ca.* 26%; and screw mill *ca.* 21%. Results on the size reduction ratio for primary and secondary comminution of residual waste in MBT plants were reported by Zwisele[50]. Results on comparative performance of different secondary size reduction of SRF for subsequent pelletising can be found in Porteous[67], with the knife mill showing the best performance in terms of PSD (FIGURE 7). Vertical-shaft hammermills can achieve a higher degree of pulverisation compared to horizontal ones[66].

<<Figure 7>>

4. CLASSIFICATION AND SEPARATION

Mechanical units for classification and separation of waste streams are central to the material flow management of MBT processes. The appropriate splitting of input waste into outputs with desirable characteristics is a challenging task. Trade-offs are inevitable, and must be resolved according to what is technically and economically feasible, satisfying both legal and market requirements. This section discusses classification and separation units, emphasising RDF/SRF production processes. An assessment of the most appropriate formulas, descriptors and tools for performance evaluation of classification/separation units is included. Some mechanical solutions of emerging importance are presented in more detail than conventional options such as screening and air classification.

4.1. Function of classification and separation operation units

Separation and classification unit processes are used to segregate input streams into output sub-streams with desirable characteristics. Output streams can either contain sorted desirable items, for example, paper and card in the light fraction of an air knife (termed “separation”); or can be separated out on the basis of their size, for example, fine fraction of a trommel under-flow (termed “classification”). Possible objectives include separation of certain size fractions, concentration of certain materials, separation of fractions with specific properties (e.g. organic fraction of municipal solid waste (OFMSW), high CV fraction), and removal of undesirable particles. From a material flow management point of view, separation/classification leads to a redistribution of properties/materials, enabling their enrichment or dilution in output streams. The operating principles of separation/classification units depend on the physical properties of the input waste materials or items. Categories of equipment according to main operating principles are[94] size (and shape) separation, density/elastic properties separation, magnetic separation, electric conductivity separation, and optical/image properties separation (chemical properties are also involved). Each of these categories can be further sub-divided.

TABLE 5 lists some types of equipment used in MBT plants. Pretz and Onasch[48] and Diaz and Savage[68] reviewed operations of mechanical processing equipment suitable for MBT plants.

<<Table 5>>

4.2. Separation and classification processes in MBT plants

Input into these units is usually a previously comminuted waste stream, either sorted or prior to size reduction. As-received waste can also pass directly through classification to avoid contamination of fractions by subsequent comminution, or because the separation unit does not demand a comminuted input, as might be the case for ballistic separators. Classification as the initial treatment unit is common in plants that use AD technology, such as the Iska, Buchen plant; Linde, Barcelona plant; Ros Roca, Avila plant; SBT, Heerenveen plant; and Whehrle[5]. More frequently, classification/separation units are placed downstream in the flowsheets. Most data refer to the combination of comminution and classification, such as hammermill followed by screens or ball-mill followed by trommel.

Other typical functions in MBT flow-lines include post-treatment within biodrying plants aimed at separating combustible high CV materials low in minerals and chemical pollutants, to form RDF/SRF; pre-treatment of input material (comminuted/not) for composting/AD to separate out a high CV fraction and concentrate the organic-rich, contamination-free fraction; post treatment of composted/anaerobically digested material for CLO production; and separation of dry recyclate fractions, typically Fe and non-Fe metals and aggregates.

4.3. Performance evaluation of classification and separation processes

4.3.1. Conventional performance descriptors

The performance of mechanical processing unit operations can be assessed in different ways and by using various descriptors. For instance, considered as heat engines, the efficiency of energy conversion of machinery can be defined as the ratio of the useful mechanical energy produced over the total energy consumed[113]. Whilst a mechanical and energy efficient approach is significant for both financial and sustainability considerations, we focus on descriptors appropriate to evaluate the material flow performance of MBT plants.

Two main approaches are identified. The first approach stems from the mining industry, where the performance of a classification of different size fractions is most important during processing (e.g. sharpness of cut, selectivity). Klumpar[114] discusses these aspects in detail in relation to the performance of air separators. The second approach originates from separation of phases or fractions according to other material properties. As there is no uniformity in the related performance terminology, two clarifications are necessary. Firstly, in the literature the term "efficiency" is often misused to denote various descriptors of performance. Rather than accurately being used to refer to the ratio of effective use of resources over the overall spent resources, it is used to describe the degree to which an operation is effective e.g. the segregation of items achieved by a separation process relative to the ideal. We take the view that the term "effectiveness" should be preferred for the descriptors that try to measure "what is achieved *vs.* what could be, or would be desirable to have been achieved", similar to the approach used by Hasselriis[61]. The term "efficiency" should be reserved for descriptors that measure the degree of losses in conversion processes. Other relevant terms, such as "yield," "recovery" and "purity" are clarified and they are discussed below. Secondly, variety and inconsistency in the terms used to describe the outputs of classification and separation processes often leads to confusion. The input (or in-feed) stream is split into two or more output streams (fractions). In the case of one main useful output fraction, which concentrates the desirable component(s) at the highest purity of all outputs, this can be referred to as the "product" or "extract" or "accepts," whilst the rest of the output fraction(s) can be referred to as "reject(s)".

For example, in the case of an air separator with only two output streams, used in RDF production, the material carried away and separated from the air stream would be the extract, and the other stream the reject. For these outputs the historic terms "lights" or "low-gravity" fraction *vs.* "heavies" or "high-gravity fraction", "combustibles" *vs.* "incombustibles", and "organics" *vs.* "inorganics" have been used respectively. These terms all denote a principal feature, commonly shared by the items in the streams separated. They either refer to the separation operating principle (e.g. low-gravity) or to a desirable property of the stream (e.g.

combustibility, or organics). All constitute simplifications which if taken literarily can be misleading. To illustrate, the separation in an air classifier does not solely depend on density, but on aerodynamic and sometimes elastic waste particle properties. The term “organics” reflected unrealistic early expectations from air separators and has been proven wrong, because the air separators cannot effectively separate organic from inorganic materials.

In the case of size classification into two streams, the terms “overscreen fraction,” “overflow” or “overs” and “underscreen fraction” or “underflow” or “unders” or “fines” have been used. However, modern equipment typically has more than two output streams and none of them may be considered useless (i.e. a reject stream), as they are part of a continuing material flow management process, depending on their position in the overall flow-chart of the plant. Hence, all output streams should be called “products” and, if possible, suitably identified by terms that approximately describe their anticipated constituents. These complexities suggest that careful interpretation of the existing literature on performance is imperative.

The performance of each process unit should be evaluated against the role it plays within the material separation process. No single parameter can describe all aspects of a mechanical unit operation performance. The most important descriptors for material flow management are defined below. The varying nomenclature that is evident in the literature is expressed in symbols compatible by large with the MFA according to Rotter et al.[49]. Conventional descriptors of separation unit operations performance are yield, recovery, purity, and overall effectiveness[61, 80, 113-117]. These are defined for the generic case of a separation unit with multiple input and output streams (products). The mode of operation of the separation or classification equipment affects the results. During measurements effort should be taken to achieve a constant state of operation over a given time frame[118].

The purity (cleanness or composition) evaluates the degree of contamination by undesirable impurities, or denotes the mass-based material composition (input)[80]. Purity C(CM)P_l is defined as the ratio of the mass of a component (or set of components) in the product over the total mass of the product (TABLE 6).

<<Table 6>>

It denotes the mass fraction of certain useful waste component(s), such as the combustible items, suitable for RDF/SRF production, present in the corresponding product. An ASTM standard covers the determination of purity[121]. The numeric values measured for purity are affected by the exact determination process that is followed, for example, with Fe materials, manual sorting for waste characterisation or proximate analysis are both plausible.

The yield $Y(P_l)$ of a product P_l is defined as the ratio of the mass (or mass flow rate) of the product over the total mass (or mass flow rate, respectively) of the input (TABLE 6). It denotes the overall mass fraction, irrespective of its composition, which is transferred to a certain output stream, and characterises the separation process[80].

The recovery R(CM)P_l of a waste component (or set of components) into a product is defined as the ratio of mass (or mass flow rate) of these component(s) in the product, over the overall mass (or mass flow rate) of these components in all the input streams (TABLE 6). It denotes the mass fraction (or percent if multiplied by 100) of a set of components present in the input that reports in a certain product[80, 114]. An ASTM standard covers the determination of recovery[118]. In continuous processes, purity is easier to determine than the mass (or mass flow rates). Hence, the recovery in the typical case of one input, two products and two sets of components (CM) and other-than-CM (NCM) can be estimated in practice through the measured purities (TABLE 6)[80, 114, 118].

The minimum requirements to describe the performance of a material separation device are that purity and recovery should be identified[118]. However, the idea of combining elements of the above descriptors to produce a single overall performance descriptor is established. More than one total effectiveness formula (in the case of binary separation) that combines recovery and purity can be found in the literature. Rietema[113] reviewed the literature for the definitions of overall efficiency E, and assessed them according to a list of mandatory and desirable requirements that such a formula should fulfil, proposing the most appropriate formula (TABLE 6). Worrell and Vesilind[115] proposed another formula that results in similar values. However, it has not been verified as to whether it satisfies the full list of the requirements proposed by Rietema[113].

In the case of size classification, i.e. screening, the effectiveness of the separation can also be assessed through the grade efficiency (or partitioning, classification) curve[114, 119]. The mass based grade efficiency (or selectivity) $G(d_{NF})P_l$ is the recovery descriptor of the portion of waste particulates of a given size (narrow size range d_{NF}) into a product P_l (TABLE 6). It expresses the mass fraction of these waste particulates of given size range that reports into a product. For example, this descriptor can be used to evaluate the effectiveness of the separation of a screen for a waste component(s) for which there is evidence that it occupies a certain range of sizes after selective comminution or in the as-received waste.

The grade efficiency curve is the plot of the grade efficiency for the consecutive narrow size range d_{NF} that input can be divided into *vs.* the waste particle size. The main portion of the curve is anticipated to be roughly linear and determines the sharpness of cut. Sharpness of cut $k_{25/75}$ can be conventionally defined as the ration of the waste particle sizes that correspond to certain selectivity points, typically 25 % and 75 % (TABLE 6)[114, 120].

In practice, performance descriptors cannot reach the unit. Composite items (e.g. complex domestic appliances) or composite materials (e.g. fibre-reinforced plastics) are constituents that cannot be fully liberated during the comminution that typically precedes separation and/or classification[65]. Contamination effects are particularly important in waste processing, because of input heterogeneity and possible comminution.

A lower than expected performance in air separation units can be attributed to stochastic effects introduced by solid particles that interact with each other or with process unit walls. Additionally, unsteady air velocities occur[122]. These effects restrict the effectiveness of separation. As a result, trade-offs are inevitable and isolated use of any descriptor regarding effectiveness can result in misleading conclusions about material flow management performance[113]. For example, the above overall effectiveness relationships can be used in any separation process that sorts out two different output streams. However, in real systems one performance objective may be more important than the other. The need for high purity of a product may necessitate a low product yield, or vice versa [61]. Data from the SRF plant in Neuss, Germany, illustrated the inverse relationship between purity and yield[44]. Advanced processing with the objective of lowering the chlorine (Cl) content of SRF, (i.e. prioritising purity) resulted in a lower SRF yield. Overall efficiency formulas cannot allow for this varying relative importance of purity and yield.

4.3.2. Mass flow modelling and simulation for waste processing plants

The need for an accurate and comprehensive picture of material flows within a processing system has led to the development of system descriptions based upon mass balances[123]. These were particularly applied to RDF production plants. Diaz et al.[124] developed a system of recovery transfer function matrices to describe each unit operation, based on waste components found in input and output materials. Hasselriis, in a similar approach, developed spreadsheets describing the split of waste components into output streams[61]. For both prediction and design purposes, modelling of processing units and overall plants has been attempted. In the 1980s, Argonne National Laboratory in the US developed the computer programme GRAB, for simulating the operation of MSW processing plants[99, 100]. Warren Spring Laboratories produced a detailed evaluation of the software using data from the former RDF plants at Byker and Doncaster in the UK[101]. However, satisfactory simulation was not achieved.

A recent application in general SRF production can be found in Caputo and Pelagagge[125]. Chang et al.[126] developed regression analysis models based on mass balances of waste components and chemical elements (ultimate analysis) to predict the heating value of RDF product for a specific production line. Chemical composition models exhibited better prediction capability. Zwisele et al.[127] developed the software interface and the initial version of a simulation tool of mechanical processing for waste treatment plants such as MBT. This includes a material database of input waste properties, computing algorithms describing unit operations, calculation of flows, and quantifying the statistical uncertainty. Mass flows, average material composition and PSD are used for each of the substance sub-groups of light solids, high-gravity solids, minerals, ferrous metals and non-ferrous metals. The limited published validation data shows an acceptable goodness of fit; parameterisation was done with empirical data of the specific plant and a stationary plant model was assumed. The authors recognised that dependencies on time (residence time), capacities (load), moisture content, etc have to be taken into account in future developments and that the model has still to be validated with other case studies.

4.3.3. Novel material flow analysis approaches

MFA constitutes a systematic analysis of the flows (inputs and outputs) and stocks of materials both spatially and temporally as defined by Brunner and Rechberger[25]. As well as providing a systematic approach, descriptors are adapted for combination with societal evaluation methods such as cost benefit analysis[25, 128]. In MFA, transfer coefficients (TC) (or transfer factors) describe the partitioning of a substance into the outputs of a process[25]. The transfer coefficient of a substance into a product is defined as the ratio of mass (or mass flow rate) of the substance in the product, to the overall mass (or mass flow rate) of the substance in all the input streams. Practically, TCs are equivalent to the mass-based recoveries of conventional performance descriptors, with the mass fraction of waste components C(CM) being replaced by the mass-based concentrations of substances $c_m(s)$ (TABLE 6).

The TCs can depict the partitioning of a preserved property, such as overall mass and absolute element quantities, over the various output streams of a process. Generally TCs are substance-specific and depend on the input characteristics and the process conditions, such as the unit operation design and operating regime. The moisture content of the waste matrix is affected by both bioconversion (e.g. biodrying) and mechanical processing (e.g. comminution). Therefore, calculations or measurements of TCs should reflect this.

In addition to the use of TCs, Brunner and Stämpfli[51] and Rotter et al.[49] advocated the use of material enrichment coefficients (MEC). The MEC (on a mass basis) is defined as the ratio of the mass concentration of a substance over the mass concentration in the input (TABLE 6). MECs indicate whether the content of a substance, such as mercury (Hg), is increasing (concentrating, enrichment, MEC>1) or decreasing (diluted, depletion, MEC<1) in an output stream of a process compared to the input. MECs can also be expressed on an energy content (EC) basis, which is in accordance with the CEN approach to classification for trace elements of concern. In another approach based on MFA principles, distributions of properties of sets of waste components are plotted against their size range[50, 86]. The MFA framework enables an expansion of the description of waste processing units, plants and systems beyond the conventional mass based descriptors of yield, recovery and purity. Contradicting objectives such as high yield and low pollutant content require a quantification of recoveries[49].

There is little published MFA-based experimental data for MBT-related SRF production. Data is available for construction waste sorting plants[25, 51, 129] and EfW plants[130, 131], enhancing our understanding of substance flows. However, limited MFA research has been conducted on the performance of classification/separation for MBT plants and RDF/SRF production lines. Rotter et al.[49] experimented with urban and rural residual waste in an attempt to identify suitable mechanical processing units for SRF production, in terms of yield, recovery, CV and pollutant loads. Yield, MEC and TCs, reported on a mass and energy basis, were measured for various combinations of separation and classification unit operations, including screening, air classification, ballistic separation and magnetic separation. Pre-treatment was restricted to bag openers and removal of oversize items, without comminution. This restricts the applicability of the conclusions regarding the current MBT configurations, as most of them use primary comminution. Theoretical mass balance results from MFA studies for German MBT plant variants have been reviewed by Fehringer et al.[132]. In most cases, the data reliability cannot be assessed, as results are based on theoretical models and assumptions derived from existing practical experience.

The combination of conventional performance descriptors with MFA related formulas can convey a more detailed and accurate description of separation and classification unit operations, and mechanical processing plant in general. These descriptors of mechanical processing performance are summarised in TABLE 6.

4.4. Performance of separation and classification units for RDF/SRF production

Almost every MBT plant configuration is capable of separating a RDF/SRF product. In 1985, Barton et al.[62] in a detailed overview accounted for the earlier phase of RDF production plants in Europe, covering plant flowcharts, mass balances and detailed operating experiences from commercial references processing mixed MSW. Thomé-Kozmiensky[133] has summarised both recent MBT and mechanical processing plant designs for RDF/SRF production. For MBT plants a main distinction can be made between plant configurations[45]. Those in which production of SRF is their principal objective, which employ an initial biodrying step coupled with downstream extensive mechanical processing; and those where RDF is a by-product of only mechanical pre-treatment, with the aim to optimally separate the OFMSW fraction for subsequent biogas production through AD or stabilisation through composting; for indicative process configurations see Hüttner[134]. Additional variations with minor capacities exist. For instance the Nehlsen Stralsund biodrying plant (FIGURE 8) directs the >65 mm pre-shredded material directly to the SRF mechanical refining part and mixes it with the suitable fractions of undersize which is biodried[89].

<<Figure 8>>

Another possibility is the inclusion of dewatered and dried digestate residue from an AD process into the RDF product[135].

The SRF output should be produced to a specification that is increasingly subject to specific commercial agreements with the end-user, in addition to national and international quality assurance and control (QA/QC) procedures. From the perspective of an MBT plant operator, this translates into three objectives[49]. The first is to achieve a high yield of the SRF product. It has been estimated that *ca.* 20-30% $^{w}/_{w}$ of the German residual household waste in urban areas and *ca.* 18% $^{w}/_{w}$ in rural areas, could be recovered as a fuel, without the inclusion of the OFMSW, after separation and possible drying losses[49]. Pretz and Onash[48] estimated lower values of *ca*. 10-15% $^{w}/_{w}$ and Thomé-Kozmiensky[133] estimated 25-50% $^{w}/_{w}$, possibly including part of the OFMSW and before any losses. Experience from biodrying MBT plants suggests an upper limit at *ca*. 40-50% $^{w}/_{w}$ ar of input residual waste, if most of the biogenic content is incorporated.

Secondly the operator seeks to raise the heating value, compared with the plant input; and thirdly to reduce the chemical (e.g. volatile trace elements of concern, such as Hg) and physical contamination (stones, glass, porcelain, ceramic, concrete, Fe and non-Fe metals) of the RDF/SRF fraction. In order to achieve high recovery rates for the RDF/SRF fraction effective concentration of combustible particles, such as plastics (excluding long-lasting plastic products), papers and cardboard, packaging composites, textiles, and wood, is needed.

In the case of biodrying, inclusion of the biomass fraction is attempted, with the possible exclusion of any particulates that fall in the fine fraction (e.g. <10 mm). Incorporation of the biogenic content into the SRF can be highly desirable in an EU/UK environment. It concurrently serves the main target of diverting biodegradable content away from landfill, and results in a secondary fuel high in biogenic content, which in certain cases qualifies for a subsidy as an alternative to fossil fuel derived sources of energy.

Achieving high net calorific value (NCV) is crucial for RDF/SRF marketability. NCV of the biodried output has already been increased by removing a significant percentage of the moisture. Mechanical processing can further improve this by separating out the incombustible mineral fraction, which largely constitutes of dry recyclables such as Fe and non-Fe metals, and secondary aggregates (stones, sand, glass, ceramics, porcelain, etc.).

4.4.1. Size classification (screening) performance

Screening unit operations are the most established processing units in waste management[136, 137]. They are used in MBT plants to sort waste particles, mainly according to their size. From the great variety of classification equipment designs, rotating drum screens (or trommels) are the most widespread, followed by vibrating screens and disk screens[68]. Typical applications are immediately downstream of the primary comminution; or even as the first unit operation to exclude items from the primary comminution that do not need size reduction. They can also be used at many other process points. For example, use of trommels to remove the fine fraction contamination (e.g. <10 mm) from the low-gravity output of air-classifiers, intended for SRF production[82]; or for removal of batteries[138].

Trommels are reported as the most proven type of classification equipment, regarding effectiveness and reliability, especially with inputs high in moisture content, “stringy” material and with PSDs widely spread over both fine and coarse sizes[68]. A common performance problem of trommels is caused by plugging of the screening media, especially in the case of coarse screening. Material that fills and obstructs the openings can restrict their effective aperture size and reduce the mass flow rate able to report to the underflow[48].

Aspects of the design, function and performance of trommels have been modelled empirically or from the first principles[99, 139-142]. Earlier theoretical attempts to predict performance of trommels, such as the GRAB[99, 100] model, have been criticised as generally unsatisfactory[101]. Empirical modelling of recovery of the input sizes fractions 20-40 mm, 10-20 mm, and <10 mm of mixed household waste to the underflow product for a 50 mm aperture size trommel was attempted, through the development of a "feed-rate index". This is defined as the flow-rate of the true oversize particles divided by the trommel cross-sectional area[139]. Model predictions were close to actual values when the trommel was operated around the specified operation regime; but at lower feed rates, model predictions were much higher. It was suggested that the model did not account for the different characteristics of the comminuted output upstream of the trommel.

4.4.2. Screening performance without upstream comminution

Screening before comminution (typically after a mild bag splitting unit) has been proposed as a simple solution to problems caused by front end pulverisation, such as cross-contamination. However, research by Rotter et al.[49] showed that simple screening as a first and single step for mechanical pre-treatment before the biological stage cannot effectively separate the easily degradable organic fraction from the high CV fraction. This is particularly evident for residual waste that has a low initial CV and that is produced in areas with effective recycling schemes based on source separation. On the one hand, increased source segregation in

Germany has led to a lower potential energy based yield for SRF/RDF fraction streams[49]. On the other hand, other separation units performed much better in the same comparative test runs. One possible partial explanation is that for screening at 40 mm this could be anticipated; experience with the use of trommels has shown that significantly different aperture sizes result in different sets of components reporting to the overflow. Coarse screening at 200 mm concentrates mainly paper, textiles and film-shaped plastics; whilst screening at the range of 40-60 mm, will in addition contain metals, dense particles and putrescibles[139].

However, in agreement with Rotter et al.[49], Soyez and Plickert[59] reported results for the CV of uncomminuted residual waste, showing that for coarser screening, the increase in the CV content of the overflow, was small: even for screening at 150 mm, the CV remained relatively low, below 14 MJ kg^{-1} (FIGURE 9).

<<Figure 9>>

Hence, Soyez and Plickert[59] believe that a comminution stage may be unavoidable for the separation of a high CV fraction, because no screen overflow of uncomminuted waste was able to meet an indicative German market threshold of 15 MJ kg^{-1}. However, as Rotter et al.[49] have shown, other separation techniques, such as ballistic separation, may be effective without preliminary size reduction.

In terms of chemical purity of the SRF product, Rotter et al.[49] suggested that the insufficient reduction of pollutants in the SRF product implies that PSDs do not correspond well to the distribution of hazardous chemicals, rendering screening unsuitable for selective removal of highly chemically polluted waste particulates.

4.4.3. Performance of comminution followed by screening

The simplest configuration for mechanical processing before a core biological stage of in-vessel composting consists of comminution followed by screening, as illustrated at the Biodegma, Neumunster plant and Linde, Linz plant[5]. A usual objective of this configuration is to separate a high CV coarse fraction from a rich-in-organics fine fraction. Organic compounds present in the OFMSW can contribute to the overall potentially to recoverable energy present in the waste and to the biogenic content of the RDF/SRF. However, a higher yield for the coarse fraction achieved by a higher inclusion of organic matter may lead to a lower overall CV. The optimal compromise between the options should be informed by input characteristics and market requirements. Fricke and Mueller[143] and Soyez and Plickert[59] have exemplified the relevant complexities.

Soyez and Plickert[59] examined the performance of comminution followed by screening. German law (No. 30 BImSchV) sets maximum limits for the CV of waste to be landfilled to 6 MJ kg^{-1}, and the minimum for energy recovery of RDF/SRF at 11 MJ/kg. An indicative market minimum, adopted for illustration purposes could be 15 MJ kg^{-1}. From an RDF/SRF production point of view, the revolving composting drum performed best. Energy based yield to the RDF output reached up to 48% $^{w}/_{w}$ for the 40 mm screen overflow, whilst CV was only slightly below the assumed quality demand of 15 MJ kg^{-1},MJ/kg. For the 80 mm screen overflow, the respective values were 31% $^{w}/_{w}$ and slightly above the CV limit. Despite the highest CV values being reached by the hammermill and the roll crusher whilst screening at 150 mm, their energy based yield was only 7% $^{w}/_{w}$ and 16% $^{w}/_{w}$ respectively.

The combination of a revolving composting drum with screening at 40 mm provided acceptable results. The load of organic dry matter from biological origin in the underflow almost doubled compared to non-crushed MSW. The slightly higher values reached by the hammermill crusher were negligible compared to the large difference in the quality of RDF output.

Hammermill comminution followed by screening at 25 mm is used in the Linde MBT processes[144]. Results verified a selective size reduction, with maximum content in hard and vegetable matter between 2-6 mm; and in paper at *ca*. 10 mm. However, a low recovery rate (only 8-10% $^{w}/_{w}$) was evident for the plastics to the overflow (>50 mm), used for RDF production[107]. The rest of the plastic mass, down to the very fine size of 2-5 mm, did not enable a maximum recovery of high CV material in the coarse fraction.

Knowledge of the input PSD and the size ranges in which waste particles concentrate can enable more effective use of the screening units by informing the appropriate separation size. Pretz and Onash[48] reported on an example of successful screening (of unknown boundary conditions, e.g. type of input) after appropriate selection of the aperture size by use of PSD. A 60 mm squared hole drum screen enabled the enrichment of OFMSW in the underflow and a fraction intended for SRF production in the overflow.

4.4.4. Performance of cascade-ball mill with flanged trommel

In such process configurations the emphasis is on separating an OFMSW optimised for subsequent AD or composting. The PSD of size-reduced output of the ball mill-trommel combination is generally log-normal and does not strictly follow RRSB distribution. Results from Koch[107] show that the cumulative weight fractions plotted in a RRSB diagram give a straight line only for the finer ground materials, with an interruption commencing at *ca*. 15-

40 mm. Data for the similar Outukumpu-Hese ball mill case were compared to other comminution processes coupled with screening (FIGIURE 10).

<<Figure 10>>

PSD results for the similar Outukumpu-Hese ball mill site were compared to other comminution processes coupled with screening. The histogram of cumulative mass frequency distribution (FIGURE 11) indicates that organic-origin material was effectively concentrated in the <40 mm fraction, with less than 3% $^{w}/_{w}$ being above 25 mm[106]. Around 64% $^{w}/_{w}$ of the organic material reported to the 0-5 mm screenings and 35% $^{w}/_{w}$ to the 5-40 mm fraction. Similarly, the 0-40 mm fraction, processed by a Outukumpu-Hese cascade mill, concentrated 97% $^{w}/_{w}$ of the organic material contained in the input waste[109]. Operators of the process claimed that compared with the size reduction achieved by hammermills, the fraction 0-40 mm contained lower levels of metals, inert material and textiles contamination[109]. Recoveries to the 0-40 mm underscreens were plastics 33% $^{w}/_{w}$, cardboard and paper 80% $^{w}/_{w}$, nappies 80% $^{w}/_{w}$, and textiles 4% $^{w}/_{w}$.

<<Figure 11>>

Koch[109] suggested that concentration of the maximum amount of organic mass in the fine fraction (<5 mm) could be favourable for the two fractions intended for RDF/SRF production (e.g. 5-40 mm and 40-80 mm). Such a fine size range OFMSW could beneficially concentrate the bulk of material that is high in moisture content. This stream would have to be adjusted to higher moisture content levels during the upstream aerobic composting or anaerobic digestion, whilst its separation could free fractions intended for RDF/SRF production from unwanted water content. Advocates of such a process configuration consider it to be more energy efficient than processes that employ less sophisticated mechanical pre-treatment and resort to drying of the total waste input for RDF/SRF. Plastic films, paper and cardboard are distributed in the particle size range of 10-40 mm, reporting in the intermediate output fraction (5-40 mm). As this fraction is intended for RDF/SRF production it should not be finely ground. The 40-80 mm product constitutes *ca*. 25% $^{w}/_{w}$, before separation, primarily concentrating wood and textiles, hard plastics, and metals. Metal and inert materials can be easily separated out.

4.4.5. RDF production and optimisation of the PSD of organic fraction for subsequent bioconversion

One of the important objectives of comminution in MBT plants that use bioconversion processes, is to optimally pre-treat OFMSW for the subsequent biological process. The OFMSW should be concentrated in the fines range, leaving the material in the coarser stream for either RDF production, or for direct landfill disposal. The yield and quality of RDF is affected by the specific mechanical pre-treatment choices for the intensity of primary comminution and the aperture in the subsequent screening. Conflicts between RDF production and optimal OFMSW bioconversion may arise.

Significantly different capabilities and restrictions for separation of the RDF fraction exist for AD and composting configurations of MBT plants. Much more extensive mechanical pre-treatment is necessary for the preparation of a suitable OFMSW for AD. In turn, this results in MBT plants being equipped with sophisticated mechanical processing unit operations, capable of effective separation of the RDF fraction. However, as there is evidence that fine comminution of the OFMSW is beneficial for biogas yield and effective fermentation, an initial pulverisation step might be included, which could result in contamination of the RDF fraction with finely comminuted impurities. MBT plants using composting to biostabilise the input for landfill disposal or CLO production, need much less sophisticated mechanical pre-processing and the need for size reduction of the OFMSW is lower. The objective here is to minimise the capacity of the composting unit and the yield to be landfilled, which may necessitate complex mechanical pre-processing. However, objective conflicts may also arise because some of the waste components could be included in both the OFMSW and RDF fractions. To illustrate this point, wood is of high CV, but can also have a beneficial role in aerobic decomposition, functioning as structural material. Legislation stemming from national waste policies can specify the appropriate split of materials, in terms of biodegradability or CV implications for the final MBT outputs.

Substrate particle size affects (amongst many other parameters) the performance of bioconversion. For composting biostabilisation, primary size reduction is generally sufficient, whilst for AD an additional maceration stage may be attempted upstream of the separation of the OFMSW, usually not affecting the RDF product. Many possible mechanisms exist, through various aspects of the bioconversion, which are dependent on the particle size, shape and condition of the substrate. Generally, the objectives to be met by optimising the PSD of the substrate are to obtain a more extensive degree of bioconversion and to reduce the process time. For instance, in the case of AD these could be exemplified by achieving higher biogas yield, reducing the digestion time, and minimising the amount and improving the quality of the digestate[146].

Optimal size ranges for substrate particulates are significantly different for the anaerobic and aerobic types of bioconversion. Smaller particles are thought to be optimal in the case of AD, where size reduction through mechanical pre-treatment is able to accelerate the bioconversion, possibly through increasing the available specific surface[147, 148]; especially for substrates of low biodegradability[146]. However, the relevant mechanisms are complicated and the PSD of the substrate is not the only or necessarily the most influential parameter affected by comminution that may impact on the bioconversion performance. Another factor that has not yet been investigated is the cutting principles (type of loading mechanism)[70, 149]. Comparative results on the influence of different degrees of substrate size reduction pre-treatment (shredding at 14 mm and maceration at 1.7 mm) showed virtually no difference on the biogas yield of laboratory scale anaerobic digestion of OFMSW for organic loading rates from 2 to 5 kg_{VS} m^{-3} d^{-1} [110].

Organic material comminuted in a cascade mill exhibits a relatively large active surface and is optimally homogenised for subsequent AD treatment, compared with other combinations of size reduction pre-treatment[106]. Further separation at *d* (mm) (*d*=3, 5 or 8) has been proposed to provide a fine fraction (0-d) rich in organics intended for biological treatment[107]. However, whilst a 0-10 mm fraction could concentrate around 86% $^{w}/_{w}$ of organics, a 0-3 mm fraction could achieve only an estimated 45% $^{w}/_{w}$. This seems to be in agreement with the relatively low biogas yield for laboratory tested anaerobic digestion of the >3 mm fraction of residual waste, pre-treated with a Loesche-Hese cascade mill-trommel combination, followed by flip-flop screening, in comparison to average values for biowaste input[108]. A similar <5 mm fraction containing mainly paper and inert material in addition to the organic mater, had a 30% $^{w}/_{w}$ yield and a characteristic particle size at *ca*. 3 mm[109]. This material flow approach biostabilises only a small fraction of the input waste (30% $^{w}/_{w}$). However, the success of such an MBT configuration depends on securing markets for the two types of RDF that are produced from the 5-40 mm and 40-80 mm mechanically separated outputs (FIGURE 12).

<<Figure 12>>

Other typical MBT approaches resort to limited or different types of mechanical pre-treatment and aerobically stabilise significantly larger mass percentages of the input waste. Koch[109] showed that biostabilisation through composting of a fine fraction (<5 mm) after comminution by a ball mill reduced treatment time to achieve the German legal stipulations for landfill storage. This outcome is partially surprising, as optimal ventilation in composting is enhanced by larger particle sizes with a higher volume of void spaces. If structural conditioning did not take place in this specific process, the result might be explained by enhanced oxygen diffusion transport, anticipated for particle sizes of about 10 mm or lower[150]. Additional results from the Brandenburg Recycling Park Hese cascade-mill indicated effective biodegradation reduction by a short intensive composting stage (FIGURE 13).

<<Figure 13>>

Silvestri et al.[151] investigated the performance of comminution by hammermill shredding followed by trommel at 80 mm, with the objective of optimally concentrating the organic fraction in the underflow for aerobic stabilisation, enabling in parallel the separation of an overflow with sufficiently low biodegradability potential, suitable for direct disposal. The input was residual MSW from three areas (Trento, Zuclo and Iscle di Taio) in the Province of Trento, Italy, after source segregation of recyclables, including kitchen and green waste. Results showed that an overflow with respiration index lower than the legal limit of 1300 mg O_2 kg_{VS}^{-1} h^{-1} was not always achievable at 80 mm, possibly because of a high content of paper and card in the overflow, in addition to the organics (TABLE 7).

<<Table 7>>

The authors speculated that screening at larger apertures (e.g. at 100 mm) could be effective in lowering the biodegradability content of the overflow. However, if the overflow material was used for RDF production this would be counterproductive, as it would lead to higher quantities of high CV materials, such as paper, reporting to the underflow.

The Nehlsen biodrying plant in Stralsund, Germany, has input of residual domestic, commercial and bulky waste. A 65 mm disk sieve is employed to separate the pre-shredded material into overflow that goes directly to SRF processing from the underflow that is biodried; the finest fraction of biodried output (<10 mm, 27% $^{w}/_{w}$ of input) is further stabilised before landfill disposal[89].

4.4.6. Air-flow (or pneumatic) separation

Air-flow separators (or air classifiers, AC) are typically present in RDF/SRF production lines of MBT plants. Air classifiers have long been established in industrial applications, such as agriculture and minerals processing, where they are used to separate components from dry mixtures[61, 63, 80]. In solid waste management (SWM) they were applied as a key part of conventional RDF production plants, operated initially on MSW and later commercial or source-separated waste[62]. Expectations for AC performance were initially high but a phase of scepticism followed in the 1990s. This can be attributed to off-the-shelf applications of ACs proven in other industrial operations, but not adapted or optimised to waste, combined with unrealistic expectations (e.g. separation of organic from inorganic items, despite their similar densimetric properties)[61, 63, 153]. Currently the confidence in the effectiveness of ACs has been re-established in practice[65].

Within MBT plants, ACs are mainly used for concentrating the high CV combustible fraction in their low-gravity product[65]. Other specialised uses include the separation of a high-plastic film and paper fraction for subsequent material recovery, and for the removal of plastic from waste intended for landfill disposal in Germany, where legislative upper limits apply on the CV of landfilled material[65]. Application of AC for compost product refinement, with emphasis on the removal of plastics, has recently been considered, with limited success[154]. Timmel[65] reported a typical throughput rate of ACs after the preceding classification at less than 15 Mg h^{-1}.

Shapiro and Galperin[80] provided a thorough overview of modern classification applications, including operation principles, features and performance parameters. However, their emphasis was not on waste separation, but on particle size separation applications. Timmel[65] focused on residual and commercial waste treatment and an older RDF-production related overview can be found in Hasselriis[61] TABLE 8 provides relevant data from Timmel[65] and other publications.

<<Table 8>>

In typical configurations, separation is based on the differences in inertial (such as density) and aerodynamic properties (such as size and shape, i.e. measured as granulometric properties) of the in-feed particles. Air flows through the in-feed waste mixture causing high-gravity waste particles (constituting the reject) to either fall freely or to be deflected towards different chutes or conveyors. The low-gravity particles (being the extract) are either carried away with the off-gasses, to be concentrated downstream in cyclones or fabric filters, or are deposited on spacious settling chambers. Up to 70% of the classifying air can be re-circulated, in cross-flow designs[48]. Within mining processing, separation occurs according to particle size[80], however, in waste treatment the density-dominant separation is more appropriate and efficient[117, 122, 155]. Other sophisticated types of ACs have been developed that incorporate additional material properties, such as elastic behaviour[65]. In residual and/or commercial waste separation, only gravity separators are used, and so far, centrifugal separators have not been introduced. Cross-flow separators prevail, in which the classifying air flows perpendicular to the waste and deflects the particles at various distances[65] (FIGURE 14).

<<Figure 14>>

The performance of ACs depends on the particular design, the mode of operation and the characteristics of the in-feed stream. Generally, for optimal separation the following are desirable[65, 80]: (1) sufficiently narrow particle size ranges in the in-feed; (2) constant, and if possible, isolated feed of the individual particles; (3) well-defined and stable air-flow and reduced turbulence; (4) pneumatic conveying through pipelines applied to the low-gravity material; (5) separation of the low-gravity material from the classifying air; and (6) repeated cleaning of all fractions.

Hasselriis[61] and Everett and Peirce[117] summarised the research that preceded the development of pulsed air classification. Bartlett[156] showed that the performance of a zig-zag air classifier is compromised at high moisture content of the input, and the amount of adsorbent materials present in the input was identified as an important parameter. The main effect was on paper density and agglomeration, although plastics were also affected and reported to the low-gravity product. The composition of the feed, such as the paper-glass ratio, is also important[157].

Both first principles and empirical modelling of the performance of air classifiers has been attempted, particularly outside waste management. For example, Wang et al.[120] used computational fluid dynamics (CFD) simulation of cross-flow AC performance for size classification and Klumpar[114] examined performance optimisation of air classification in closed circuits with grinding. There is little research that is directly relevant to waste sorting. However, the principles for density-dominant separation through pulsed air classification are discussed in Vesilind[122] and Everett and Peirce[117]. Validation of the air classifier unit operation of the GRAB[99, 100] computer model using data from UK RDF plants showed adequate results for the raw mixed waste at that time, but different coefficients would be necessary for pulverised waste[101]. Parameters used were air flow, particle size and density, shape, and coefficient of variation. He et al.[155] showed that non-waste simulation of airflow patterns within passive pulsing air classifiers can raise total effectiveness by 6-8% compared with conventional ACs. Biddulph and Connor[158] used effective diffusivity to model and evaluate the performance of low-gravity and high-gravity products for different duct designs of ACs, operated at high values of air/solid ratio, reporting better performance for lower values.

The exact performance of air-separators has to be evaluated by pilot tests, as accurate design calculations are thought to be impossible because of the problems associated with the granulometric description of waste particles[65]. The selection criteria for the appropriate air-separation equipment include waste composition, particle size of waste stream to be sorted, required throughput rate and required performance[65].

Rotter et al.[49] presented a large scale comparative study on configurations of separation and classification equipment for SRF production for residual waste. This study provided insights into the material flow management performance of ACs. AC unit performance was among the top performing ballistic separation processes, which include air knife and crosswise. They achieved high enrichment in lower heating value (LHV) because of the high plastics percentage. However, this led to a high Cl content. Additionally, failure to incorporate the wet components into the SRF caused a high enrichment of cadmium (Cd). These results indicate that for the purpose of mechanical post-treatment of biodried output, air-classification may perform closer to ballistic separation both in terms of yield and Cl content, as it would be less difficult to incorporate the paper, card and textile fractions. TABLE 9 reviews results on air classification performance.

<<Table 9>>

4.4.7. Ballistic separation

Ballistic separation has a wide range of applications, including removal of mineral contaminants from grains and nuts, sorting construction waste, concentration of paper and packaging material in MRFs, sorting of plastics[160], conventional mechanical RDF production plants, and various roles in MBT plants[5]. Possible applications within MBT flowcharts include initial separation and classification upstream of the typical primary comminution step (typically performed by a trommel), removal of mineral and metallic contamination from the RDF/SRF fraction (typically performed by air classifiers), and refinement of the biologically treated output for landfill disposal, for example, to meet a maximum CV restriction, or for CLO production[152].

The operating principles of ballistic separators depend on differences in specific density (densimetric separation) in conjunction with other material properties, such as elastic properties (hardness), shape, and size. It combines separation with classification, resulting in at least three output streams. The waste components are separated by following different trajectories as they impact on a series of parallel, inclined, metallic belts (paddle plates) that vibrate by rotating eccentrically and against each other (FIGURE 15)).

<<Figure 15 >>

First the low-gravity, soft, flat/foil-shaped (2-D), particles (such as paper, cardboard, textiles, plastic foils and bags) bounce or are moved forwards and upwards in a circular movement by the rotating action of the paddles, reporting to the so-called “low-gravity material" or "light fraction"[162]. Secondly, the high-gravity, hard, 3-D particles (e.g. minerals like glass and stones, containers such as tins and steel, wood, hard/massive plastic particles) roll or bounce in a downwards diagonal reverse direction, transported to the so-called "high-gravity material" or "heavy fraction." Thirdly, in addition to separation, screening is also achieved by the use of perforated paddles that enable the small-size particles (such as sand, kitchen waste, dust) to fall through and be collected in the "screenings" or "underscreens" or "fine fraction."

Varying designs options enable optimisation of ballistic separators for specific inputs and objectives. The main distinction can be made between one, two or three stage designs[152]. Additional screens can be added (stacked on top of each other) increasing throughput and the number of screening outputs. Possible adverse impacts on performance aspects are the purity of outputs[163], caused by material falling from the upper screens and interfering with the operation of the lower decks. Different types of paddle perforations (e.g. punched or net-shaped) and aperture sizes can be specified according to the in-feed material composition. Further adaptability is offered by controlling the in-built adjustable angle of inclination of the complete set of paddles[152], and the frequency of paddle rotation[68].

No detailed modelling of the performance of ballistic separators was found in the literature. However, there is a considerable difference in the density of non-combustible components (stones, glass, ceramic, porcelain and metal) with densities above 2 g cm^{-3} and the combustible components (plastics, wood, paper, textiles) with densities around 1 g cm^{-3} [164]. Densimetric separation could thus in principle be used for separating combustible from non-combustible waste fractions for RDF/SRF production. However, in a ballistic separator additional physical-mechanical properties are used for separation and classification resulting in the recovery of waste components not being based entirely on their density. In addition, absorbed water may change the density of the waste particles, as is often the case for paper and card.

Experiments on a two-step ballistic separator with horizontal first level paddles in the aerobic stabilisation MBT plant at Linkenbach, Germany (treating residual domestic and commercial waste) were conducted in November 2002[152]. The performance of the ballistic separator was measured in the main air classifier role, aiming at the concentration of combustibles in the low-gravity, >45 mm product, by directing minerals in the high-gravity, >45 mm product, with the parallel objective of enriching the organic fraction in the <45 mm screenings for subsequent aerobic stabilisation. In-feed was the overflow of a drum screen with round mesh at 100 mm, treating comminuted waste. In the first two paddle levels of ballistic separator 45 mm screen apertures were used.

The low-gravity, >45 mm product reached a yield of *ca*. 77% $^{w}/_{w}$, in which accumulation of the high CV fraction was evident by the high recovery of paper/cardboard (91% $^{w}/_{w}$), films (97.2% $^{w}/_{w}$), sanitary products (97.3% $^{w}/_{w}$.), etc). However, the high-gravity fraction accounted for a yield of 13% $^{w}/_{w}$ with a relatively high LHV (9.2 MJ kg^{-1}), resulting in an energy-based yield for the low-gravity product of 83.1% $^{w}/_{w}$. This was exemplified by the recovery of some high CV materials into the high-gravity product, namely wood (46.0% $^{w}/_{w}$.), plastics (16.2% $^{w}/_{w}$), composite materials (21.4% $^{w}/_{w}$), and textiles/shoes (14.7% $^{w}/_{w}$). According to the authors, this would necessitate a further treatment step for recovery of a light, high CV fraction from the high-gravity stream. A high-gravity solid trap proved effective in this role, rendering a high in LHV low-gravity product at a 55% $^{w}/w$ yield[152]. On the other hand, most of the combustible components that were not satisfactory recovered to the ballistic separator low-gravity product (hard/bottle plastics, composites and textiles/shoes) are generally components of a high specific chemical pollution load, as indicated by Rotter et al.[49]. Hence, the current outcome, despite being partially detrimental to the overall process energy-based yield to the RDF/SRF stream, might be desirable in terms of lowering the level of chemical contamination of the RDF/SRF product. MFA results for the ballistic separation of uncomminuted residual urban waste, with upstream removal of bulky items and metals and screening at 40-150 mm, provided lower values for yields of the unit operation input to the low-gravity product TABLE 10)[49].

<<Table 10>>

In the same Linkenbach MBT set of tests, glass was entirely directed to the ballistic separator screenings (recovery 100%) in which the organic fraction was also concentrated[152]. Although this is beneficial for RDF quality, it would highly contaminate the organic fraction, for non-landfilling or landfill cover uses. Organic content was largely split between the low-gravity product and screenings. A significant percentage of the metal content (63.8% $^{w}/_{w}$) was recovered in the low-gravity fraction. Effective separation of metals would demand subsequent treatment of both the low and high-gravity fractions.

In a second Linkenbach MBT set of tests, ballistic separator performance was evaluated directly upstream of the primary comminution and compared with an existing drum screen at 100 mm[152]. The three-fold aim was to concentrate the RDF-intended fraction in the low-gravity product, achieve high recovery of minerals and metals in the low-gravity product and separate an OFMSW of low LHV in the screenings. In each run identical paddle apertures were used in both decks, at 75 mm and at 45 mm. The low-gravity fraction yield was 31.9% $^{w}/_{w}$. and 36.4% $^{w}/_{w}$ respectively, comparing favourably to the 28.3% $^{w}/_{w}$ reached by the drum screen. The overall energy-based recovery was also higher for the ballistic separator runs, due to the higher mass yield and only slightly lower LHV (11.9 MJ kg^{-1} ar for the drum screen and at 11.0 MJ kg^{-1} ar for both the ballistic separator tests). Rough optical inspection indicated that the mineral content of the ballistic separator low-gravity product was composed of smaller particles with planer shape in comparison to the drum screen overflow. The authors speculated that this could cause fewer problems during a final size reduction step for control of the RDF PSD than the larger mineral particles apparent in the drum screen output. However, experience from the use of ballistic separators for plastics sorting has indicated that effectiveness as a “primary” separator of plastics can be low, especially if the input has been compacted in refuse collection vehicles, as plastic bottles that would normally report to the high-gravity product become flattened after compaction and report to the low-gravity output[163]. On the other hand, for RDF/SRF production purposes this may be desirable, depending on the chemical pollution load of the misplaced components.

Other large-scale MFA tests conducted by Rotter et al.[49], with similar objectives but with uncomminited waste, provided evidence for the generally superior performance of ballistic separators as the first sorting unit operation. However, performance on lowering the chemical contamination load for the RDF/SRF intended product was better than on mass yield grounds. Comparative tests included screening at 30 mm, three stage air knife classification, two-stage crosswise air classification, foil suction combined with infrared (IR) plastic detection, and ballistic separator units with paddle openings at 40 mm, with or without upstream screening. In all cases, bulky item removal and magnetic separation took place. Yield on an as received mass basis ranged from 5% $^{w}/_{w}$ ar for foils-suction with IR plastic detection to 60% $^{w}/_{w}$ ar for screening at 30 mm. TC values were in accordance with the identified yields. In most cases, Cl enrichment took place in the final product, up to 70%. Energy-based MECs resulted in lower pollutant elemental enrichment, in comparison to the mass-based.

Apparently contradictory results initially warned against the danger of generalisation when dealing with the material flow management performance of separation and classification unit operations. The fact that the yield to the low-gravity output of the ballistic separator (*ca*. 45% $^{w}/_{w}$ ar; of after 11% $^{w}/_{w}$ ar of the test input removal of bulky and ferrous items) was lower than to the 40 mm overscreens of the size classifier (*ca*. 62% $^{w}/_{w}$ ar; after 8% $^{w}/_{w}$ ar of the test input removal of bulky and ferrous items)[49] seemingly contradicts with the previous results[152]. However, the two cases treat waste inputs significantly differently (uncomminuted versus comminuted), the screening is operated at different openings (40 mm versus 100 mm) and different designs of ballistic separators were used. This apparent contradiction could be explained by the much higher yield anticipated for the overscreen of 40 mm for an uncomminuted waste input, compared with the yield anticipated for the 100 mm overscreen treating a comminuted input.

Tests with ballistic separators were the only way to achieve significant dilution of polluting substances (negative MEC) in the final SRF product, with the best results reported for direct application of ballistic separation, without previous screening[49]. This can be attributed to the greater ability of ballistic separators to incorporate wet high CV items (paper, cardboard and textile) into the low-gravity stream. For example, paper has a Cl content lower than 0.5% $^{w}/_{w}$ d, which is below the average in residual waste. Additionally, high recovery of the highly chemically polluted components in streams other than the low-gravity products enables the concentration of a low-polluted SRF stream. This is in agreement with evidence from Herhof MBT plants that reduced specific load for some trace elements of concern was reached in the low-gravity product of the ballistic separator[164].

4.4.8. Sensor detection and sorting

Various sensor detection and separation technologies are available including optical sensors, image recognition, X-ray fluorescent, X-ray transmission, and IR and near-infrared (NIR), each with different strengths and weaknesses[94]. This technological field is currently signicifantly developing. Harbeck and Kroog comprehensively reviewd emerging technologies applied in the mining industry, a constant source of technology transfer to the waste processing[165]. They considered as most promising detaction methods the X-ray transmission, evaluation of thermographic images and electromagnetic measurements, because they are independent of the item surface, dirt or moisture, qualities similarly desirable in waste sorting. Colour-based sorting devices (optical sensors) have been used for over 20 years. Relatively new developments are X-ray systems[166], image detection and NIR detection coupled with pneumatic discharge[48]. These technologies offer novel capabilities for chemically-based waste sorting waste, in line with the emerging higher requirements for effective material flow management. If their effectiveness can be demonstrated, this could constitute a major breakthrough in waste handling. Promising combinations of NIR with image analysis, using sophisticated cameras, enable separation of materials based on specialised optical characteristics, such as the surface design.

In NIR, a fast scanning spectrometer analyses the molecular structure of moving objects by NIR light. Spectrums of the most commonly used materials have been developed, enabling selective recovery of materials. Air nozzles, activated for a fraction of a second, blast the identified waste particle, blowing it out of its trajectory to an appropriate discharge gate. Throughputs of 7-9 Mg h^{-1} are achievable with a machine width of 2000 mm[48]. Recovery percentages as high as 90% for high CV components (e.g. plastics, wood, paper, cardboard, diapers) are thought to be feasible. Nevertheless, cellulose-based items can only be detected at lower percentages of 50-60%.

Use of NIR in MBT plants could theoretically be used for removal of plastics with chlorinated compounds like polyvinylchloride (PVC). However, this technology is not able to detect chloride salts present in kitchen/yard waste or in other kitchen waste contaminated components[167]. However, the organic-bound chlorine fraction present in plastics (*ca*. 85% ^{w}/w. of overall Cl) is the most detrimental part. The potential to use NIR to separate out the plastic fraction from RDF/SRF produced via biodrying MBT, so as to increase its biogenic content, has been investigated in Germany[168], with promising results.

However, these technologies still need to overcome some challenges. In a large-scale test of a foil suction apparatus combined with IR plastic detection for SRF production from uncominnuted urban residual waste, mixed results were reported. Despite the high separation of the components with high chemically polluted content, the yield to the SRF product was just 5% (after bulky items and metal recovery)[49]. Zeiger[166] reported some of the potential limitations of the NIR applications, when used as an alternative or supplement to air classification for RDF/SRF production. The detected and removed output intended for RDF/SRF production contained mainly light-coloured plastics, untreated wood and various textiles *ca.* >50 mm. Many dark plastic components, coated and treated woods, and mixed materials that are difficult to treat cost-efficiently with NIR remained in the residual fraction (0-50 mm and high-gravity items).

Due to these difficulties, Zeiger[166] proposed the use of X-ray sorting. Typical applications in a RDF/SRF producing MBT could be removal of SRF impurities (inorganic matter and highly chemically polluted matter), and separation of the high-gravity fraction from domestic and commercial waste input, for the effective concentration of the OFMSW.

4.4.9. Separation of metals and batteries

Effective processes to separate Fe and non-Fe waste particles are generally available and have been summarised elsewhere[94]. Typical equipment for Fe metals are overhead belts and drum magnets, with magnetic separators with alternating pole systems being particularly effective; and eddy-current separators for non-Fe[48], using either centric or eccentric polar systems. Downstream of these two basic unit operations, sensor sorting systems (inductive, NIR, and X-ray) can also be used for more sophisticated separation[112]. The role and objectives of magnetic separation equipment in MBT plants vary[68], but include protection of downstream equipment from wear and tear, extraction of secondary raw material according to end-user specifications (e.g. detinning industry, and iron and steel industry), and removal of contamination from RDF/SRF or the OFMSW stream to be treated in AD.

Recovery of Fe-metals can be up to 95%[48]. Eddy-current separators effectively separate non-Fe metals, particularly for flat and isolated items, which makes screen sizing upstream and feeding with a vibration conveyor beneficial. From the non-Fe metals, aluminium (Al) is the most important, both commercially and as a contaminant for SRF, with achieved yields up to 90%, and purities *ca.* 60-70%, as Al often comes combined with other materials.

Batteries constitute a main source of chemical pollution. Until effective systems of collection at source are implemented, they will continue to constitute a major challenge for material management in MBT plants. Possible contamination of SRF, OFMSW or secondary raw metals is evident. Avoiding breakage and effective separation are imperatives for sustainable resource management. Around 90% of batteries are magnetic or slightly magnetic[164] and can report to the fine-particle Fe fraction. For example, in the Herhof-Asslar plant, they are manually picked from the ferrous material conveyor and returned to the manufacturers for appropriate recycling. For best results, permanent magnetic neodymium drum separators can be used[48]. However, they do attract weak magnetic items contaminated with organic adhesives.

There is evidence that for certain process configurations, waste particles with high specific loads in trace elements of concern report to the metal product. In experiments with different process configurations for SRF production, Rotter et al.[49] reported that batteries, electronic waste and other composite materials partially concentrate in the metal stream product, resulting in mainly Cd, and to a lesser extent lead (Pb), enrichment in the metal output. Further evidence from Herhof MBT plants showed enrichment of the non-Fe metals output with trace elements of concern, possibly because of electronic scrap particles[164]. The contamination of the Fe and/or non-Fe secondary raw products with trace elements of concern creates problems with their quality and marketability. In addition, the problem of the same high-pollution components contaminating the SRF product is not fully avoided by magnetic separation, as some of these items still report to the fuel stream output[49].

4.4.10. Position and performance of unit operations in MBT plant flow-charts

A challenge observed in RDF production plants during the 1980s using hammermills was to liberate and selectively reduce the size of coarse items, whilst avoiding over-pulverisation that leads to cross-contamination[62]. Recently, rotary shears have been used in preference to hammermills. Another possible partial improvement could include use of screening equipment ahead of the hammermill. Retrofitting the RDF Byker plant, UK, by including a bag splitter followed by a trommel before the primary shredder achieved positive results in the final RDF quality: extensive test results, including impact on downstream operations are available[169].

Screening is often used upstream of other separation processes as a pre-treatment. Experience indicates that a coarse pre-screening of 100-300 mm can be beneficial. If this coarse pre-screening is omitted, screening of mixed MSW input at <100 mm can lead to substantial agglomeration, resulting in contamination of the overflow with material intended for the underflow[48].

Operating experience from RDF production plants in the 1980s has shown that appropriate feedstock preparation is important for the effective operation of separation units[62]. Whilst comminution is not mandatory, ACs should be at least preceded by a size classification unit operation, such as a trommel, to optimize the sorting effect[49, 65]. With air-knife and crosswise air classification, the maximum allowable particle size in the AC in-feed is in the range of 250-350 mm[49]. However, the use of trommels ahead of ACs can affect their performance[65]. Unwanted secondary composites, such as large textile agglomerations, may be formed and lead to AC operational faults. Bar-shaped particles can report to the trommel underflow, even if one of the other dimensions of the particle is larger than the aperture size of the trommel, resulting in items exceeding the maximum desirable size.

On the other hand, ballistic separators are non-sensitive to a dispersed PSD of the input stream. When treating residual waste previously screened at 0-150 mm, the performance was slightly worse than treating the unscreened stream[49]. This indicated that screening ahead of ballistic separators may not render the desired result.

It is evident that drying of waste facilitates can facilitate the flow of waste matrices[62] and subsequent mechanical processing. Moisture content of the as delivered residual waste (*ca.* 15-40% $^{w}/_{w}$ [164]; *ca.* 35-55% $^{w}/_{w}$ [133]) is unfavourable for efficient screening. Typically, biodried output has moisture content lower than 15% $^{w}/_{w}$, but fluctuations are common. Reduction of moisture content by biodrying reduces the formation of lumpy material that sticks together and creates problems for efficient separation. Low-gravity yield of air classifiers for RDF/SRF production could benefit from a dried input. For example, eddy-current separators, separating non-Fe metallic material, can particularly benefit from operating with a comminuted dried and disaggregated material[48, 164]. They are most effective with a mono-layer of single particles. However, ballistic separators can effectively incorporate wet input fractions into the low-gravity product[49]. This indicates that if such a unit is used before composting/AD for RDF/SRF production, the output would have increased drying needs. Alternatively, after biodrying, this problem could be avoided. If processing SRF into hard pellets is necessary, e.g. for subsequent shaft reactor gasification, a moisture content not exceeding 10% should be achieved[133].

4.5. Mechanical processing conclusions

Evolving objectives of material flow management and higher standards determine the needs for mechanical processing in MBT plants that produce RDF/SRF. Segregating out waste fractions with the desired chemical composition progressively becomes more important in the design of these systems. For example, with the objective of high-grade SRF production, it is not sufficient to separate a comminuted coarse fraction just on a PSD basis. The need to obtain the maximum achievable yield in high CV, low in pollutant load and possibly high in biogenic content SRF demands definition and selective separation of waste fractions on the basis of their biochemical properties[49, 170].

Specific material flow performance descriptors and overall analytical tools can significantly facilitate the achievement of plant objectives. For example, PSDs can be a useful tool to inform the quality of waste fractions to be processed, if used properly. MFA has recently been employed to accurately map and predict behaviour of MBT systems, along with the conventional performance descriptors of mass-based yield, recovery and purity. MFA can depict the partitioning of preserved properties of waste, such as content in trace elements of concern, into the output fractions. Despite some very promising experimental results reported in recent studies, most of the data comes from theoretical investigations. There is a need for additional experimental MFA research on a test and commercial reference plant scale.

Results on mechanical processing of residual waste in MBT plants are limited, often come from non-peer-reviewed sources, and some lack application of standardised methods and/or statistical analysis. Data from MBT plants comes from a variety of plant configurations, operated towards different objectives and with specific feedstock. This restricts their comparability and possible wider applicability of results.

Biodrying appears to provide the advantage of optimally preparing the waste for mechanical treatment. Promising results in terms of selective comminution and fast biodegradation were achieved by ball-mill pre-treatment. Overall MFA data verified the difficulty of effective chemical separation solely by mechanical means. Zinc (Zn) and Cl are difficult to dilute in SRF produced from residual MSW, because of the highly diffused distribution within various waste components[49]. Advances in processing equipment, such as ballistic separators or NIR and X-ray sorting, may provide better solutions for specific uses.

5. RDF/SRF QUALITY MANAGEMENT INITIATIVES

5.1. Importance of quality management for RDF/SRF marketability

Quality management for RDF/SRF plays a key role in efforts to establish viable market outlets, not least by creating confidence in suppliers, end-users,[46] and regulators[75]. Quality management is concerned with activities that direct an organisation to fulfil the requirements of involved parties[171]. Quality management systems (QMS), consist of: quality planning, quality assurance (QA) and quality control (QC) schemes, and a general framework for a QMS for SRF has been provided by CEN[75]. At the current stage of the development for RDF/SRF this has been largely limited to QA/QC. Quality assurance (QA) addresses the whole range of customer requirements, including the quality of organisation performance (documentation, timing, logistics, and proper use of equipment), and product quality, in terms of reproducable levels of key properties[172]. Product requirements can be specified by: the regulator, related institutions, associations, or pressure groups, specific customers; or the producer in anticipation of customer requirements. These may take the form of product and/or process standards (e.g. product certificates provided on the basis of an assessment guideline), technical specifications, contractual agreements between producers and retailers/end-users, trade and/or involved parties provisional agreements (e.g. quality marks), or regulatory requirements (e.g. regulations in permits)[171, 173].

Standardisation, namely the development of classes and specifications for key product features against which fuels can be controlled, is an important part of QA. Market confidence in waste-derived products can be built, when standards are in place and adequate quality control is implemented. Encouraging examples in the UK context are the "Compost Quality Protocol"[174], a quality protocol for the production and use of compost, (a recent update from the previous BSI PAS 100:200, a publicly available standard for composted materials[175]); and the code of good practice for landspreading of biosolids, commonly known as the "safe sludge matrix"[176]. Lasaridi et al.[177] have argued for EU compost quality standards, which would harmonise the wide range of limit values currently in place within the various member states. According to CEN[30, 58], European Standards (ENs) for SRF could potentially guarantee the quality of fuel for energy producers, enabling the efficient trading of SRFs and increasing public trust. Standards could provide access to permits for SRF use; enable the rationalisation of design criteria for thermal recovery units; result in cost savings for co-incineration plants, reducing the need for compliance monitoring; facilitate trans-border movements; aid communication with equipment manufacturers; and ease reporting on the use of fuels from renewable energy sources. However, standardisation in isolation cannot guarantee increased market share [172]. The European market for SRF/RDF is still developing and remains unpredictable. For example, in Germany, the ban on landfilling of thermally recoverable and untreated biodegradable fractions of MSW has resulted in an increase in MBT-derived RDF/SRF production, far exceeding the available utilisation capacity[45]. This shortfall in the capacity for MBT-derived RDF/SRF has led to some material being treated in conventional waste incineration plants (WIP), whilst the surplus RDF is temporarily baled and stored in "depositories" in landfill sites[178]. From 2008, the RDF/SRF utilisation capacity is anticipated to rise, mainly through the construction of new mono-combustion plants[45]. Recent scenarios predicting an overall surplus of RDF availability to at least 2013[178] have been superseded by a predicted shortfall for RDF/SRF during 2011-2012[37, 42].

The marketability of MBT-produced RDF/SRF depends largely on successful implementation of QA/QC schemes, especially, in the light of the wider technical, financial, policy and legislative challenges[23, 37, 42, 45, 179, Juniper, 2005 #713, 180-182]. RDF/SRF is anticipated to face high competition from standard fossil fuels and proven substitute fuels, such as biosolids (sewage sludge), used tyres and rubber, used oils and solvents, ground offal, biomass, scrap timber, carpet scraps and bleaching soils[5, 45]. An analysis of current and future quantities and prospects for these secondary fuels has been compiled by Thomé-Kozmiensky[133]. Standardisation and development of guidance on quality assurance plans for the European market of solid biofuels has also advanced recently[172, 183, 184].

MBT-derived RDF/SRF product quality encompasses three critical aspects; the degree of variability, level of desirable properties and level of contaminants. It is critical for MBT plants to attain and ensure WDFs of acceptable variability. Competitive secondary fuels produced from less variable commercial/industrial waste streams or mono-batches may have an inherently more acceptable profile[185]. A quality-certified SRF does not necessarily imply a high fuel quality. Instead, it relates to a more consistent, continuously produced fuel that meets the quality demanded by end-users and their regulators. Producing SRF of known and consistent quality out of the mixed/residual MSW input to MBT processes, characterised by high temporal variability and heterogeneity, is a major technical challenge[5, 49]. However, in addition to MBT-derived SRF of invariable quality, the development of specialised SRF products, adapted to specific thermal recovery end-uses, produced by suitably designed MBT plants, could prove similarly critical for its future competitiveness[36, 181]. The recent retrofitting of the Nehlsen biodrying plant in Stralsund to provide three different qualities of SRF vividly illustrates this need[89].

The RDF/SRF contaminant properties and combustion behaviour critically affects its potential applications. Problems with low quality RDF characteristics, particularly high chlorine and trace metals content, have led to a decline in co-combustion applications in Germany[49, 52]. The ability of mechanical flow-stream separation in MBT plants to fully achieve the desired low levels of chemical contamination has been questioned[5, 49, 52]. RDF acceptability problems have been attributed to both unfavourable properties and variability in RDF input[5]. The existing surplus in RDF/SRF production in countries such as Germany is likely to force MBT operators to produce SRF of higher and/or more application-specific quality, leading to lower SRF yield and a higher volume of residual fraction that needs adequate disposal (incineration or landfill). This would imply higher technical difficulties and may demand retrofitting of existing SRF production lines, with more acute dilemmas for material flow management; and increased operational costs for MBT plants[45]. One implication of moving towards more technically complex unit processes in order to produce SRF of more consistent and required quality is the additional energy consumption associated with a lower yield of SRF and more reject materials. An optimal balance among the objectives of SRF product quality, cost and overall health and environmental protection, should be sought.

Quality management can build consensus upon perceived RDF/SRF quality. Measurements pertaining to the same RDF batch conducted with different sampling plans and analytical determination, performed at varying points of product life (e.g. within the production plant or just before end-use), by different laboratories, and for stakeholders with partly conflicting interests, may result in surprisingly diverging results, as has been reported for Germany[186]. Hence, implementation of appropriate QA/QC for MBT production lines of RDF/SRF based on a sound scientific basis is imperative. In this manner, actual and perceived issues stemming from unfavourable constituents and variability in residual waste input composition can be addressed[185]. In addition, the production of a consistent, fit-for-purpose product, that is acceptable to regulatory authorities can be verified, possibly at a reduced cost through avoidance of duplicate or unnecessarily frequent QC[183].

5.2. Standards and quality assurance/control for RDF/SRF

Quality assurance and control systems for WDF already exist and new ones are under development. In the 1980s in the US, the American Society for Testing and Materials (ASTM) defined classes of RDF based on the form of final product and type of production processes[57, 187]. In Europe, QA/QC schemes have been applied internally by producers and/or end-users, for example, RWE Umwelt AG[185]. Many national initiatives were launched around 2000, achieving different degrees of implementation. Quality control procedures and standards for RDF/SRF have been described and discussed elsewhere[5, 30, 32-34, 46, 49, 75, 185, 186, 188-190]. TABLE 11 summarises the current QA/QC initiatives for WDFs in Europe.

<<Table 11>>

These attempts at WDF quality management differ substantially. They may apply nationally or regionally; be legally binding or constitute trade provisional agreements; rely upon waste input origin or final product quality; or refer to all or specific end-users. Schulz-

Ellermann[33] provides an overview of the current status of European standards and QA/QC schemes for SRF. TABLE 12 lists the limits for key properties from existing European SRF quality standards.

<<Table 12>>

In the following section the CEN European standard for SRF is briefly presented. This is followed by a discussion of the key properties of SRF that should be taken into account during the design and operation of the MBT processes, from the perspective of specific end-users.

5.3. SRF classification and specification by CEN

The CEN technical standard for SRF specification and classes constitutes part of the wider extensive ongoing research and development effort for a European SRF QA/QC system[58]. Major findings of the pre-normative research were published as a technical report document[196], where the relative scientific evidence and rationale for final choices is detailed.. Development of this standard has been adapted to customer-specific requirements, both technical and legislative, such as meeting the Waste Incineration Directive (WID) emission limits. Achievable quality of WDFs has also been considered. It applies at the interface between SRF producer and intended end-user, rather than being input oriented[58].

Class codes (1-5), defined by boundary values without overlapping (i.e., closed intervals), have been finally adopted for each of three key fuel properties[196]. They serve as indicators of SRF performance with respect to economics (mean NVC), measured as received); technology (mean chlorine content, measured dry); and environment (median and 80th percentile values for Hg content, measured dry - specific statistics apply depending on the available number of measurements)[58, 190]. Each property should be determined according to specified sampling plans, including sample preparation and analytical techniques. The degree of chemical contamination can be expressed either on per mass (mg kg^{-1}) or per energy output (mg MJ^{-1}) basis[190, 196]. The most appropriate method depends on the intended information required.

Each property value can fall within five classes. The SRF is assigned a class number for each property and the combination of the three class numbers defines its class code. TABLE 13 summarises the recommended classes, descriptors and values.

<<Table 13>>

Four other key SRF descriptors have been proposed, but not included in the final classification scheme for simplicity and practicality reasons. They are ash content (% d), moisture content (% ar), and sum of heavy metals (mg kg^{-1} d)[190, 196]. The sum value of Cd plus thallium (Tl) (Cd+Tl) has also been proposed as an important environmental descriptor. In the final CEN draft, Cd+Tl was rejected on the basis that Hg alone mostly results in a higher or equal classification than the Cd+Tl value of the same SRF, resulting in a more conservative and hence sufficiently environmentally safe coding, and Tl has no influence on the classification of Cd+Tl, because of the relatively low value of Tl compared to Cd.

5.4. SRF product quality standards for specific end-uses

5.4.1. Specifications for end uses *vs.* classification

Class codes are a tool for identifying and pre-selecting SRF by giving an immediate, but inevitably simplifying, image of the SRF quality. However, class codes cannot predict the actual performance of SRF when used (see TABLE 2) for a list of possible RDF/SRF uses). Definition of specific SRF properties and value ranges, thresholds and limits most relevant to each SRF utilisation plant in accordance with the particular technical characteristics, and legal demands of each thermal recovery process, is imperative for its marketability[36].

In order to appropriately characterise SRF, physical-mechanical, chemical and biological descriptors should be identified. Ultimate and proximate analyses are the minimum prerequisite to assess the thermal recovery behaviour and performance of a fuel[197]. Specifying SRF according to the CEN guidance demands a general list of obligatory and voluntary descriptors to be quantified. Properties should be measured according to appropriate, existing, or under development, CEN standard methods[190]. However, Thomé-Kozmiensky[133] and Beckmann et al.[36] stressed that effective use in varying applications demands the determination of a more complete list of properties (TABLE 14**).**

<<Table 14>>

For example, characterisation of the reaction-related properties is critical, especially for co-combustion applications. For instance, Hilber et al.[198] have recently developed a method for assessing the process-specific combustion behaviour of low in char-formation RDF/SRF: the de-volatilisation of SRF at specific temperatures is measured by multi-sample thermo-gravimetric analysis (TGA). In the case of biofuel QA/QC, which has similarities with WDFs, the significance and interrelationships of important physical-mechanical fuel properties have been investigated by Hartmann[199]; and the chemical properties reviewed by Obernberger et al.[200]. Eckardt and Albers[46] investigated the current use of specification properties and limits proposed by plant operators in various thermal recovery applications of SRF.

However, even within each specific category of RDF/SRF end-uses, it can be challenging to agree upon defensible specifications that are applicable to every end-use. A wealth of available expertise has been incorporated in the relevant CEN report[196]. Despite that it might still be evident that there is limited understanding of RDF/SRF behaviour within the various possible thermal recovery systems, resulting in the absence of robust technical and environmental criteria for their use as substitute fuel[46]. Furthermore, generalisation on fuel combustion behaviour is not advisable, and plant-specific investigations are preferable, because, for instance, transfer factors for elements of concern are highly process and operation mode-specific[36, 196, 198]. In addition, it is usual practice for each plant to prepare its own unique blend of substitute and raw fuels, leading to varying, case-specific contract specifications[5, 46].

In co-combustion of RDF/SRF with fossil fuels (and other WDFs), the actual degree of substitution varies, depending on the comparable quality of the RDF/SRF with the rest of the fuels, along with any related legal stipulations. Substitution of the original fuels by RDF/SRF depends on compatibility of the RDF/SRF properties with the thermal recovery process, typically designed for fossil fuels. For example, pulverised hard coal-fired plants with wet bottom boiler types (i.e., with molten slag with cyclones) (WBB) are more tolerant to the shape and dimensions of SRF, in comparison to plants with dry bottom boilers (DBB)[196]. It has been estimated that coal-fired plants may reach up to 20% ^{w}/w. substitution in the long run[190]; for cement kilns the percentage may vary between 50-100% ^{w}/w. Dedicated fluidised bed combustion (FBC) and gasification/pyrolysis plants are not constrained by such limitations. However, Beckmann and Thomé-Kozmiensky[45] stressed that substitution rates as low as 1% ^{w}/w. have been established for various thermal SRF recovery applications in the German state of North Rhine Westphalia. Even these low substitution rates have to be proven in future practice and for higher rates process-specific limit values should be convincingly defined for reaction kinetic properties. For confidentiality reasons, contract-based specifications do not often fully reach the public domain. This constrains the development of a wider consensus on what constitutes accepted, fit-for-purpose RDF/SRF quality.

Nevertheless, it has been argued that maximum acceptable concentrations of trace elements of concern in SRF may be used to indicate its environmental suitability for a certain end-user[190]. Maximum values exist in national legislation regarding blending of wastes with fossil fuels. They usually apply to the most volatile elements, namely Hg and Cd or Cd+Tl. Standards also apply to the "sum of other heavy metals."[33]. An indicative list of SRF environmental classes that could be accepted for certain technologies, based on conservative assumptions for trace elements is presented in TABLE 15.

<<Table 15>>

van Tubergen et al.[190] calculated estimations for the value ranges of SRF class-coding properties that could be accepted for different end-uses. For comparison, Eckardt and Albers[46] provided data on Cd, Hg and Tl limits specified for SRF by certain thermal recovery commercial references in Germany.

The most important descriptors and acceptance values/classes for the main SRF end-users, focusing on potential properties of concern, are discussed below. Beckmann and Thomé-Kozmiensky[36] have detailed the experience in Germany. SRF particle form, size and shape exemplify the differences in the end-user specifications and NVC are discussed separately.

5.4.2. Cement industry

The cement industry has a long-established experience with use of WDFs[189], especially for wet processes, but increasingly for modern dry ones[190]. Use of substitute fuels up to 50% ^{w}/w. has led to changes in the operating features of the cement industry, such as flame characteristics, shape and stability, and ignition properties[36]. The wide range of values for properties of RDF/SRF required by cement kiln operators indicates the resilience of this end-use[196]; but also reflects the variety of cement kiln configurations. NCV is the most important single parameter for substitute fuel selection in the cement industry[181, 190]. The German cement industry has the highest median NCV of RDF used (not exclusively MBT-derived), compared with other end-uses, being *ca.* 21 MJ Kg^{-1}. TABLE 16 provides an overview of existing standards applicable to RDF/SRF used in the European cement industry.

<<Table 16>>

Concerns have arisen about the possible major technical and environmental problems that relate to fuel properties. These are outlined below and were reviewed in detail by van Tubergen et al.[190], the subsequent CEN technical report[196], and Beckmann and Thomé-Kozmiensky[36].

(a) Kiln system operation: various possibilities exist for firing SRF in different types of cement production plants, leading to different SRF specifications[201, 202]. For example, SRF clinker firing in a dry method is possible in[36] kiln exit (primary firing), where only high CV (LHV *ca*. 20 MJ Kg^{-1}), dispersible SRF is suitable to achieve gas temperatures *ca.* 1600 °C and avoid reducing conditions. This is also possible in kiln entrance (secondary firing), which is less demanding in LHV terms. Use in the calcinatory is even less demanding [36, 181]: larger SRF material, of lower LHV and higher ash content can be accepted. Cl, sulphur (S) and alkali content (Na, K) can form compounds that build up in the kiln system, causing accumulation, clogging and unstable operation[189]. Excessive Cl content in dry processes may block the pre-heater with condensed volatile chlorides, according to end-users' experience, and as acknowledged by specifications from Belgium, Germany and France[190]. Acceptable Cl content depends on the degree of substitution, K and Na content, and existence of salt bypass. Wet processes are more tolerant, accepting up to 6% ^{w}/w ar input Cl content. Recently developed chlorine bypass equipment has been reported to be able to achieve thermal substitution rates of fossil energy above 30%, reducing chlorine content in the hot meal by approximately 50%[203]. Nevertheless, in general salt bypass systems result in loss of mass and energy, incurring additional operational costs[46]. High moisture content can reduce the kiln productivity and efficiency. Ash content affects the chemical composition of the cement, and may necessitate adjustment of the raw materials mix[189].

(b) Air emissions: most of the trace elements are absorbed in the clinker product with the exception of the volatile elements Hg and thallium (Tl) that transfer to the raw flue gas, but to a lesser degree compared with other thermal recovery technologies. In the case where RDF/SRF with high ash content is used, the subsequent low NCV (e.g. 3.2-10 MJ kg^{-1} ar), results in *ca.* ten times higher values of Hg concentrations, expressed on an energy substitution basis (mg MJ^{-1} ar), compared with low-ash RDF/SRF (NCV *ca*. 11.7-25.5 MJ kg^{-1} ar)[196]. However, there is evidence that Hg can be virtually removed from off-gasses by electrostatic precipitators in the kiln system. Juniper[5] reviewed literature on dioxins and furans emissions from cement kilns that substitute fossil fuels with a percentage of WDFs, and found no significant increase in the measured concentrations in the stack gasses due to the use of WDFs. A recent report concluded that co-processing of alternative fuels fed to the main burner, kiln inlet or the preheater/precalciner does not appear to influence or change the emissions of persistent organic pollutants (POPs), including pesticides, hexachlorobenzene (HCB), industrial chemical polychlorinated biphenyls (PCBs) and PCDD/Fs[202].

(c) Clinker and cement product quality: the concerns of the cement industry focus around Cl, S and alkali content (affecting overall product quality); phosphate content, which influences setting time; and chromium, which can cause an allergic reaction to sensitive users[189]. An investigation of the potential effects of co-combustion of various WDF (other than RDF/SRF) in the cement production industry showed only a slight increase in trace element concentrations (Antimony (Sb), Cd, Zn) in the final product[201]. Cd, Copper (Cu) and Sb from municipal waste fuel constituted a relatively more significant input to the clinker composition compared with other fuel sources. Despite the significant differences among individual leaching characteristics of trace elements, it has been established that the release of trace elements from concrete is negligibly small during its operational life-span; and that there is no systematic correlation between the total content of trace elements in cement mortar and the leaching from mortar, even under the worst-case scenario.

With respect to the use of substitute fuels containing elevated concentrations of trace elements in clinker production, Opoczky and Gavel measured a positive effect on its grindability[204]. Chromium (Cr), Zn, barium (Ba), nickel (Ni), titanium (Ti), and phosphorus (P) generally improve grindability of clinkers by facilitating the clinker formation process during the molten phase and by forming solid solutions with silicate minerals (alite, belite) during clinker burning.

5.4.3. Direct co-combustion in coal-fired power plants

In Europe there is limited recent experience of SRF use for electricity generation, which is mainly restricted to small-scale plants in Germany, the Netherlands, Italy[190], and in the UK[205]. To illustrate this, RECOFUEL has been a considerable EU research programme that begun in 2004 to investigate the potential use of WDF in large-scale coal-fired power plants[190, 206]. Deposits of metallic aluminium and aluminium oxides were evident at the beater mill surfaces, which could have resulted from the relatively high Al_2O_3 content of the specific SRF used at the trial[206].

Requirements vary according to plant design and coal type, but are generally higher than alternative options for RDF/SRF thermal recovery[181]. The Jänschwalde brown coal power plant (BCPP) in Germany uses SRF at an average calculated substitution rate of 1.8% $^{w}/w$, without any significant impact on operational performance and emissions[36]. However, for a more conclusive evaluation, results from continuous long-term operations are required. More demanding specifications apply for the Werne hard coal power plant (HCPP)[207], as reported by Beckmann and Thomé-Kozmiensky[36]. A summary of the relevant specifications can be found in Beckmann[208], cited by Beckmann and Thomé-Kozmiensky[36]. Specific technical and environmental issues with SRF quality during direct co-combustion with various types of coal, in different boiler technologies have been identified:

(a) Air emissions and air pollution control: it may prove difficult to control emissions of highly volatile trace elements, such as Hg, Cd, and Tl[190]. These emissions largely remain in the vapour phase or become absorbed on ultra fine particulates for which air pollution control removal efficiencies are low. Increased capture of volatile trace elements preferentially partitioning in the flue gas will demand use of capital-expensive equipment and create secondary hazardous waste in need of careful management and costly treatment/disposal[5]. In addition, control of nitrogen oxides (NO_x) and sulphur dioxide (SO_2) emissions to WID limits may demand the use of additional air pollution control (APC) equipment. If selective catalytic reduction (SCR) is used for NO_x abatement, accelerated aging and deactivation of the SCR catalyst should be anticipated in both high and low dust designs, because of the higher RDF/SRF content in alkali metals[5].

(b) Airborne particulate matter (PM): initial results from test runs of the RECOFUEL project at the Weisweiler RWE power plant, co-combusting Rheinish brown coal with low LHV (8.15 MJ kg^{-1}) with RDF/SRF of higher LHV (15.4 MJ kg^{-1}) (REMONDIS SBS® produced from sorting of residual MSW) at relatively high thermal substitution rate (8.5% of overall thermal input) showed no significant changes of the flue gas emissions that could be allocated to the SRF use[206]. Trace elements such as Cd, Cr, Cu, Pb and Zn are of concern for their presence in airborne PM, associated with acute respiratory symptoms in humans. Evidence by Fernandez et al.[209] indicates that concentrations of these elements in ash can be higher when MBT-derived RDF/SRF is co-combusted than when only German bituminous coal is combusted[209]. However, comparison of ash-derived PM of non-MBT RDF co-

combusted at 30-34 % ^{w}/w substitution rate, with that of German bituminous coal alone, did not reach conclusive results on the health impacts of long-term exposure on mice. Exposure to coal/RDF ash particles was found less desirable than exposure to coal ash particles alone. Staged operation mode of coal/RDF co-combustion (leading to low NO_x emissions) exacerbated only short-term lung injury in mice.

(c) Quality of marketable by-products: concerns have been expressed regarding the potentially adverse impact on the quality of marketable by-products i.e. boiler ash, pulverised fly ash (PFA) and gypsum. Their chemical, physical and mineralogical properties may be affected[5]. Possible increases in trace element content and higher contents of unburned carbon and alkaline metal species could result in values that are unacceptable by secondary raw material standards or customer specifications. However, combustion studies at a pulverised hard coal DBB using dried sewage sludge, which typically has a higher trace element concentration compared with typical MBT-derived SRF, showed insignificant change in the by-product quality[190]. Bulky contaminants in the RDF/SRF can become incorporated in the by-products lowering their quality. RDF/SRF should be free from bulky undesirable constituents that are incombustible (metal particles) or may not be completely combusted because of insufficient residence time in the combustion chamber (e.g. hard plastics, polystyrene, and wood chips)[46]. Chlorine may adversely influence the ash quality intended as filler in cement, accordingly limiting the acceptable substitution rate.

(d) Plant operation: WDFs have been reported as having lower softening point (SP) and melting point (MP) temperatures than coal, resulting in an increased scaling or corrosion potential[36]. The corrosion potential is enhanced by a lower S content, higher alkali and higher trace elements of concern, estimated as low for S/Cl>4 and as high for S/Cl<2[79], as cited by Beckmann and Thomé-Kozmiensky[36]. Hence, the Cl concentration of the overall fuel mixture should be restricted to prevent high temperature corrosion. Design and construction materials of the boiler affect the maximum allowable Cl content, estimated up to 0.2% ^{w}/w in the Netherlands and 0.4% ^{w}/w in the UK[190]. Alkali metals are molten at combustion temperatures (slagging), increasing the risk of accumulation of fused deposits on the heat transfer surfaces (fouling)[5]. Abrasive RDF/SRF constituents, such as grit and glass particulates, may erode the heat transfer tubes[5]. Heavy wooden and plastic compounds even at particle size of 20 mm exhibit different combustion behaviour than pulverised hard-coal and have to be separated out[181]. A higher moisture content of SRF (10-20 % wt.) compared with that of coal (*ca.* 5% ^{w}/w.) could result in increased gas water content and subsequently increased gas volume in the boiler, restricting the substitution rate of SRF to 5-10% ^{w}/w.[5]. Additional operational end-user issues regarding RDF/SRF storage, mechanical pre-processing, blending, conveying and feeding have been summarised elsewhere[5].

5.4.4. Co-combustion in industrial boilers

US Department of Environment data indicates that *ca*. 25% of the fuels currently used in industrial boilers, furnaces and process heaters, to satisfy steam and heat production needs, are solid and can potentially be substituted by SRF[5]. In the UK, the most viable cases are the paper and pulp, and metallurgical industries. In these cases, potential corrosion of the heat transfer surface by Cl and S can prove critical to the performance of an industrial boiler. In the steel industry, there is limited possibility for using RDF/SRF, mainly by injecting it directly into the blast furnace to provide additional heating energy. This may demand low concentrations of Cl, S, major inorganics and trace elements of concern.

5.4.5. Indirect co-combustion and dedicated mono-combustion

Thermal pre-treatment of RDF/SRF creates various attractive alternative scenarios for their use[5, 45, 46, 205]. These include mono-combustion, for example, by fluidised bed combustion (FBC), namely thermal recovery in a dedicated plant that uses RDF/SRF as the only fuel source, and indirect thermal recovery of RDF/SRF, by feeding with RDF/SRF pyrolysis and/or gasification systems, or FBC prior to introducing the char/syngas to conventional power plants. The term combustion is used here within the terms co/mono-combustion to denote any thermal recovery process (e.g. pyrolysis), following the established terminology which does not restrict it to its accurate scientific definition.

In Germany such plants run in continuous operation, typically using lower quality RDF. Examples include gasification of RDF in circulating FBC with the produced gas used at the calciner firing of a kiln at the Ruedersdorf cement works, pyrolysis of RDF in a rotary kiln and feeding of the syngas and the appropriately processed char in to the boiler of the Hamm power station, and combustion of the pyrolysis coke in an FBC[45]. Hamel et al.[210] reviewed the literature of gasification process configurations with the thermal recovery of SRF derived from biodrying MBT; they have also developed and tested a fit-for-purpose two-stage gasifier, based on a parallel arrangement of fixed bed gasifier and bubbling fluidised bed combustor modules.

Relevant SRF quality standards for such end-uses are thought to be less demanding than those for co-combustion in power and cement plants[5, 36, 46, 181]. Ibbetson and Wengenroth[181] have stressed that for dedicated RFD/SRF plants that produce steam and power (FBC or grate fired systems) the important quality parameters are the ones affecting steam temperature and plant availability (particle size, metallic Al, alkali metals content, glass chlorine content), rather than CV.

For circulating FBC, least variable fluidisation behaviour and narrow PSD are required, whilst the process is more tolerant to wider ranges of elemental analysis and LHV[36]. In dedicated gasification for subsequent syngas use in power plant boilers, fouling and corrosion of heat transfer surfaces by compounds of released alkali metals such as Na and K salts, could be a problem. In FBC co-combustion the most harmful elements are Cl and alkali metals causing corrosion and fouling; and Al, which can lead to bed agglomeration and blocking of air injection ports[34]. Kobyashi et al.[211] provided evidence that mixing of calcium compounds into RDF/SRF can effectively remove HCl from the flue gases, even in a high temperature regime, for circulation FBCs; the mechanism of removal has been initially discussed by Liu et al.[212]. Volatile matter content was found to be the critical parameter to waste biomass gasification performance for air-stream gasification[213].

Kilgalllon et al.[214] have reviewed the literature and performed thermodynamic modelling on the fate of trace contaminants in various gasification systems co-gasifying coal with biomass-rich fuels. They concluded that fuel gas compositions vary significantly between gasification systems, and the most trace and alkali metals exhibit increased volatility when compared with their behaviour in combustion systems, with their volatility being influenced by the S and Cl concentrations. Na and K, and trace elements Pb, Zn, Cd, tin (Sn) (and vanadium (V) in certain systems) can pass to the gas turbine through the fuel gas path at potentially harmful levels; Hg, boron (B), Sb, and selenium (Se) also can pass through the gas turbine.

RDF/SRF can be treated by pyrolysis to produce a homogenised, high CV char fuel[215], with Cl, S and the content of trace elements of concern the most relevant properties in technical and environmental terms. Enrichment of certain trace elements (Cd, Cr, cobalt (Co), Ni, Pb, Zn) has been observed in the char, demanding a more intensive removal of these contaminants during the RDF/SRF production. Similarly, enrichment in the Cl content in the char (char: 1.30% ^{w}/w. d, from Herhof dry-stabilate RDF/SRF: 1.05% ^{w}/w. d), because of absorption on inorganic ash compounds after its release, could cause acceptability problems. In another case, only the pyrolysis gas from rotary-tube pyrolysis of SRF is fed into the steam generator of a power plant, with the char undergoing additional separate treatment[36].

5.4.6. RDF/SRF particle form, particle size limitations and homogeneity

Particle form and size are obligatory descriptors in the CEN SRF specification. Kock[216] proposed a new modelling method for characterisation of combustion properties of heterogeneous flues as RDF/SRF, relying on the PSD of RDF/SRF. Conveying and dosing of RDF/SRF into the processes, and firing technology, affect the appropriate delivery form (pellets, bales, briquettes, chips, flakes, fluff, powder, etc), size range and shape of RDF/SRF[46]. TABLE 15 provides suitable preparation forms and storage for intended uses.

Clear differences exist in the preferred medians and tolerated ranges of the feeding particle sizes appropriate for RDF/SRF[46]. RDF/SRF used in the cement industry should be appropriately small in size to avoid blockage of conveyors. Hard plastic particles should be <15 mm. In addition, contractual practice for cement kilns shows that the fine fraction (typically <10 mm particle size) is not favoured to form part of SRF. Two-dimensional SRF particles have been specified in a recent UK contract for cement kiln use.

In fluidised bed gasification at the Ruedersdorf Cement Works, 3-D WDF size specifications apply[217] (*ca.* 30 x 10 x 5 mm), as cited in Beckmann and Thomé-Kozmiensky[36]. The lowest mean particle size is demanded by the electricity generating plants designed for pulverised coal, so that the required trajectory in the boiler can be achieved, incurring more of a cost than a technical challenge[205]. The Jänschwalde BCPP specifications for SRF are maximum permissible particle size of non-pelletised material 25 mm, with 3 % wt. allowance for oversize <50 mm[36]. The specifications for the Werne HCPP are higher, with dispersible SRF of particle size <20 mm, suitable for direct injection in to the firing process[207] (cited in Beckmann and Thomé-Kozmiensky [36]).

The case of the Nehlsen biodrying plant in Stralsung, Germany, exemplifies the need for multiple SRF qualities produced to specifications of different end-users. Three SRF qualities are produced[89]: (1) pelletised SRF with bulk densities between 0.25 and 0.35 Mg m^{-3} and particle size <25 mm, suitable for power plants and the cement industry; (2) post-shredded SRF, with bulk density 0.15-0.25 Mg m^{-3} and particle size 50-80 mm, for industrial firing plants; and (3) raw SRF with bulk density 0.15-0.25 Mg m^{-3} and particle size <200 mm, intended for the heat and power plant in Stavenhagen.

The size of RDF pellets was shown to influence the temperature distribution inside the pellet during their combustion in an internal recirculation FBC[211]. Eco-deco SRF, used in FBC, has to be shredded to a mean particle size of 100-150 mm[5]. Circulating fluidised bed combustion systems demand a narrow SRF PSD; in the Neumuenster plant, particle sizes <250 mm are accepted[36]. Herhof Stabliate® SRF produced in the Dresden plant is pelletised in 20 mm, to be used in a methanol production plant[218]. At the Osnabrueck plant, SRF output is post-shredded to 40 mm, pelletised in soft pellets and pressed for loading on trucks, for use in cement kilns[219]. It has been speculated that the degree of homogeneity of RDF/SRF can affect performance of APC equipment present in end-use industries. If greater homogeneity is achieved, pollutant emission peak loads, typical in thermal recovery of unsorted waste, may be significantly reduced[164].

5.5. Biogenic content of SRF

Advances in alternative and renewable energy fuels aim to reduce reliance on fossil fuels, and mitigate the contribution of waste management in global warming potential. As a result, the biogenic (or biomass) content of waste included in RDF/SRF is becoming increasingly important environmental descriptor, reflecting policy and financial drivers[179]. The draft CEN standard (CEN/TS 15440:2006) defines "biogenic" as material "*produced in natural processes by living organisms but not fossilised or derived from fossil fuels*"[75], namely as a characteristic stemming from the origin of the material rather than as a measurable property. CEN has issued guidance on the relative difference between biogenic and biodegradable fractions of SRF, which whilst despite largely overlapping should not be treated as identical (CEN/TR 14980:2004)[220]. Determination of the biogenic content of SRF is gradually being incorporated into standard practice, and could prove critical for its marketability as a quality-certified fuel, as well as for earning subsidies. The relative financial importance of biomass content for RDF/SRF use has been discussed by Juniper[5]. The wider policy framework for MBT-derived RDF/SRF use in Europe has been analysed by Garg et al.[23].

In terms of renewable energy production in the EU, specialists have agreed a minimum 50% biogenic content for MSW-derived RDF/SRF to qualify as a renewable energy source[168]. However, in the UK, the renewables obligation certificates (ROCs) set the threshold values much higher. All electricity that is produced by waste from thermal treatment by gasification and pyrolysis qualifies. Additionally, any biogenic percentage of waste-derived fuels qualifies for ROC subsidisation in the case of combined heat and power energy from waste plants (CHP EfW)[221]. The overall biogenic content percentage that has to be met by a fuel to qualify has been lowered from 98% to 90%, still a challenging target for MBT-derived SRF, which typically also concentrates high CV materials of fossil fuel origin, such as plastics. A public ROC consultation process was opened with the aim to revisit previous decisions, based on a report on carbon balances[222] In the US a recent report prepared by the Energy Information Administration (EIA) has estimated that 56% of the heating value available in the MSW comes from biogenic sources[223].

In terms of alternative energy sources, carbonaceous emissions released during energy production stemming from the biomass content of fuels are considered as "CO_2-neutral" from a global warming potential point of view. Hence, the CO_2 emission factor of fuels is based merely on the fossil carbon content and the biogenic content is ignored[224]. This is reflected in the EU emission trading scheme (EU-ETS).

Stipulations for biomass content of waste-derived fuel in order to qualify for ROCs and EU-ETS will determine the processing objectives for the biomass fraction in MBT plants. Enabling implementation could favour concentration of biomass content of residual waste into RDF/SRF. Currently existing measures clearly favour CHP EfW and not the co-combustion of RDF/SRF in conventional electricity generating plants.

Scientifically appropriate analytical determination of biogenic content of contaminated biomass fuel streams has recently been investigated, with the so called "selective liberation method" being the currently applicable state-of-the-art[173, 194]. Selective liberation has been adopted by the CEN QA/QC guidance as normative, along with the manual sorting method, and the informative reductionistic method[75, 225]. CEN has agreed to further develop another available method for the determination of biogenic content, the carbon isotope method ("^{14}C method"). It is hoped this will overcome the restrictions faced by the selective liberation method. The ^{14}C method is anticipated by CEN to be standardised in 2008[226], with current progress summarised in the relevant CEN published document[227]. It has the relative advantage that can be applied to either the fuel itself or the off-gasses produced during the thermal recovery. The selective liberation method has been the most practiced the previous years, as confirmed by Flamme[224], who reviewed European methods; and denoted by the German government adopting it for immediate use. In the UK, the DTI/Ofgem Biomass Fuels Working Group has issued sampling guidance but has not yet adopted a position on the actual measurement[228].

Potential co-combustion of SRF with other fuels (purely fossil or biomass) has led to the development of measurement methods applicable at the location of SRF thermal recovery. Fellner et al.[229] proposed the determination of biogenic content during EfW co-incineration using a model based upon typical process/ regulatory monitoring data; Mohn et al.[230]compared this method with the ^{14}C off-gasses method finding their results in good agreement. Recently, Staber et al.[231] provided an up-to-date comparison of the available methods.

5.6. SRF quality management conclusions

The importance of implementing quality management schemes to the SRF production line of MBT plants is gaining recognition. The CEN/TC 343 initiative for harmonisation across Europe is significant in setting a new benchmark. This is exemplified by the requirements for robust sampling plans when dealing with highly heterogeneous material streams such as residual waste. Most of the available drafts for development from CEN are still under validation processes. It is necessary to apply the required quality management schemes in a way that fulfils the intention to avoid duplication of quality control by producers and end-users, whilst achieving optimal, scientifically defensible sampling.

Satisfactory understanding of the exact behaviour of MBT-derived SRF during the many available thermal recovery processes is still to be gained. This would demand use of characterisation techniques, such as TGA, along with those conventionally used. Biogenic content is becoming an increasingly important descriptor, reflecting the increased recognition of the potential global warming effect of waste. Accurate determination of biogenic content is necessary. Sufficient characterisation and long-term operational data at higher degrees of substitution in co-combustion outlets are necessary in order to estimate the technical feasibility for SRF. Such results could result in more detailed and scientifically defensible specifications becoming available.

Differentiation of SRF production to meet specific end-user requirements is also imperative for the future marketability of SRF. For instance, certain SRF quality criteria for co-combustion in power plants are higher than those applying for cement kilns. It might be technically (and financially) challenging for many MBT process plants to produce suitably high SRF quality, whether achieving desirable levels of properties or low variability, especially for these more demanding applications. From a material flow management point of view, achieving a lower pollution potential for RDF/SRF raises the issue of appropriate intermediate and final sinks for the pollutants that should be directed away from the RDF/SRF stream. The inevitable trade-off questions do not have established or unanimously accepted answers.

6. MBT-DERIVED RDF/SRF: QUALITY ACHIEVED

6.1. Introduction

This review has illustrated the need for quality assured SRF, summarised existing and upcoming European standards, and the science, environmental engineering and performance of the main processes from which RDF/SRF can be produced. In this final section the SRF quality that has been achieved by European MBT plants is discussed.

MBT-derived RDF/SRF is poorly characterised, resulting in uncertainty about the quality achieved. A review of the literature shows that little data is available in the public domain and from which very few data are reported in peer-reviewed publications. This refers both to elemental/substance composition and physical/biochemical properties, both necessary for product quality assurance, evaluation of its environmental performance, and sustainable material flow management purposes.

Data from available and reliable resources were statistically analysed in an effort to improve understanding of RDF/SRF quality and the magnitude of variation. European data originates from MBT plants in Germany, Italy and the Netherlands.

6.2. RDF/SRF produced by biodrying MBT plants

6.2.1. Herhof: Stabilat®

SRF produced by the Herhof plant in Asslar (FIGURE 16) is used as co-fuel for local combustion and district heating systems. SRF from the Rennerod plant is used in cement kilns and other non-specified co-combustion operations. SRF from Dresden is co-combusted with coal for methanol production[5].

<<Figure 16>>

FIGURE 17 presents PSD data for Stabilat® (or Trokenstabilat®, (TST)), derived by sieve analysis. It shows that the fractions with particle size lower than 60 mm are largely dominated by material high in biomass content[168]. The biomass content on a mass basis constitutes 92% of the 3-10 mm, 74% of the 10-25 mm, and 70% of the 25-60 mm. The 60-250 mm fraction has biomass content lower than 35%. The method for determining the biomass content is not mentioned, and so the results should be regarded with some reservation. Herhof maintains that the native-organic content of Stabilat® is around 65-70%.

<<Figure 17 here>>

The environmental performance of Stabilat® in terms of greenhouse gas emissions during combustion compares favourably with fossil fuels[168]. According to Herhof's results, specific fossil CO_2 emissions of Stabilat® was 24 gCO_2 MJ^{-1}, less than half that of natural gas (56 gCO_2 MJ^{-1}), which is the fossil fuel with the lowest value. TABLE 15 shows values relevant to the SRF performance as an alternative fuel, suitable for fossil fuel substitution. FIGURE 18 presents indicative values for the Stabilat® item composition.

<<Figure 18>>

<<Table 17>>

6.2.2. Nehlsen: Calobren®

SRF from the Rugen plant is used in a cement kiln. Nehlsen maintains that the measured values for SRF are all less than 75% of the threshold values specified in the cement kiln contract[5].

6.2.3. Eco-deco SRF

SRF from MBT plants that use the Italian Eco-deco biodrying process is produced in Italy and the UK. In the London Frog Island plant the 39% ^{w}/w of the input waste is processed into a SRF with NCV of ca 16 KJ kg^{-1}(June 2006 data); higher values up to ca 18.5 KJ kg^{-1} have been reported for the Italian plants[233]. SRF is used as a co-fuel in cement kilns and in an on-site fluidised bed boiler. SRF specification results from two Italian plants indicate that it complies with the standard class quality of the Italian UNI 9903-3 quality control system[5]. In the UK the SRF outputs have to meet specifications agreed with the specific cement industry end-users. Ultimate analysis including measurements made at various points during 2003 at the Montanaso plant showed mean concentrations of carbon (C) 42.22% ^{w}/w; hydrogen (H) 6.06% ^{w}/w; and nitrogen (N) 0.83% ^{w}/w (basis of reporting, d or ar, not denoted).

6.3. Content of trace elements of concern in SRF

The quality of MBT-derived SRF has not been extensively evaluated. Rotter et al.[49] compared the content of trace elements of concern in SRF from early MBT plants against the limit concentrations of the Swiss Agency for the Environment, Forest and Landscape (BUWAL) standard for cement kilns (FIGURE 19)[49].

<<Figure 19>>

Almost all the median values of the examined elements exceed the guide limits, apart from rare elements such as beryllium (Be) and vanadium (V). However, if this SRF was compared with other, less strict standards, it would perform much better. For example, according to the CEN proposed standards, Hg class code, based merely on median value (80th percentile were not provided), would be Class 2 (0.02<0.03 mg MJ^{-1} ar). According to a CEN published document, a cement kiln may be willing to accept waste up to Hg class code 4[196]. Careful use of standard is necessary in order to evaluate the suitability of SRF for each specific intended use, because every set of limit values serves different purposes and reflects varying underlying realties. For example, the BUWAL standard is based on strict considerations regarding cement production material flows. Conversely, the CEN standard classification is general and indicative, and has incorporated considerations of the achievable SRF quality into the proposed limits.

6.4. Comparison of fossil fuel with substituted RDF/SRF

Heilmann and Bilitewski[170] compared coal with RDF produced from German MBT-treated residual waste. Gendebien et al.[32] compared the toxic load of SRF produced by biodrying in Germany with other primary and substitute fuels. Heering et al.[164] showed that the per energy unit generated heavy metal concentrations of the Herhof dry-stabilate and the range of values variation are of the same order of magnitude with certain fossil fuels it substitutes. Stabilat© compares favourably in terms of content in trace elements of concern with coal. Herhof declared an average NCV of 15 MJ kg^{-1} for the Stabilat©, rendering it comparable to the CV of dried and processed lignite[168].

6.5. Statistical analysis of available MBT-derived SRF data-series

6.5.1. Input data quality and SRF statistical analysis limitations

In this section, statistical analysis of a heterogeneous compilation of existing data on MBT-derived RDF/SRF, derived under diverging boundary measurement conditions, is presented. Statistical analysis is challenging for many reasons, including paucity of data and different statistics reported in the literature data (e.g. mean or median to estimate location). TABLE 18 summarises background information on data sources. Available data is mainly found in reports[5, 32, 190, 194], along with a few peer-reviewed publications[164, 215, 234]. These data series are mostly derived from quality assurance systems internally implemented by MBT plant operators to satisfy end-user contractual requirements and/or to demonstrate compliance with national standards. The RDF/SRF has been produced from varying input materials (different countries/regions and residual or mixed waste collection schemes), treated in MBT plants with different design and operational configurations (but predominantly biodrying), prepared from different fractions of the input waste (e.g. partially including or excluding the biomass fraction), and prepared to different national standards and end-user requirements (mainly cement kilns, but also dedicated FBC and power plants).

<<Table 18>>

Different objectives and methodologies applied alongside the entire measurement process, including sampling plans, sub-sampling and sample preparation, analytical determination techniques, and dissimilar statistical analysis before final reporting of data in the literature restrict the potential for meaningful comparison of data by further statistical analysis.

Additionally, not all the diversifying methodological details of measurement are clearly stated for each case. It has been proposed that the number of analyses performed for each data series can cautiously be used to guarantee a minimum reliability of the data[190]. The majority of the data sets used in our analysis are based on >10 samples/analyses (lower limit proposed by CEN).

The effect of sampling plans on specific data series is anticipated to be critical, and much higher than the uncertainties introduced by differences at the analytical stage. The CEN guidance for SRF sampling plans[237] DD CEN/TS 15442:2006 incorporated elements of the latest developments in Gy's theory of sampling[238-241], developed over the last fifty years[242]. Enhanced reliability can be expected for data series that followed the sampling theory, such as the TAUW investigation[194]; compliance with national quality assurance systems, such as the Italian Eco-deco data[5]; and constituting average measurements over long time periods (Nehlsen plant)[5]; those that have been assessed had independently, such as the Herhof-Stabilate® SRF, investigated by Niederdränk et al.[215].

Publicly available data is statistically analysed to produce the most representative and thorough overview of the achieved quality by MBT-derived RDF/SRF to date. Available statistics of input data on RDF/SRF sample properties is largely limited to: (1) measure of (central) location of the sample population (mean and/or median); (2) measure of the upper limit (80th percentile and/or max) values; and (3) limited reported values for their spread (typically in the form of standard deviation).

The selection and validity of statistical tools for describing properties of waste is highly debatable. Certain aspects of the ongoing debate are addressed by van Tubergen et al.[190] and Pehlken et al.[78]. Simplifying, it can be generally assumed that population distributions (or probability density function curves) for many of the properties of waste-derived products exhibit skewness and lengthy distribution tails (long-tailedness)[78]. Typically positive skewness is evident.

During the pre-normative research for CEN SRF standards TAUW investigated the type of statistical distribution that is suitable to describe the properties of SRF. The study included outputs from biodrying plants and from mechanical sorting of the high CV fraction of residual waste, analysing 35 samples for each case. Results of the Kolmogorov-Smirnov test for Cl, Hg, Cu, and Cr have shown that for both plant cases the type of distribution that best fits these properties was log-normal rather than normal, with the exception of Hg for biodrying which was normally distributed[194]. However, the CEN technical committee draft has opted for Cl to be classified by the mean rather than the median, implying a normal distribution would suffice; indeed there is a certain degree of overlap between the two forms of distribution. Conversely, Hg has to be classified according to both median and 80th percentile values, implying that a skewed long-tailed distribution is anticipated.

Other data reported on SRF from Eco-deco and Nehlsen biodrying processes [5] indirectly verify that many properties are not fully normally distributed. Data series for which values for both mean and median are available show varying degrees of difference between these two statistics, establishing that their distributions are skewed, hence not normal. For instance, Pb and Cr show clear positive skewness in all three available data sets; whilst Hg shows mixed behaviour, including one case of negative skewness.

The central trend and the spread of the values for each property are estimated by calculating and graphically presenting in box-plots the minimum, lower quartile, median, upper quartile and maximum value for both median and 80th percentile of input data.

Calculations and graphics were made with Statistica 8®[243], following typical box-plot convetions (see FIGURE 20). Preferably statistical analysis should be performed only on median and 80^{th} percentile input SRF data statistics, but in practice means were also used to indicate the location. Median and 80^{th} percentile are measures of location and upper values respectively, independent of the form of distribution and robust to outliers. They are therefore suitable to describe properties of RDF/SRF that show log-normal distribution or skewness and longtailedness in general. In the case of normally distributed property, median is identical to the arithmetic mean. High percentiles, like the 80^{th} percentile, are particularly useful for estimating the upper values of concentrations of trace metals of concern (e.g. Cd), as demanded in practice. The alternative would be to employ data points that are statistics based on normally distributed populations (arithmetic mean, standard deviation etc); however, this assumption does not hold for many of the waste measurands, especially for analytes expected to be present at trace concentrations.

However, median values were not available for all the cases; as a compromise mean values were also used to indicate the location of input data series. For properties that exhibit positive skewness, the overall average central trend of the median values is biased towards higher values when means are used instead of medians. However, the differences between medians and means, despite evidence for non-symmetrically distributed properties, are not significant in all cases, as shown by the cases for which comparative data are available. The number of means used instead of medians for each property are shown in TABLE 19. For Pb only mean values were used, as there were very limited median values. Given that Pb exhibits positive skewness, the average location of Pb is then overestimated.

The significance of the results is also restricted by the fact that data series of different reliability are given equal, non-weighed treatment (e.g. values resulting from long and short time series results); and by the low number of available data-series on RDF/SRF properties, ranging from 14 to 4 (properties with fewer data points available are not analysed). As received (ar) values were converted to dry basis (d) for the properties necessary to do so, by using the median(/mean) moisture content values, where available. As received net calorific values were transformed into dry basis by applying the proposed CEN formula[244]for the calculation of analyses to different bases[245]. This has rendered certain NCV (d) to be much higher than values reported in the literature (e.g. Eco-deco values[5]), possibly calculated by a different conversion formula. Nevertheless, given the limitations, calculation of medians and use of box-plots can provide the most appropriate, accurate and clearly presented account for the RDF/SRF properties.

6.5.2. Results and discussion of statistical analysis on MBT-derived RDF/SRF properties

Results related to key technical, environmental and economic aspects of RDF/SRF quality are summarised in TABLE 19. Box-plots are used to graphically represent the main findings (FIGURE 20- FIGURE 26).

<<Table 19 >>

<<Figures 20-26>>

Results were generally within the expected range and are logically consistent. The 80th percentile values are higher than the median values, with certain exceptions, such as the maximum values of Hg reported on a mass basis. Coefficients of variation (*CV*) (%) are calculated for each statistic to estimate the scale-free dispersion of the analysed populations. The *CV* ranged from 13.1% for the location of NCV ar, to 95.9% for the location of Cu.

The location of median NCV ar (FIGURE 20) falls within the range of Class 3 of the proposed CEN classes, with the lower and upper quartiles being at 15.4 MJ kg^{-1} ar and 16.8 MJ kg^{-1} ar respectively, showing a narrow spread. The location of MC medians (FIGURE 21) is at 13.4% ^{w}/w ar, with the maximum value being more than three times the interquartile range higher than the upper quartile (Q3= 14.2% ^{w}/w ar) and hence depicted as an extreme value (star) in the box-plot. The ash content location of medians (FIGURE 21) is at 21.1% ^{w}/w, but the upper quartile reaches as high as 25.1% ^{w}/w, which can be uninviting for the most demanding end-uses of RDF/SRF.

The Cl content quality achieved by MBT-derived SRF appears generally good (FIGURE 22), but this result should be cautiously interpreted. The central trend of Cl content median values is at 0.50% ^{w}/w d; a hypothetical SRF with the same value would be classified as Cl class 2. The maximum reported location value is at 1.05% ^{w}/w d. However, the data series included RDF/SRF with unexpectedly low location values for Cl, especially for measurements reported on a dry basis and stemming from plants that do have not yet incorporated sophisticated sorting (e.g. NIR) to screen out high-Cl components: the minimum being at 0.29% ^{w}/w d. Detailed calculations by Schirmer et al.[246] established that the average total Cl content (TCC) in MBT-derived RDF/SRF produced from residual MSW can be anticipated to fall in the range of 0.6-0.8% ^{w}/w d. Anticipated values for RDF/SRF produced from biodrying plant configurations are *ca.* 0.1% ^{w}/w d higher than values for MBT plants that just separate mechanically RDF/SRF before biological treatment[246]. We speculate that the unexpectedly low values reported in the literature could reflect difficulties in the sampling methods and analytical measurements used. Schirmer et al.[167] have pointed out the particular challenge of determining total chlorine. Importantly, they stressed that combustion digestion methods underestimate the inorganic portion of Cl in samples with high ash content, which is problematic for QA/QC purposes.

The data indicate that the content of MBT-derived RDF/SRF in trace elements of concern (often called “heavy metals”) is generally acceptable in most of the cases (FIGURE 23-26). This can be illustrated by comparing the upper quartile of the location data for trace elements (range that includes the 75% of the population values, from low to high) with, for example, the German limits for SRF[186]): As: Q3[As]=3.4 mg kg^{-1} d < German limit=5 mg kg^{-1} d; Cd: Q3[Cd]= 2.2 mg kg^{-1} d < German limit=4 mg kg^{-1} d; Cr: Q3[Cr]=90 mg kg^{-1} d < German limit=125 mg kg^{-1} d; Ni: Q3[Ni]=40 mg kg^{-1} d < German limit=80 mg kg^{-1} d. From the elements for which sufficient data series existed for statistical analysis, only Cu (Q3[Cu]= 448 mg kg^{-1} d < German limit=350 mg kg^{-1} d), and Pb (Q3[Pb]=208 mg kg^{-1} d < German limit=190 mg kg^{-1} d) upper quartiles of location exceed the limits. The spread of the Cu values reported in the literature is much higher than that of Cr, as can be seen from their interquartile ranges in FIGURE 23. For data regarding each plant the 80^{th} percentile values are considerably higher than the median in many cases. This could verify the need to resort to statistical description and classification of trace element content with an indication of both location (median) and upper values (80^{th} percentile).

However, this is slightly less evident for Hg. Reported on mass basis (FIGURE 25), the location of medians is at 0.46 mg kg^{-1} d and location of 80^{th} percentile at 0.53 mg kg^{-1} d. Reported on an energy basis (FIGURE 26), in agreement with the CEN classification system, location of Hg medians is at 0.023 mg MJ^{-1} ar and location of 80^{th} percentiles is at 0.024 mg MJ^{-1} ar, showing unexpectedly similar values. This may be due to fewer data points for the 80^{th} percentile. Hence, an equivalent imaginary SRF with same median and 80^{th} percentile values would be cautiously classified as CEN Hg class 2, which is towards the high end of possible qualities.

7. CONCLUSIONS AND RECOMMENDATIONS

A significant objective for MBT is to achieve effective material flow management of residual waste that involves extracting homogeneous fractions of known biochemical composition. The benefits of this are twofold: to concentrate contaminants separately and direct them towards appropriate onward disposal or treatment mechanisms; and to produce recyclates to a desired quality, prolonging their residence time in the anthroposphere.

7.1 Appropriate descriptors for evaluating unit process operations

Since MBT is a generic process that can be broken down into many process unit operations, it is important to understand, through characterisation studies, the relative contribution that each unit makes by using appropriate descriptors. Conventional descriptors such as yield and purity of waste components have typically have been applied. PSD, if used appropriately, can be useful in describing comminution results and for modelling size-dependent mechanical processing. The move from a predominantly disposal-led waste sector to one that is more resource based, demands the use of analytical tools such as MFA. MFA, via TCs and MECs, can provide the ability to map flows of preserved properties of waste, such as trace elements, into the output fractions. This can enable the optimisation of MBT processes to effectively separate waste fractions into outputs of desired quality e.g. known chemical composition.

This is of value to waste companies because it provides the basis for a targeted reduction in pollution load of MBT outputs that potentially has a positive effect on end-user emissions.

7.2 Performance of process units and implications for output quality and MBT design

MFA has recently been employed to accurately map and predict behaviour of MBT plants. Despite some very promising experimental results reported in recent studies, most of the data comes from theoretical investigations. There is a need for additional experimental MFA research on a test scale and full commercial basis.

MFA data have so far demonstrated the difficulty in achieving effective chemical separation solely by mechanical means. The recent application of additional processing technology combined with mechanical methods in MBT plants, such as NIR sorting, 3-stage ballistic separators and x-ray sorting, offers a significant opportunity to improve this situation.

There is invariably a trade off between achieving a high quality of recoverable outputs and the properties of reject material e.g. RDF/SRF with a low Cl content can result in a significant yield of rejects that require subsequent treatment or disposal. The selection of intermediate and final sinks of materials diverted away from RDF/SRF production therefore needs careful consideration. Adittionally, attempting to produce SRF of higher specifications and more consistent quality may demand resorting in more energy demanding plant configurations, adversely affecting the sustainability of such choices.

Recent studies have provided results for particular aspects of process unit operations. Biodrying systems appear to offer the advantage of optimally preparing the waste for mechanical treatment. Promising results for selective comminution and fast biodegradation were achieved by ball-mill pre-treatment. Zn and Cl in particular are difficult to dilute in

RDF/SRF produced from residual MSW because of their highly diffused distribution in waste components. There is a need for careful selection of unit operations, their arrangement in the flow line and improvements in their design or use of new developments to achieve higher quality recoverable outputs. For example, with the objective of high-grade SRF production, it is not sufficient to separate a comminuted coarse fraction just on a PSD basis.

7.3 Quality management for SRF production

The importance of implementing quality management schemes to the SRF production line of MBT plants is gaining recognition. The CEN/TC 343 initiative for harmonisation across Europe is significant in setting a new benchmark, but still under validation.

When dealing with highly heterogeneous material streams such as residual waste or SRF, the adoption of robust standardised sampling plans based on established sampling theory that takes account of the inherent heterogeneity of waste materials is vital.

Differentiation of SRF production to meet specific end-user requirements is vital for the future marketability of SRF due to the different needs of end-users e.g. certain SRF quality criteria for co-combustion in power plants are higher than those applying to SRF-dedicated thermal recovery facilities such as gasification plants. A satisfactory understanding of the exact behaviour of MBT-derived SRF during the many available thermal recovery processes is still to be gained. Sufficient characterisation and long-term operational data at higher degrees of SRF substitution as an alternative fuel in co-combustion outlets are necessary in order to estimate the technical feasibility for SRF. Such results could inform the debate surrounding specifications.

Biogenic content is becoming an increasingly important descriptor, reflecting the increased recognition of the potential global warming effect of waste. There is a need to standardise the measurement methodology before biogenic content can be determined accurately. Data produced from validated methodologies could support scientifically sound regulation.

7.4 Statistical analysis for MBT-derived SRF

Results from literature data on MBT-derived RDF/SRF were generally within the expected range and logically consistent. SRF achieved quality could potentially prove able to respond to legislative and market needs if improvements are achieved e.g. reduction of the Cl content. Coefficient of variation ranged from 13% to 96%, which reasonably reflect the variability in SRF production, properties and measurement conditions.

The location of median net calorific values (ar) falls within the range of Class 3 of the proposed CEN classes, showing a narrow spread. The ash content location of medians is at 21% $^{w}/w$, but the upper quartile reaches as high as 25% $^{w}/w$, which is less appealing to the most demanding end-users of RDF/SRF. The Cl content appears generally good; the central trend of Cl content median values is at 0.5% $^{w}/w$ d. However, we speculate that the unexpectedly low values reported in the literature could reflect unresolved issues related to sampling plans and the analytical methods used. Reported data indicate that the content of trace elements in MBT-derived RDF/SRF is generally acceptable in most cases (within end-user specifications or regulatory limits). From the elements for which sufficient data series existed to enable statistical analysis, only Cu and Pb showed a high potential to exceed the German specification limits.

7.5 General evaluation

Most of the unit operations currently used in MBT plants have an established track record. The waste input materials, specific MBT plant objectives and output requirements have evolved considerably since the earlier RDF plants and associated “dirty” composting plants that relied on mechanical processing. However insufficient scientifically-derived data is available in the public domain on the performance of individual process unit operations that would inform the design of MBT plants to meet the needs of the modern sustainable resource management agenda.

Mixed MSW is a challenging waste stream for waste treatment processes such as MBT. However, through improved upstream source separation (e.g. removal of dry recyclates, food waste or green waste for composting), segregation and recognition of changing waste streams, the properties of residual MSW are changing significantly. The biodegradable content for example may be expected to significantly reduce during the next 10 years. This will have an impact on the performance of MBT systems that are yet to demonstrate an ability to adapt.

This review relates to material flow management. However, there are important wider considerations to be made. MBT is generally a highly mechanised process that is energy intensive. A wider sustainability appraisal of MBT performance, compared with alternative technologies such as anaerobic digestion, therefore warrants investigation to consider issues such as energy consumption, emissions and value in materials recovery.

Additional data on specific material properties (e.g. physical properties) are needed to build confidence on MBT-derived SRF as a viable alternative to fossil fuels. Further research is needed to enhance our understanding of what constitutes appropriate data at the operational and regulatory level and suitable statistical analysis for MBT-derived SRF and other waste-derived products to enable appropriate and harmonised reporting in the future. The performance of MBT systems requires continued scrutiny to establish a viable waste treatment technology for improved handling of material flows in accordance with sustainable resource management.

8. ACKNOWLEDGEMENTS

The funding for this project is made possible by donations from Waste Recycling Group Limited through the Landfill Communities Fund of Grantscape (Project No. URN 158/327). Additional donations have been made by the following organisations for which the project team is grateful: Biffa Waste Services Ltd, Cambridgeshire County Council, Cemex, Defra, Donarbon Ltd, Dorset County Council, Enviros, Luton Borough Council, Norfolk Environmental Waste Services, SITA, Summerleaze Ltd, Sustainable Development Research Centre, Viridor and Wasteology Systems Ltd. We acknowledge the members of the project steering group and Rebecca Roy for assisting with formatting of the manuscript.

9. APPENDIX

Notation

Symbol type	**Symbol**	**Explanation**
Properties	CV	Coefficient of variation
	d	Particle size
	d_e	Effective particle size
	d_x	Cumulative fraction finer than d: x percentage passing through the screen/sieve (undersize fraction, underflow) with aperture size d
	$d_{63.2}$	Characteristic particle size (Y(d) = 0.632)
	d_{90}	Nominal product size (Y(d) = 0.9)
	d_{95},	Nominal top size (Y(d) = 0.95)
	MC	Moisture content
	MC_{air}	Moisture content of air
	MC_{waste}	Moisture content of waste matrix
	m	Mass
	τ	Mean residence time
	n	Measure of uniformity (breadth) of PSD
	η_{dmesh}	Size reduction ratio measured for screen/sieve with aperture d
	Y(d)	Particle size distribution (PSD) function

Symbol type	Symbol	Explanation
Subscripts	dmesh	Screen/sieve with aperture d
	I	I input to unit operation
	inicial	Initial plant or process input values
	max	Maximum value
	MSW	Municipal solid waste
	P	Product, output of unit operation
	waste	Waste matrix
	x	Percentage passing through screen/sieve (undersize fraction, underflow)
General	%	Percent
	Ø	Diameter
	®	Proprietary
Selected units	ar	As received (or wet) basis of reporting*
	d	Dry basis of reporting*
	daf	Dry, ash-free basis of reporting*
	Mg	Mega gram (or ton)
	Mg a^{-1}	Mega gram per year (or tpa: ton per annum)
	$^{w}/_{w}$	Weight fraction or percent
	ºC	Degrees Celsius

* These typical conventions for fuels adopted by the CEN SRF standards are followed throughout this paper.

10. REFERENCES

[1] Heermann, C., Using Mechanical-Biological Treatment for MSW in Europe, *BioCycle* 44 (10), 58, 2003.

[2] TBU - Eunomia - Greenpeace, Cool waste management. A state-of-the-art alternative to incineration for residual municipal waste, February 2003, Greenpeace Environmental Trust, London, 2003.

[3] Müller, W. and Bulson, H., Significance of bio-mechanical waste treatment in Europe, In: *Waste 2004 - Integrated Waste Management and Pollution Control: Policy and Practice, Research and Solutions*, 28-30 September 2004, Stratford-upon-Avon, UK, 2004.

[4] Bardos, R.P., Composting of mechanically segregated fractions of municipal solid waste – a review, SITA Environmental Trust, contractor: r^3 Environmental Technology, 2005.

[5] Juniper, Mechanical-biological treatment: a guide for decision makers, processes, policies and markets, CD-ROM, v1, March 2005, Juniper Consultancy Services, UK, 2005.

[6] Steiner, M., MBT in Europe: roles & perspectives, *Warmer Bull.* 102 14, 2005.

[7] Steiner, M., MBT in Europe: roles & perspectives (part 2), *Warmer Bull.* 103 8, 2006.

[8] Stegmann, R., Mechanical biological pre-treatment of municipal solid waste, In: *Proceedings Sardinia 2005. Tenth international waste management and landfill symposium*, 3-7 October 2005, S. Margherita di Pula, Cagliari, Italy, 2005.

[9] Kuehle-Weidemeier, M., The current situation of MBT in Germany, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.

[10] Binner, E., Mechanical biological pre-treatment of residual waste in Austria, In: *Sustainable Waste Management*, *Proceedings of the International Symposium*, 9-11 September 2003, University of Dundee, Scotland, UK, Dhir, R.K., Newlands, M.D., and Dyer, T.D. (Eds.), 2003.

[11] Neubauer, C., Mechanical-biological treatment of waste in Austria: current developments, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.

[12] Papadimitriou, E.K., Stentiford, E., and Barton, J.R., *Deploying mechanical biological treatment in the UK*, *Wastes Management*, p.2, 2002.

[13] Enviros, Mechanical biological treatment & mechanical heat treatment of municipal solid waste, Department of Environment Food and Rural Affairs (DEFRA), UK, 2005.

[14] Ibbetson, C., UK market development of solid recovered fuel from MBT plants, In: *Waste 2006 - Sustainable waste and resource management*, 19-21 September 2006, Stratford-upon-Avon, UK, 2006.

[15] Bayard, R., de Brauer, C., Ducom, G., Morais, J.d.A., Achour, F., Moretto, R., Naquin, P., Sarrazin, B., Gourco, J.P., Riquier, L., and Berthet, J., Mechanical biological treatment and residual waste landfill in France: a case study, In: *International Symposium MBT 2005*, 23-25 November 2005, Hanover, Kühle-Weidemeier, M. (Ed.), Cuvillier Verlag, Göttingen, Germany, 2005.

[16] Haritopoulou, T. and Lasaridi, K., Mechanical-biological treatment experiences in Greece: problems, trends and perspectives, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.

[17] Pires, A., Martinho, M.G., and Silveira, A., Could MBT plants be the solution of fulfil Landfill Directive targets in Portugal?, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.

[18] GTZ, Sector project. Mechanical-biological waste treatment, Deutsche Gesellscharft fur Technische Zusammenarbeit (GTZ), Division 44 - Environment & Infrastructure, Eschborn, Germany, 2003.

[19] Lornage, R., Redon, E., Lagier, T., Hébé, I., and Carré, J., Performance of a low cost MBT prior to landfilling: study of the biological treatment of size reduced MSW without mechanical sorting, *Waste Manag.* 27 (12), 1755, 2007.

[20] Pereira, C.J., Practical experience with MBT in emerging nations - example Brazil, In: *International Symposium MBT 2005*, 23-25 November 2005, Hanover, Kühle-Weidemeier, M. (Ed.), Cuvillier Verlag, Göttingen, Germany, 2005.

[21] Tränkler, J., Visvanathan, C., and Kurupan, P., Mechanical biological waste treatment – the south-east Asian experiences, In: *Proceedings Sardinia 2005. Tenth international waste management and landfill symposium*, 3-7 October 2005, S. Margherita di Pula, Cagliari, Italy, 2005.

[22] Raninger, B., Bidlingmaier, W., Rundong, L., and Qi, W., Management of municipal solid waste In China - mechanical biological treatment can be an option? The Sino-German RRU-BMW Research Project to apply BMWM within the framework of waste management related policies, In: *International Symposium MBT 2005*, 23-25 November 2005, Hanover, Kühle-Weidemeier, M. (Ed.), Cuvillier Verlag, Göttingen, Germany, 2005.

[23] Garg, A., Smith, R., Hill, D., Simms, N., and Pollard, S., Wastes as co-fuels: The policy framework for solid recovered fuel (SRF) in Europe, with UK implications, *Environ. Sci. Technol.* 41 (14), 4868, 2007.

[24] Council of the European Union, Council Directive 1999/31/EC on the landfill of waste, L 182, 16-07-1999, European Commission - Official Journal of the European Communities, 1999.

[25] Brunner, P.H. and Rechberger, H., *Practical handbook of material flow analysis*, Lewis Publishers, Washington, D.C., US, 2004.

[26] European Commission, Communication from the Commission: towards a thematic strategy on the prevention and recycling of waste, COM(2003) 301 final, 27 May 2003, Brussels, 2003.

[27] McDougal, F., White, P., Franke, M., and Hindle, P., *Integrated solid waste management: a life cycle inventory*, 2nd ed, Blackwell Science, Oxford, 2001.

[28] Baccini, P. and Brunner, P.H., *Metabolism of the anthroposphere*, Springer, New York, 1991.

[29] Kronberger, R., Waste to recovered fuel: cost-benefit analysis, April 2001, European Commission, Directorate-General for Energy and Transport, 2001.

[30] European Committee for Standardisation, Solid recovered fuels, PD CEN/TR 14745:2003, European Committee for Standardisation (CEN), 2003.

[31] European Recovered Fuel Organisation, BREF waste treatment. Solid recovered fuels, European Recovered Fuel Organisation (ERFO), IAR Aachen, 2003.

[32] Gendebien, A., Leavens, A., Blackmore, K., Godley, A., Lewin, K., Whiting, K.J., Davis, R., Giegrich, J., Fehrenbach, H., Gromke, U., del Bufalo, N., and Hogg, D., Refuse derived fuel, current practice and perspectives, B4-3040/2000/306517/MAR/E3, WRc Ref: CO5087-4, July 2003, WRc for the European Commission-Directorate General Environment, WRc, IFEU, Ecotec, Eunomia, Brussels, 2003.

[33] Schulz-Ellermann, H.-J., Production of RDF in Europe today and development of standard, In: *FEAD-Congress Entsorga 2003*, 24 September 2003, Cologne, Germany, European Federation of Wastes and Environmental Services (FEAD), 2003.

[34] Wilén, C., Salokoski, P., Kurkela, E., and Sipilä, K., Finnish expert report on best available techniques in energy production from solid recovered fuels, The Finnish Environment 668, Finnish Environment Institute, Helsinki, Finland, 2004.

[35] Oakdene Hollins, Quantification of the potential energy from residuals (EfR) in the UK, Commissioned by The Institution of Civil Engineers and The Renewable Power Association, March 2005, 2005.

[36] Beckmann, M. and Thomé-Kozmiensky, H.C.K.J., Substitute fuels – potential applications | [Ersatzbrennstoffe - Einsatzmöglichkeiten], *Aufbereitungs Technik/Mineral Processing* 47 (5), 10, 2006.

[37] Greiner, T., Swings and roundabouts. Demand for RDF swells in Germany, *Waste Management World* May-June 33, 2007.
[38] Frigerio, M., High quality solid recovered fuel (HQ-SRF): international perspectives of potential use and cost ranking among renewable energy sources, In: *Proceedings Sardinia 2007. Eleventh international waste management and landfill symposium*, 1-5 October 2007, S. Margherita di Pula, Cagliari, Italy, 2007.
[39] Silva, R.B., Barreiro, F., Navais, J.M., M, C., and Martin Dias, S., Refuse derived fuel production and use in Portugal, In: *Proceedings Sardinia 2007. Eleventh international waste management and landfill symposium*, 1-5 October 2007, S. Margherita di Pula, Cagliari, Italy, 2007.
[40] Glorius, T., van Tubergen, J., Thomas, P., Khoury, A., and Uepping, R., Solid recovered fuels. Contribution to BREF "Waste Treatment“, European Recovered Fuel Organisation (ERFO), Institute of Processing and Recycling of Solid Waste (I.A.R.), RWTH Aachen, Undated.
[41] Steiner, M., Status of mechanical-biological treatment of residual waste and utilization of refuse-derived fuels in Europe, In: *The future of residual waste management in Europe*, 17-18 November 2005, Luxembourg, ORBIT Association, Centre de Recherche Public Henri Tuodor, 2005.
[42] Greiner, T., Market research: development of plant capacities for refuse derived fuel plants as a market for high calorific MBT output in Germany, In: *International Symposium MBT 2007*, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.
[43] Hill, D., Garg, A., Smith, R., Pollard, S.J.T., and Longhurst, P., Appraisal for options of solid recovered fuel (SRF) utilisation within the UK, In: *Venice 2006 - Biomass and Waste to Energy Symposium*, November 29 - December 1, 2006, Cini Foundation, Island of San Giorgio Maggiore, Venice, Italy, EuroWaste, 2007.
[44] Roos, H.-J. and Peters, W., Advanced processing of municipal solid waste for the production of high-grade quality fuels, In: *Proceedings Sardinia 2007. Eleventh international waste management and landfill symposium*, 1-5 October 2007, S. Margherita di Pula, Cagliari, Italy, 2007.
[45] Beckmann, M., Karl, H.C., and Thomé-Kozmiensky, H.C.K.J., Waste-derived fuels – opportunities and problems | [Ersatzbrennstoffe - Chancen und probleme], *Aufbereitungs Technik/Mineral Processing* 47 (4), 28, 2006.
[46] Eckardt, S. and Albers, H., Specifying criteria for the utilisation of refuse derived fuels (RDF) in industrial combustion plants, In: *Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium*, 6-10 October 2003, S. Margherita di Pula, Cagliari, Italy, 2003.
[47] von Blottnitz, H., Pehlken, A., and Pretz, T., The description of solid wastes by particle mass instead of particle size distributions, *Resour. Conservat. Recycl.* 34 (3), 193, 2002.
[48] Pretz, T. and Onasch, K.-J., Mechanical processing of municipal solid waste with modern sorting technologies, In: *Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium*, 6-10 October 2003, S. Margherita di Pula, Cagliari, Italy, 2003.
[49] Rotter, V.S., Kost, T., Winkler, J., and Bilitewski, B., Material flow analysis of RDF-production processes, *Waste Manag.* 24 (10), 1005, 2004.

[50] Zwisele, B., Material flow and process analysis in MBT plants, In: *International Symposium MBT 2005*, 23-25 November 2005, Hanover, Germany, Kuehle-Weidemeier, M. (Ed.), Cuvillier Verlag, Göttingen, Germany, 2005.

[51] Brunner, P.H. and Stampfli, D.M., Material balance of a construction waste sorting plant, *Waste Management & Research* 11 (1), 27, 1993.

[52] Kost, T., Rotter, S., and Bilitewski, B., Chlorine and heavy metal content in household waste fractions and its influence on quality control in RDF production processes, In: *Sardinia 2001, Eighth International Waste Management and Landfill Symposium*, 1-5 October 2001, S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, 2001.

[53] Her Majesty's Stationery Office, The Landfill (England and Wales) (Amendment) Regulations 2004, 0110493168 Statutory Instrument 2004 No. 1375, The Stationery Office HMSO, 2004.

[54] Wiemer, K. and Kern, M., *Mechanical biological treatment of residual waste based on the dry stabilate method*, M.I.C. Baeza-Verlag, Witzenhausen, Germany, 1994.

[55] Calcaterra, E., Baldi, M., and Adani, F., An innovative technology for municipal solid waste energy recovery In: *C.I.P.A. - Centro di Ingegneria per la Protezione dell' Ambiente*, CIPA (Ed.), C.I.P.A, Milano, Italy, 123, 2000.

[56] Adani, F., Baido, D., Calcaterra, E., and Genevini, P., The influence of biomass temperature on biostabilization-biodrying of municipal solid waste, *Bioresour. Technol.* 83 (3), 173, 2002.

[57] Alter, H., The history of refuse-derived fuels, *Resour. Conservat.* 15 (4), 251, 1987.

[58] European Committee for Standardisation, Solid recovered fuels – specifications and classes, DD CEN/TS 15350:2006, European Committee for Standardisation (CEN), 2006.

[59] Soyez, K. and Plickert, S., Material flux management of waste by mechanical biological pre-treatment, In: *Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium*, 6-10 October 2003, S. Margherita di Pula, Cagliari, Italy, 2003.

[60] The Composting Association, A guide to in-vessel composting. Plus a directory of system suppliers, The Composting Association, Wellingborough, UK, 2004.

[61] Hasselriis, F., *Refuse-derived fuel processing*, Butterworth Publishers, Boston, MA, US, 1984.

[62] Barton, J.R., Poll, A.J., Webb, M., and Whalley, L., *Waste sorting and RDF production in Europe*, Elsevier Applied Science Publishers, London, 1985.

[63] Tchobanoglous, G., Theisen, H., and Vigil, S.A., *Integrated solid waste management: engineering principles and management issues*, Mc-Graw Hill, New York, 1993.

[64] Manser, A.G.R. and Keeling, A.A., *Practical handbook of processing and recycling municipal waste*, CRC Press, Lewis Publishers, 1996.

[65] Timmel, G., Air-flow separation for residual waste treatment | [Aerostromsortierung bei der restabfallaufbereitung], *Aufbereitungs-Technik/Mineral Processing* 47 (4), 16, 2006.

[66] Pichtel, J., *Waste management practices: municipal, hazardous, and industrial*, CRC Press, Taylor & Francis Group, Boca Raton, FL, US, 2005.

[67] Porteous, A., *Refuse derived fuels*, Applied Science Publishers, Halsted Press, London, 1981.

[68] Diaz, L.F. and Savage, G.M., Approaches to mechanical-biological treatment of solid wastes, In: *International Seminar and Workshop "The sustainable landfilling"*, 13-15 June 2005, Abbey of Praglia (Padua), Italy, CISA, Sanitary Environmental Engineering Centre, 2005.

[69] Barton, J.R., Mechanical processing - what it can do and cannot do, In: *DEn/DoE/DTI Integrated Municipal Waste Management Seminars*, 25 June 1992, Bristol, UK, 1992.

[70] Schubert, G. and Bernotat, S., Comminution of non-brittle materials, *Int. J. Miner. Process.* 74 (Supplement 1), S19, 2004.

[71] Pourghahramani, P. and Forssberg, E., Review of applied particle shape descriptors and produced particle shapes in grinding environments. Part I: particle shape descriptors, *Miner. Process. Extr. M.* 26 (2), 145, 2005.

[72] Hogg, R., Turek, M.L., and Kaya, E., The role of particle shape in size analysis and the evaluation of comminution processes, *Particul. Sci. Technol.* 22 (4), 355, 2004.

[73] Allen, T., *Particle size measurement*, 5th ed, Chapman and Hall, London, 1997.

[74] American Society for Testing and Materials, Manual on test sieving methods, 0803104766, American Society for testing and Materials (ASTM), Philadelphia, PA, US, 1985.

[75] European Committee for Standardisation, Solid recovered fuels – quality management systems - particular requirements for their application to the production of solid recovered fuels, PD CEN/TR 15358:2006, European Committee for Standardisation (CEN), 2006.

[76] Nakamura, M., Castaldi, M.J., and Themelis, N.J., Measurement of particle size and shape of New York city municipal solid waste and combustion particles using image analysis, In: *Proceedings of the 16th Japan Society of Waste Management Experts (JSMWE) Fall Conference*, Sendai, Japan, 2005.

[77] Nakamura, M., Castaldi, M.J., and Themelis, N.J., Numerical analysis of size reduction of municipal solid waste particles on the travelling grate of a waste-to-energy combustion chamber, In: *Proceedings of the 14th Annual North American Waste to Energy Conference, NAWTEC14*, Tampa, FL, 2006.

[78] Pehlken, A., Uepping, R., and Pretz, T., Process assessment and quality assurance in waste processing | [Prozessbewertung und Qualitätssicherung in der Abfallaufbereitung], *Aufbereitungs-Technik/Mineral Processing* 46 (5), 21, 2005.

[79] Deutsches Institut für Normung e.V., Investigations of the raw material in hard-coal-mining; determination of the particle-size-distribution > 20 μm by sieve-analysis, 03-1985, Deutsches Institut für Normung e.V. (DIN), 1985.

[80] Shapiro, M. and Galperin, V., Air classification of solid particles: a review, *Chem. Eng. Process.* 44 (2), 279, 2005.

[81] Trezek, G.J., Savage, G.M., and Obeng, D.M., Size reduction in solid waste processing: 2nd year progress report 1972-1973, EPA Report under Grant No. EPA R-801218, 1973.

[82] Trezek, G.J. and Savage, G.M., MSW component size distributions obtained from the Cal resource recovery system, *Resour. Recov. Conserv.* 2 (1), 67, 1976.

[83] Ruf, J.A., Particle size spectrum and compressibility of raw and shredded MSW, PhD Thesis, University of Florida, FL, US, 1974.

[84] Miller, A.P. and Clesceri, N.L., *Waste sites as biological reactors. Characterization and modelling*, CRC Press, Lewis Publishers, Boca Raton, FL, US, 2003.

[85] Pfannkuch, H.O. and Paulson, R., *Grain size distribution and hydraulic properties,* [www page] Available at: http://web.cecs.pdx.edu/~ian/geology2.5.html (Retrieved on: 15-12-2006).

[86] Zwisele, B., The necessity of material flow and process analyses for the assessment and optimization of waste management plants | [Die Notwendigkeit von Stoffstrom-Und Prozessanalysen zur Beurteilung und Optimierung abfallwirtschaftlicher Anlagen], *Aufbereitungs-Technik/Mineral Processing* 46 (5), 34, 2005.

[87] McCabe, W., Smith, J.C., and Harriott, P., *Unit operations of chemical engineering,* 6^{th} ed, McGraw Hill, New York, 2001.

[88] Spencer, D.B., Temple, J.W., Forsythe, D.M., and Bond, B.E., Large-scale rotary shear shredder performance testing, *J. Energ. Resour. Tech.* 107 (2), 289, 1985.

[89] Breuer, W., Experiences with the operation of the Nehlsen drying plant Stralsund, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.

[90] Campbell, G.M. and Webb, C., On predicting roller milling performance: part I: the breakage equation, *Powder Technol.* 115 (3), 234, 2001.

[91] King, R.P., *Modelling and simulation of mineral processing systems*, Butterworth-Heinermann Publications, Oxford, UK, 2001.

[92] Husemann, K., Modeling of Comminution Processes | [Zur Modellierung von Zerkleinerungsprozessen], *Chem. Ing. Tech.* 77 (3), 205, 2005.

[93] van Schaik, A., Reuter, M.A., and Heiskanen, K., The influence of particle size reduction and liberation on the recycling rate of end-of-life vehicles, *Miner. Eng.* 17 (2), 331, 2004.

[94] Tchobanoglous, G. and Kreith, F., *Handbook of solid waste management*, 2^{nd} ed, McGraw Hill, New York, 2002.

[95] Nikolov, S., Modelling and simulation of particle breakage in impact crushers, *Int. J. Miner. Process.* 74 (Supplement 1), S219, 2004.

[96] Shiflett, G.R. and Trezek, G.J., Parameters governing refuse comminution, *Resour. Recov. Conserv.* 4 (1), 31, 1979.

[97] Savage, G.M., Diaz, L.F., and Trezek, G.J., On-site evaluation of municipal solid waste shredders, *Resour. Recov. Conserv.* 5 (4), 343, 1981.

[98] Vesilid, P.A., Rimer, A.E., and Worrell, W.A., Performance characteristics of a vertical hammermill shredder, In: *Proceedings 1980 ASME national waste processing conference*, Washington, D.C., US, ASME, 1980.

[99] Savage, G.M., Claub, J.C., and Diaz, L.F., Models of unit operations used for solid-waste processing, ANL/CNSV-TM-152, September 1984, Argonne National Laboratory (ANL), Argonne, IL, US, 1984.

[100] Geyer, H.K. and Grammel, S.J., Municipal solid waste processing systems computer model, ANL/ENG/TM-03 (draft), March 1985, Argonne National Laboratory (ANL), Argonne, IL, US, 1985.

[101] Wheeler, P.A. and Barton, J.R., Evaluation of the GRAB refuse processing simulation program and its future potential. Final report, ETSU B 1180, June 1987, Department of Energy, contractor: Warren Spring Laboratory, 1990.

[102] Woldt, D., Schubert, G., and Jäckel, H.G., Size reduction by means of low-speed rotary shears, *Int. J. Miner. Process.* 74 (Supplement 1), S405, 2004.

[103] McCormick, P.G. and Froes, F.H., The fundamentals of mechanochemical processing, *JOM* 50 (11), 61, 1998.
[104] Faculty of chemical technology. University of Split, *Ball mill. Chemistry dictionary and glossary*, [www page] Available at: http://www.ktf-split.hr/glossary/en_index.html Last update: 2005 (Retrieved on: 20-10-07).
[105] Suryanarayana, C., *Mechanical alloying/milling* CRC Press, Taylor & Francis Group, Boca Raton, FL, US, 2004.
[106] Koch, P., Werning, W., and Pickert, B., Treatment of domestic refuse and residuals using the modular Hese MBWT process | [Haus- und restmüllbehandlung mit dem modularen Hese-MBA-verfahren], *Aufbereitungs-Technik/Mineral Processing* 42 (6), 284, 2001.
[107] Koch, P., The role of size reduction in facilities for mechanical-biological treatment of domestic refuse (MBWT) | [Die rolle der zerkleinerung in anlagen zur mechanisch-biologischen abfallbehandlung von hausmüll (MBA)], *Aufbereitungs-Technik/Mineral Processing* 43 (4), 25, 2002.
[108] Schade-Dannewitz, S., Studies on the mechanical-biological treatment of northern Thuringian waste | [Untersuchungen zur mechanisch-biologischen Behandlung Nordthüringer Restabfälle], *Aufbereitungs-Technik/Mineral Processing* 46 (4), 12, 2005.
[109] Koch, P., The role of selective size reduction in facilities for mechanical- biological treatment of domestic refuse | [Zum Einfluss der selektiven Zerkleinerung auf Entwurf und Betrieb von mechanisch-biologischen Abfallbehandlungsanlagen von Haus- und Restmüll], *Aufbereitungs-Technik/Mineral Processing* 45 (8-9), 13, 2004.
[110] University of Southampton, *The effect of particle size on the bio-processing of wastes*, Pickering, J., (Ed.) Technologies Research and Innovation Fund (TRIF), TRIF event, 2006.
[111] Jackson, D.V., The economics of recycling - the national field, In: *Waste recycling - the next steps for local authorities*, 1 November 1978, 1978.
[112] Kohaupt, U., Metal sorting in waste treatment - improvement of quality and economic backbone, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.
[113] Rietema, K., On the efficiency in separating mixtures of two constituents, *Chem. Eng. Sci.* 7 (1-2), 89, 1957.
[114] Klumpar, I., Measuring and optimizing air classifier performance, *Separ. Technol.* 2 (3), 124, 1992.
[115] Worrell, W.A. and Vesilind, P.A., Testing and evaluation of air classifier performance, *Resour. Recov. Conserv.* 4 (3), 247, 1979.
[116] Vesilind, P.A. and Rimer, A.E., *Unit operations in resource recovery engineering*, Prentice Hall, Engelwood Cliffs, NJ, US, 1981.
[117] Everett, J.W. and Peirce, J.J., The development of pulsed flow air classification theory and design for municipal solid waste processing, *Resour. Conservat. Recycl.* 4 (3), 185, 1990.
[118] American Society for Testing and Materials, Standard test method for determination of the recovery of a product in a materials separation device, E 1108-828 (Reapproved 2004), July 1986, American Society for testing and Materials (ASTM), Philadelphia, PA, US, 1986.

[119] Schweitzer, P.A., (Ed.) *Handbook of separation techniques for chemical engineers* 3rd ed. McGraw-Hill, 1997.
[120] Wang, Q., Melaaen, M.C., and De Silva, S.R., Investigation and simulation of a cross-flow air classifier, *Powder Technol.* 120 (3), 273, 2001.
[121] American Society for Testing and Materials, Standard test method for composition or purity of a solid waste materials stream, E 889-82 (Reapproved 2004), May 1983, American Society for testing and Materials (ASTM), Philadelphia, PA, US, 1983.
[122] Vesilind, P.A., Air classification of shredder refuse, *Conserv. Recycling* 9 (1), 35, 1986.
[123] Rhyner, C.R., Schwartz, L.J., Wenger, R.B., and Kohrell, M.G., *Waste management and resource recovery*, CRC Press, Boca Raton, 1995.
[124] Diaz, L.F., Savage, G.M., and Golueke, C.G., *Resource recovery from municipal solid wastes*, Vol. 1, CRC Press, Boca Raton, FL, US, 1982.
[125] Caputo, A.C. and Pelagagge, P.M., RDF production plants: I. Design and costs, *Applied Thermal Engineering* 22 (4), 423, 2002.
[126] Chang, Y.H., Chang, N.B., and Chen, W.C., Systematic evaluation and uncertainty analysis of the refuse-derived fuel process in Taiwan, *J. Air Waste Manag. Assoc.* 48 (6), 537, 1998.
[127] Zwisele, B., Rosenkranz, J., and Nordwig, A., Simulation of mechanical processing in waste management, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.
[128] Döberl, G., Huber, R., Brunner, P.H., Eder, M., Pierrard, R., Schönback, W., Frühwirth, W., and Hutterer, H., Long-term assessment of waste management options - a new, integrated and goal-oriented approach, *Waste. Manag. Res.* 20 (4), 311, 2002.
[129] Huang, W.L., Lin, D.H., Chang, N.B., and Lin, K.S., Recycling of construction and demolition waste via a mechanical sorting process, *Resour. Conservat. Recycl.* 37 (1), 23, 2002.
[130] Belevi, H. and Langmeier, M., Factors determining the element behavior in municipal solid waste incinerators. 2. Laboratory experiments, *Environ. Sci. Technol.* 34 (12), 2507, 2000.
[131] Belevi, H. and Moench, H., Factors determining the element behavior in municipal solid waste incinerators. 1. Field studies, *Environ. Sci. Technol.* 34 (12), 2501, 2000.
[132] Fehringer, R., Brandt, B., Brunner, P.H., Daxbeck, H., Neumayer, S., Smutny, R., Villeneuve, J., Michael, P., Kranert, M., Schultheis, A., and Steinbach, D., MFA manual. Guidelines for the use of material flow analysis (MFA) for municipal solid waste (MSW) management, Project AWAST, Contract title: EVK4-CT-2000-00015, Vienna University of Technology – Institute for Water Quality and Waste Management, Resource Management Agency, Buraeu de Rechercheures Geologiques et Minieres, Stuttgard University – Institute for Water Quality and Waste Management, Undated.
[133] Thomé-Kozmiensky, K.J., Processing concepts for substitute fuels | [Aufbereitungskonzepte für ersatzbrennstoffe], *Aufbereitungs-Technik/Mineral Processing* 43 (4), 11, 2002.
[134] Hüttner, A., Maximum recovery of the outputs of MBT and AD plants treating grey fraction or combined MSW, In: *Biometa 05*, 14-15 November 2005, 2005.
[135] HAASE, *Welcome to Luebeck MBT plant*, 2005.

[136] Williams, E., Review of the literature on the use of trommels in waste processing and resource recovery, DOE Contract No. AGO 1-76CS20167, July 1981, National Centre for Resource Recovery, Washington, D.C., US, 1981.
[137] Sullivan, J.W., Hill, R.M., and Sullivan, J.F., Place of the trommels in resource recovery, In: *Proceedings of National Waste Processing Conference*, Detroit, MI, US, ASME, 1992.
[138] Lau, S.T., Cheung, W.H., Kwong, C.K., Wan, C.P., Choy, K.K.H., Leung, C.C., Porter, J.F., Hui, C.W., and Mc Kay, G., Removal of batteries from solid waste using trommel separation, *Waste Manag.* 25 (10), 1004, 2005.
[139] Wheeler, P.A., Barton, J.R., and New, R., An empirical approach to the design of trommel screens for fine screening of domestic refuse, *Resour. Conservat. Recycl.* 2 (4), 261, 1989.
[140] Stessel, R.I., A new trommel model, *Resour. Conservat. Recycl.* 6 (1), 1, 1991.
[141] Stessel, R.I. and Cole, K., Laboratory investigation of a new trommel model, *J. Air Waste Manag. Assoc.* 46 (6), 558, 1996.
[142] Piekarczyk, M. and Ciurej, H., Trommel screens for waste utilization. Computer aided design, *Archives of Civil Engineering* 44 (1), 107, 1998.
[143] Fricke, K. and Mueller, W., Stabilisation of residual waste by mechanical-biological treatment and consequences for landfills. Final report for the German Federal research project on mechanical-biological treatment of waste before landfill, IGW, Witzenhausen, 1999.
[144] Pilz, G., Stoffstromtrennverfahren der Linde-KCA (In German) | [Material separation for Linde-KCA], In: *Reformbedarf in der Abfallwirtschaft | [Necessary reform for waste management]*, Thomé-Kozmiensky, K.J. (Ed.), TK Verlag, Neuruppin, Germany, 347, 2001.
[145] Koch, P., Pickert, B., and Wayman, P., The role of selective size reduction in facilities for mechanical biological treatment of domestic refuse, In: *Biodegradable and residual waste management: 1st UK Conference and exhibition*, 18-19 February 2004., Harrogate, UK, E.K. Papadimitriou and E.I. Stentiford (Ed.), Cal Recovery Europe Ltd, 2004.
[146] Delgenes, J.P., Penaud, V., and Moletta, R., Pretreatments for the enhancement of anaerobic digestion of solids wastes, In: *Biomethanization of the organic fraction of municipal solid wastes*, Mata-Alvarez, J. (Ed.), IWA Publishing, London, 201, 2003.
[147] Palmowski, L.M. and Mueller, J.A., Anaerobic degradation of organic materials. Significance of the substrate surface area, *Water Sci. Technol.* 47 (12), 231, 2003.
[148] Palmowski, L.M. and Mueller, J.A., Influence of the size reduction of organic waste on their anaerobic digestion, *Water Sci. Technol.* 41 (3), 155, 2000.
[149] Baaden, A., Mundhenke, R., Mueller, J.A., and Schwedes, J., Physical properties and comminution behaviour of organic materials, In: *Reprints 10th European Symposium on Comminution*, Heidelberg, Germany, 2002.
[150] Haug, R.T., *The practical handbook of compost engineering*, CRC Press, Lewis Publishers, Boca Raton, FL, USA, 1993.
[151] Silvestri, S., Dallago, L., Odorizzi, G., Zorzi, G., Gardelli, G., and Ragazzi, M., Biological stabilization of residual solid waste: technologies and methods, In: *Proceedings Sardinia 2005. Tenth international waste management and landfill symposium*, 3-7 October 2005, S. Margherita di Pula, Cagliari, Italy, 2005.

[152] Mueller, W., Niesar, M., and Turk, T., Optimized mechanical treatment and material segregation through ballistic separation within mechanical biological waste treatment, In: *Proceedings Sardinia 2003, Ninth International Waste Management and Landfill Symposium*, 6-10 October 2003, S. Margherita di Pula, Cagliari, Italy, 2003.
[153] Peirce, J.J., Understanding technology: new concepts for air classification in waste processing and resource recovery, In: *Proceedings – Frontiers in Education Conference*, West Lafayette, IN, US, IEEE, 1991.
[154] Savage, G., Diaz, L., and Goldstein, N., A compost screening primer, *BioCycle* 46 (5), 55, 2005.
[155] He, Y.Q., Wang, H.F., Duan, C.L., and Song, S.L., Numerical simulation of airflow patterns within passive pulsing air classifiers, *Zhongguo Kuangye Daxue Xuebao/Journal of China University of Mining and Technology* 34 (5), 574, 2005.
[156] Bartlett, J., The effect of moisture on air classification on municipal solid waste, MSc Thesis, Duke University, Durham, NC, US, 1983.
[157] Taub, J., The effect of feed composition on air classifier performance, MSc Thesis, Duke University, Durham, NC, US, 1981.
[158] Biddulph, M.W. and Connor, M.A., A method of comparing the performance of air classifiers, *Resour. Conservat. Recycl.* 2 (4), 275, 1989.
[159] Flitton, J.T., Refuse handling and processing by air classification, In: *Refuse Handling and Processing*, 11 May 1978, London, Institution of Mechanical Engineers, 1978.
[160] Wakita, S., Recycling of waste plastics in NKK, *SEAISI Quarterly (South East Asia Iron and Steel Institute)* 31 (4), 60, 2002.
[161] Mitsubishi Rayon Engineering, *Ballistic sorter*, [www page] Available at: http://www.mrc.co.jp/mre/english/recycle/recycle_05.html Last update: 2004 (Retrieved on: 15-09-2007).
[162] Bilitewski, B., Recyclinganlagen für Haus- Und Gewerbeabfäll (In German) | [Recycling plants for household and commercial waste], *Müll & Abfall* Beiheft 21 1985.
[163] O.Key Engineering, *Which screen do I need?*, [www page] Available at: http://www.okay.co.uk/products_mrfs_which_one.htm (Retrieved on: 20-2-2007).
[164] Heering, B.M., Heering, M., and Heil, J., Processing waste to useful fractions with the Herhof dry stabilization technique | [Aufbereitung von Restabfall zu verwertbaren Teilfraktionen mit dem Herhof-Trockenstabilatverfahren], *Aufbereitungs-Technik/Mineral Processing* 40 (1), 11, 1999.
[165] Harbeck, H. and Kroog, H., New developments in sensor-based sorting | [Neue Entwicklungen in der Sensorgestützten Sortierung], *Aufbereitungs-Technik/Mineral Processing* 49 (5), 4, 2008.
[166] Zeiger, E., Sorting waste streams with mogensen X-ray sorting systems | [Sortierung verschiedener abfallströme mit mogensen-röntgensortiertechnik], *Aufbereitungs-Technik/Mineral Processing* 47 (3), 16, 2006.
[167] Schirmer, M., Janz, A., Bilitewski, B., and Rotter, S., Sources of chlorine in MSW and RDF – species, analytical methods and requirements on improved separation methods, In: *Proceedings Sardinia 2005, Tenth International Waste Management and Landfill Symposium*, 3-7 October 2005, S. Margherita di Pula, Cagliari, Italy, 2005.

[168] Wengenroth, K., New developments in the dry stabilate process | [Neue Entwicklungen beim Trockenstabilat-Verfahren], *Aufbereitungs-Technik/Mineral Processing* 46 (3), 14, 2005.
[169] Barton, J.R. and Wheeler, P.A., The benefits of front end trommelling in processing municipal solid wastes. Trials at the Byker plant, LR 661 (MR)M June 1987, Department of Trade and Industry, contractor: Warren Spring Laboratory, 1987.
[170] Heilmann, A. and Bilitewski, B., High-grade fuel derived from residual waste, In: *Sardinia 1999, Seventh International Waste Management and Landfill Symposium*, 4-8 October 1999, S. Margherita di Pula, Cagliari, Italy, CISA, Environmental Sanitary Engineering Centre, 1999.
[171] British Standards Institution, Quality management systems - fundamentals and vocabulary, BS EN ISO 9000:2005, British Standards Institution (BSI), 2005.
[172] Valtanen, J., Alakangas, E., and Levlin, J.-E., Fuel quality assurance, In: *International Conference. Standardisation of solid biofuels*, 6-7 October 2004, Leipzig, Germany, Hein, M. and Kaltschmitt, M. (Eds.), Institute for Energy and Environment, 2004.
[173] Cuperus, J.G. and van Dijk, E.A., Determination of the biomass fraction in solid recovered fuels, R003-3907341JGC-D01-D, 6 June 2002, TAUW, Deventer, The Netherlands, 2002.
[174] Environment Agency, Compost quality protocol, Waste & Resources Action Programme (WRAP), Oxon, UK, 2007.
[175] British Standards Institution, Specification for composted materials, BSI PAS 100:2005, 31 March 2005, British Standards Institution (BSI), 2005.
[176] Mason, C., *Landspreading sewage sludge on agricultural land*, [www page] Available at: http://www.netregs.gov.uk/netregs/sectors/1770583/1771509/1774438/?version=1&lang=_e Last update: 16-07-2007 (Retrieved on: 15-09-2007).
[177] Lasaridi, K., Protopapa, I., Kotsou, M., Pilidis, G., Manios, T., and Kyriacou, A., Quality assessment of composts in the Greek market: the need for standards and quality assurance, *Journal of Environmental Management* 80 (1), 58, 2006.
[178] Saft, R.J. and Elsinga, W., Source separation, composting a win for greenhouse gas reduction, *BioCycle* 47 (6), 50, 2006.
[179] Ibbetson, C., Chappell, J., and Wengenroth, K., European market development - solid recovered fuel from MBT plants, In: *International Symposium MBT 2005*, 23-25 November 2005, Hanover, Kühle-Weidemeier, M. (Ed.), Cuvillier Verlag, Göttingen, Germany, 2005.
[180] Garg, A., Smith, R., Hill, D., and Pollard, S.J.T., An integrated, quantitative appraisal of options for the utilisation of solid recovered fuel (SRF) from the mechanical-biological treatment of MSW, Report to Grantscape No. 760828/1, July 2007, Cranfield University, Integrated Waste Management Centre (IWMC), Cranfield, UK, 2006.
[181] Ibbetson, C. and Wengenroth, K., Optimisation of fuels from MBT processes, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.
[182] Michels, N., Tenders and contracts for the sale of RDF, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.

[183] Langheinrich, M. and Kaltschmitt, M., Implementation and application of quality assurance systems, In: *International Conference. Standardisation of solid biofuels*, 6-7 October 2004, Leipzig, Germany, Hein, M. and Kaltschmitt, M. (Eds.), Institute for Energy and Environment, 2004.

[184] Alakangas, E., Lensu, T., Haglund, N., and Nitschke, M., Bioenergy 2003 – 2005. Action 2: Development of standards to achieve market harmonisation in the bioenergy field. Review of the present status and future prospects of standards and regulations in the bioenergy field, PRO2/P2031/05, 9-9-2005, VTT Processes, NAH Consulting, Elsam Engineering, 2005.

[185] European Commission, IPPC draft reference document on best available techniques for waste treatment industries, MA/EIPPCB/WT_Draft_2, January 2004, Institute for Prospective Technological Studies, European IPPC Bureau, Seville, Spain, 2004.

[186] Flamme, S., Quality certification mark for secondary fuels RAL-GZ 724 | [Gütezeichen für Sekundärbrennstoffe RAL-GZ 724], *ZKG Int.* 58 (8), 51, 2005.

[187] American Society for Testing and Materials, Annual ASTM standards. Vol 11.04, Vol 11.04, American Society for testing and Materials (ASTM), Philadelphia, PA, US, 1985.

[188] European Association of Waste Thermal Treatment Companies for Specialised Waste, *Methodology for the determination of technical co-incineration criteria*, [www page] Available at: http://www.eurits.org/pages/coincineration.asp# (Retrieved on: 15-09-2007).

[189] World Business Council for Sustainable Development, *Guidelines for the selection and use of fuels and raw materials in the cement manufacturing process*, Cement Sustainability Initiative (CSI), WBCSD, Geneva, Switzerland, 2005.

[190] van Tubergen, J., Glorius, T., and Waeyenbergh, E., Classification of solid recovered fuels, February 2005, European Recovered Fuel Organisation (ERFO), 2005.

[191] Finish Standards Association, Solid recovered fuel. Quality control system, 24-01-2000, Finish Standards Association (FSF), 2000.

[192] German Institute for Quality Assurance and Certification, Solid recovered fuels. Quality assurance, RAL-GZ 724, June 2001, German Institute for Quality Assurance And Certification (RAL), 2001.

[193] Zanotta, C., I.D.E.A. GRANDA: over 4 years experience of co-firing HQ-SRF in cement kiln, In: *Proceedings Sardinia 2007. Eleventh international waste management and landfill symposium*, 1-5 October 2007, S. Margherita di Pula, Cagliari, Italy, 2007.

[194] Cuperus, J.G., van Dijk, E.A., and de Boer, R.C., Pre-normative research on SRF, R001-4271783EDA-rvb-V01-NL, 13 September 2005, TAUW, Deventer, The Netherlands, 2005.

[195] Environment Agency, *Substitute fuels protocol for use in cement and lime kilns*, Environment Agency (EA), 2005.

[196] European Committee for Standardisation, Key properties on solid recovered fuels to be used for establishing a classification system, PD CEN/TR 15508:2006, European Committee for Standardisation (CEN), 2006.

[197] Niessen, W.P., *Combustion and incineration processes*, 3rd ed, Marcel Dekker, New York, 2002.

[198] Hilber, T., Martensen, M., Maier, J., and Scheffknecht, G., A method to characterise the volatile release of solid recovered fuels (SRF), *Fuel* 86 (1-2), 303, 2007.
[199] Hartmann, H., Physical-mechanical fuel properties - significance and impacts, In: *International Conference. Standardisation of solid biofuels*, 6-7 October 2004, Leipzig, Germany, Hein, M. and Kaltschmitt, M. (Eds.), Institute for Energy and Environment, 2004.
[200] Obernberger, I., Brunner, T., and Baernthaler, G., Chemical fuel properties - significance and impact, In: *International Conference. Standardisation of solid biofuels*, 6-7 October 2004, Leipzig, Germany, Hein, M. and Kaltschmitt, M. (Eds.), Institute for Energy and Environment, 2004.
[201] Achternbosch, M., Bräutigam, K.-R., Gleis, M., Hartlieb, N., Kupsch, C., Richers, U., and Stemmermann, P., Heavy metals in cement and concrete resulting from the co-incineration of wastes in cement kilns with regard to the legitimacy of waste utilisation, FZKA 6923, October 2003, Forschungszentrum Karlsruhe, Karlsruhe, Germany, 2003.
[202] SINTEF, Formation and release of POPs in the cement industry, 2nd ed, 23 January 2006, World Business Council for Sustainable Development (WBCSD), Geneva, Switzerland, 2006.
[203] Danuvola, L. and Freimann, W., Chlorine bypass, *World Cement* 37 (1), 107, 2006.
[204] Opoczky, L. and Gavel, V., Effect of certain trace elements on the grindability of cement clinkers in the connection with the use of wastes, *Int. J. Miner. Process.* 74 (Supplement 1), S129, 2004.
[205] Cozens, P., EfW - an alternative vision, In: *Biodegradable and residual waste management: 1st UK conference and exhibition*, 18-19 February 2004, Harrogate, UK, Papadimitriou, E.K. and Stentiford, E.I. (Eds.), Cal Recovery Europe Ltd, 2004.
[206] Kakaras, E., Grammelis, P., Agraniotis, M., Derichs, W., Shchiffer, H.-P., Maier, J., Hilber, T., Glorius, T., and Becker, U., Solid recovered fuel as coal substitute in the electricity generation sector, *Thermal Sci.* 9 (2), 17, 2005.
[207] Schultz, W., Einsatz von Sekundärbrennstoffen in Grosskraftwerken. Sekundärbrennstoffe und erneuerbare Energien (In German) | [Application of secondary fuels in main power stations. Secondary fuels and renewable energy], In: *Bundesgütegemeinschaft Sekundäbrennstoffe e.V.*, *Entsorga 2003*, Clogne, 2003.
[208] Beckmann, M. and Thomé-Kozmiensky, H.C.K.J., Das Ersatzbrennstoffproblem (In German) | [The waste-derived fuel problem], In: *Ersatzbrennstoffe 5 - Herstellung und Verwertung | [Waste-derived fuels 5 - production and utilisation]*, November 2005, Berlin, Germany, Neuruppin, S. (Ed.), TK-Verlag, 2005.
[209] Fernandez, A., Wendt, J.O.L., Wolski, N., Hein, K.R.G., Wang, S., and Witten, M.L., Inhalation health effects of fine particles from the co-combustion of coal and refuse derived fuel, *Chemosphere* 51 (10), 1129, 2003.
[210] Hamel, S., Hasselbach, H., Weil, S., and Krumm, W., Autothermal two-stage gasification of low-density waste-derived fuels, *Energy* 32 (2), 95, 2007.
[211] Kobyashi, N., Itaya, Y., Piao, G., Mori, S., Kondo, M., Hamai, M., and Yamaguchi, M., The behavior of flue gas from RDF combustion in a fluidized bed, *Powder Technol.* 151 (1-3), 87, 2005.

[212] Liu, G.-Q., Itaya, Y., Yamazaki, R., Mori, S., Yamaguchi, M., and Kondoh, M., Fundamental study of the behavior of chlorine during the combustion of single RDF, *Waste Manag.* 21 (5), 427, 2001.

[213] Jand, N., Brandani, V., and Foscolo, P.U., Thermodynamic limits and actual product yields and compositions in biomass gasification processes, *Ind. Eng. Chem. Res.* 45 (2), 834, 2006.

[214] Kilgallon, P., Simms, N.J., and Oakey, J.E., Fate of trace contaminants from biomass fuels in gasification systems, In: *Materials for advanced powered engineering 2002*, Lecomte-Beckers, J., Carton, M., Schubert, F., and Ennis, P. (Eds.), Forschungszentrum Juelin GmbH, Liege, France, 903, 2002.

[215] Niederdränk, J., Wirtgen, C., and Heil, J., Studies of the thermal upgrading of mechanically and biologically treated waste, *Aufbereitungs-Technik/Mineral Processing* 44 (2), 2003.

[216] Kock, O., Development of a characterization method for the combustion behavior of solid recovered fuels, *Chem. Eng. Tech.* 27 (7), 743, 2004.

[217] Kehl, l.P., Scharf, K.-F., Scur, P., and Wirthwein, R., Die Betriebsergebnisse aus den ersten 30 Monaten mit der neuen Ofenlinie 5 im Zementwerk Rüdersdorf (In German) | [Results from the first 30 operating months of new stove line 5 in the cement works at Rüdersdorf], *ZKG Int.* 51 (8), 410, 1998.

[218] Herhof Environmental, Biological-mechanical waste plant - Dresden, Saxony, Germany, Undated.

[219] Herhof GmbH, Clean energy from waste, Undated.

[220] European Committee for Standardisation, Solid recovered fuels. Report on relative difference between biodegredable and biogenic fractions of SRF, CEN/TR 14980:2004, European Committee for Standardisation (CEN), 2005.

[221] Department of Trade and Industry, Renewables obligation order 2006 – final decisions, January 2006, Department of Trade and Industry (DTI), 2006.

[222] Environmental Resources Management, Carbon balances and energy impacts of the management of UK waste streams, WR0602, 1 January 2006, Defra, contractor: Environmental Resources Management (ERM), Oxford, UK, 2005.

[223] Energy Information Administration, Methodology for allocation municipal solid waste to biogenic and non-biogenic energy, 20585, May 2007, Energy Information Administration (EIA), U.S. Department of Enegry, Washington, D.C., US, 2007.

[224] Flamme, S., The biogenic content in substitute fuels | [Biogener anteil in ersatzbrennstoffen], *Aufbereitungs-Technik/Mineral Processing* 47 (3), 40, 2006.

[225] European Committee for Standardisation, Solid recovered fuels – specifications and classes: final draft, CEN/TC 343/WG 2 N092 Final Draft, European Committee for Standardisation (CEN), Undated.

[226] European Committee for Standardisation, Solid recovered fuels – method for the determination of the biomass content, DD CEN/TS 15350:2006, European Committee for Standardisation (CEN), 2006.

[227] European Committee for Standardisation, Solid recovered fuels – determination of the biomass content based on the ^{14}C method PD CEN/TR 15591:2007, European Committee for Standardisation (CEN), 2007.

[228] Ofgem, Renewables obligation: fuel measurement and sampling guidance, 57/07, 29 March 2007, Ofgem, London, 2007.

[229] Fellner, J., Cencic, O., and Rechberger, H., A new method to determine the ratio of electricity production from fossil and biogenic sources in waste-to-energy plants, *Environ. Sci. Technol.* 41 (7), 2579, 2007.
[230] Mohn, J., Szidat, S., Fellner, J., Rechberger, H., Quartier, R., Buchmann, B., and Emmenegger, L., Determination of biogenic and fossil CO_2 emitted by waste incineration based on $^{14}CO_2$ and mass balances, *Bioresour. Technol.* 99 (14), 6471, 2008.
[231] Staber, W., Flamme, S., and Fellner, J., Methods for determining the biomass content of waste, *Waste. Manag. Res.* 26 (1), 78, 2008.
[232] Diaz, L.F., Papadimitriou, E.K., Savage, G.M., Eggerth, L.L., and Stentiford, E.I., Selective aspects of the treatment of biodegradable waste in the European Union, In: *Proceedings. 2002 International symposium. Composting and compost utilisation*, 6-8 May 2002, Columbus, OH, USA, Frederick, C.M.J., Rynk, R., and Hoitink, H.A.J. (Eds.), 2002.
[233] Scotti, S. and Minetti, G., Suitability of MBT facilities in treatment of different kinds of waste, In: *International Symposium MBT 2007*, 22-24 May 2007, Hanover, Germany, Kuehle-Weidemeir, M. (Ed.), Cuvillier Verlag, 2007.
[234] Paoli, P., Dell'Andrea, E., Brozzi, B., Teardo, G., and Casarin, F., Vesta Fusina RDF production plant and co-combustion in the ENEL power plant: experimentation and continued operation results, In: *Proceedings Sardinia 2007. Eleventh international waste management and landfill symposium*, 1-5 October 2007, S. Margherita di Pula, Cagliari, Italy, 2007.
[235] Heering, B.-M., Untersuchungen zur herstellung von verwertbaren stoffen aus restabfall nach mechanisch-biologischer behandlung (In German) | [Investigations for the production of usable materials from the residues of mechanical-biological treatment], PhD Thesis, Rheinisch- Westfälische Technische Hochschule, Aachen, 2001.
[236] Zeschmar-Lahl, B., Jager, J., and Ketelsen, K., (Eds.) *Mechanisch-biologische Abfallbehandlung in Europa / Verband der Kommunalen Abfallwirtschaft und Stadtreinigung (VKS) / Verbindung mit der Arbeitsgemeinschaft Stoffspezifische Abfallbehandlung (ASA) (In German) | [Mechanical-biological waste treatment in Europe / Association of Municipal Waste Management and City Cleaning (VKS) / In retation to the Registered Association for Material-Secific Waste Treatment (ASA)]*, Blackwell Wissenschafts-Verlag, Berlin, 2000.
[237] European Committee for Standardisation, Solid recovered fuels – methods for sampling, DD CEN/TS 15442:2006, European Committee for Standardisation (CEN), 2006.
[238] Gy, P., Sampling of discrete materials – a new introduction to the theory of sampling: I. Qualitative approach, *Chemometr Intell Lab Syst* 74 (1), 7, 2004.
[239] Gy, P., Sampling of discrete materials: II. Quantitative approach – sampling of zero-dimensional objects, *Chemometr Intell Lab Syst* 74 (1), 25, 2004.
[240] Petersen, L., Minkkinen, P., and Esbensen, K.H., Representative sampling for reliable data analysis: theory of sampling, *Chemometr Intell Lab Syst* 77 (1-2 SPEC. ISS.), 261, 2005.
[241] Petersen, L. and Esbensen, K.H., Representative process sampling for reliable data analysis - a tutorial, *J Chemometr* 19 (11-12), 625, 2005.

[242] Gy, P., Part IV: 50 years of sampling theory – a personal history, *Chemometr Intell Lab Syst* 74 (1), 49, 2004.
[243] StatSoft, Statistica 8. Data analysis software system, Version 8, 2008.
[244] European Committee for Standardisation, Solid recovered fuels – method for the determination of the calorific value, DD CEN/TS 15400:2006, European Committee for Standardisation (CEN), 2006.
[245] European Committee for Standardisation, Solid biofuels – calculation of analyses to different bases, DD CEN/TS 15269:2006, European Committee for Standardisation (CEN), 2006.
[246] Schirmer, M., Ma, W., Hoffmann, G., and Rotter, S., Origin and fate of chlorine in RDF production processes, In: *Proceedings Sardinia 2007. Eleventh international waste management and landfill symposium*, 1-5 October 2007, S. Margherita di Pula, Cagliari, Italy, 2007.

FIGURES

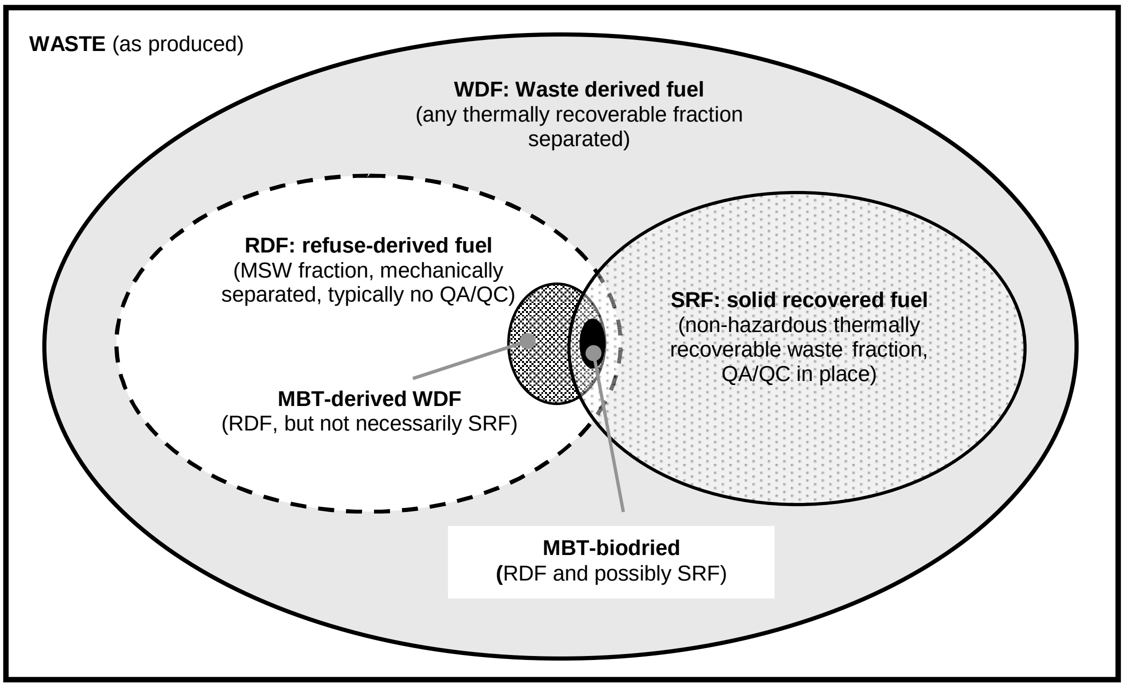


FIGURE 1 Venn diagram exemplifying terminology used for thermally recoverable waste fractions in mechanical-biological treatment plants (MBT) and their quality assurance/quality control (QA/QC).

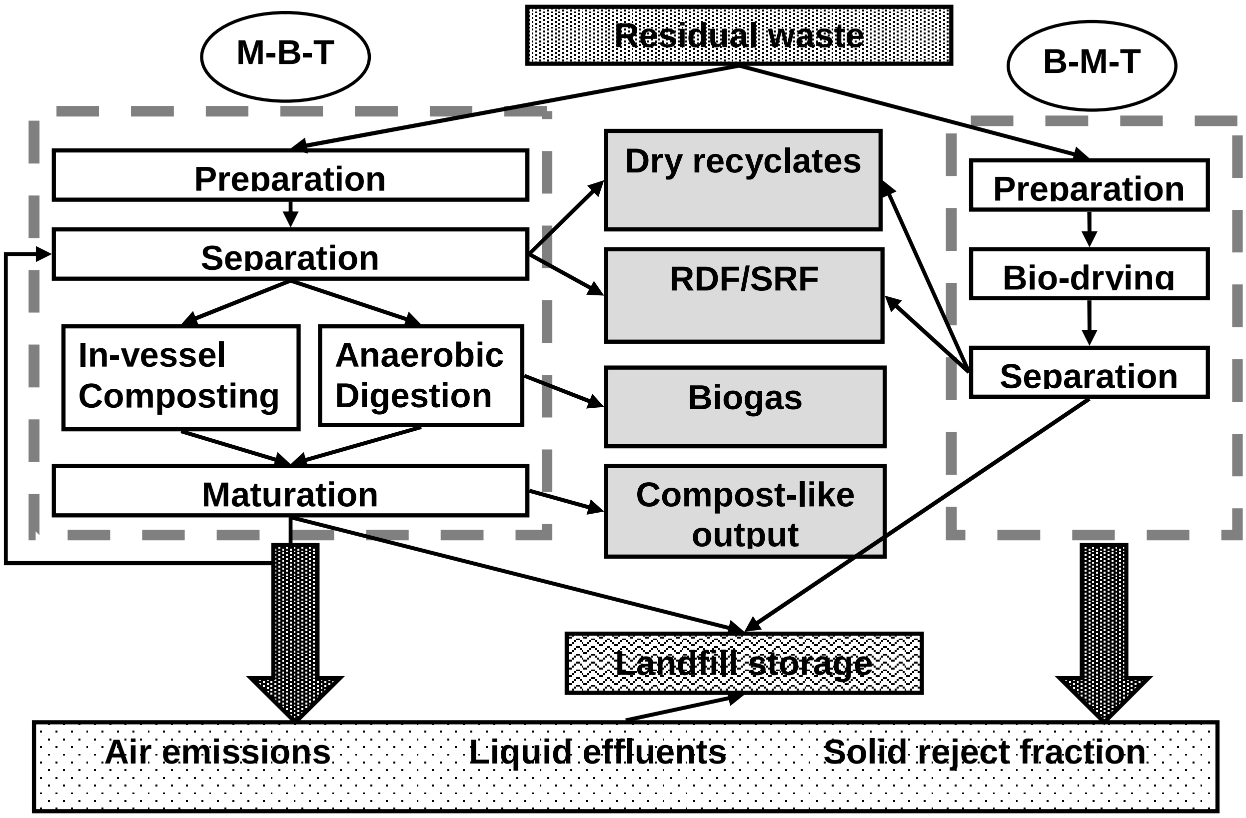


FIGURE 2 Simplified schematic of potential flow-line options for mechanical-biological treatment plants: different position for the core biological unit and the refuse-derived fuel/solid recovered fuel (RDF/SRF) production stage. B-M-T: biological-mechanical treatment. Adapted from Enviros[13]

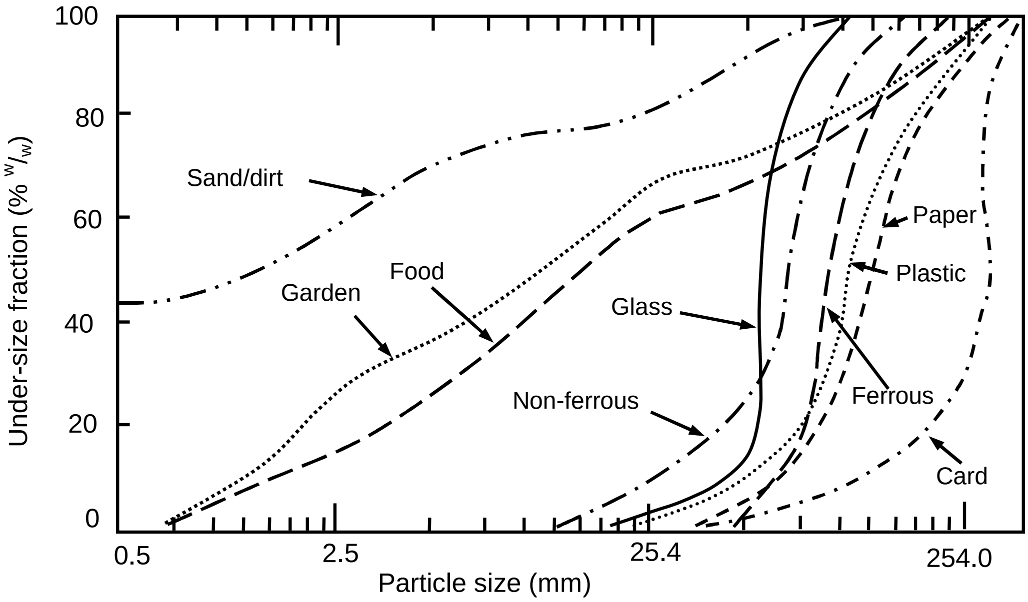


FIGURE 3 Particle-size distribution (PSD) of components of raw mixed household waste, in semi-logarithmic diagram. Each type of material spreads over a characteristic range of sizes, potentially allowing selective screening through the selection of suitable screen aperture. For example, a screening unit with 25 mm openings could theoretically concentrate all of the paper card and plastic in the overflow fraction. Redrawn from Ruf[83], cited in Hasselriis[61]

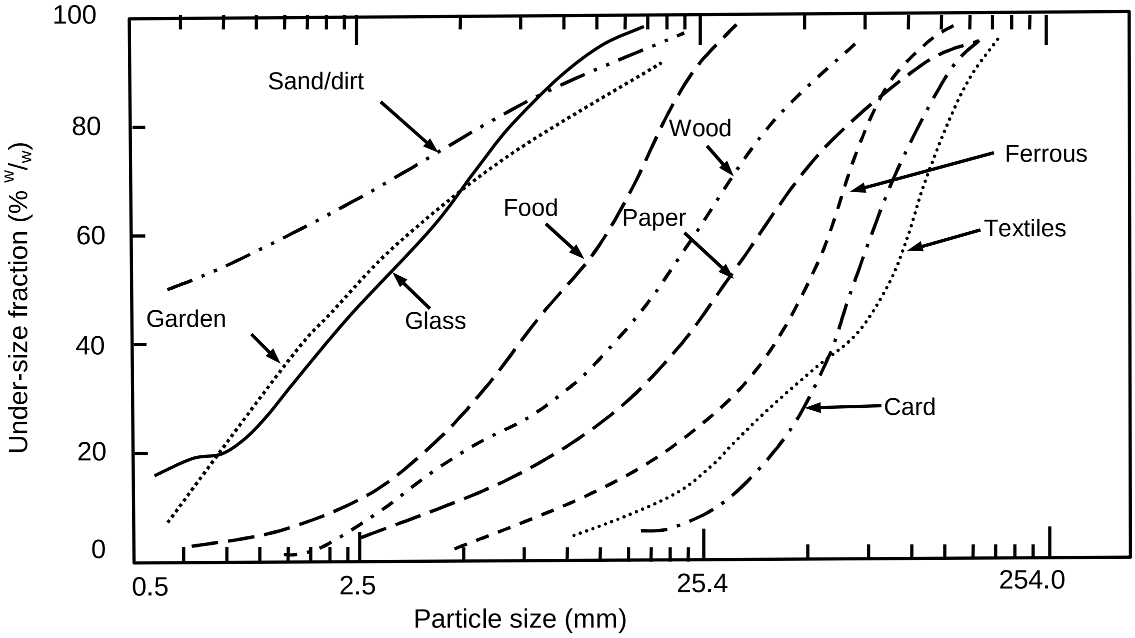


FIGURE 4 Particle-size distribution (PSD) of components of single-shredded MSW, in semi-logarithmic diagram. After shredding each waste component (e.g. paper) tend to occupy a wider range of sizes, compared with before size reduction (see FIGURE 3). This could restrict the potential for selective screening of certain waste components after shredding. Redrawn from Ruf[83], cited in Hasselriis[61]

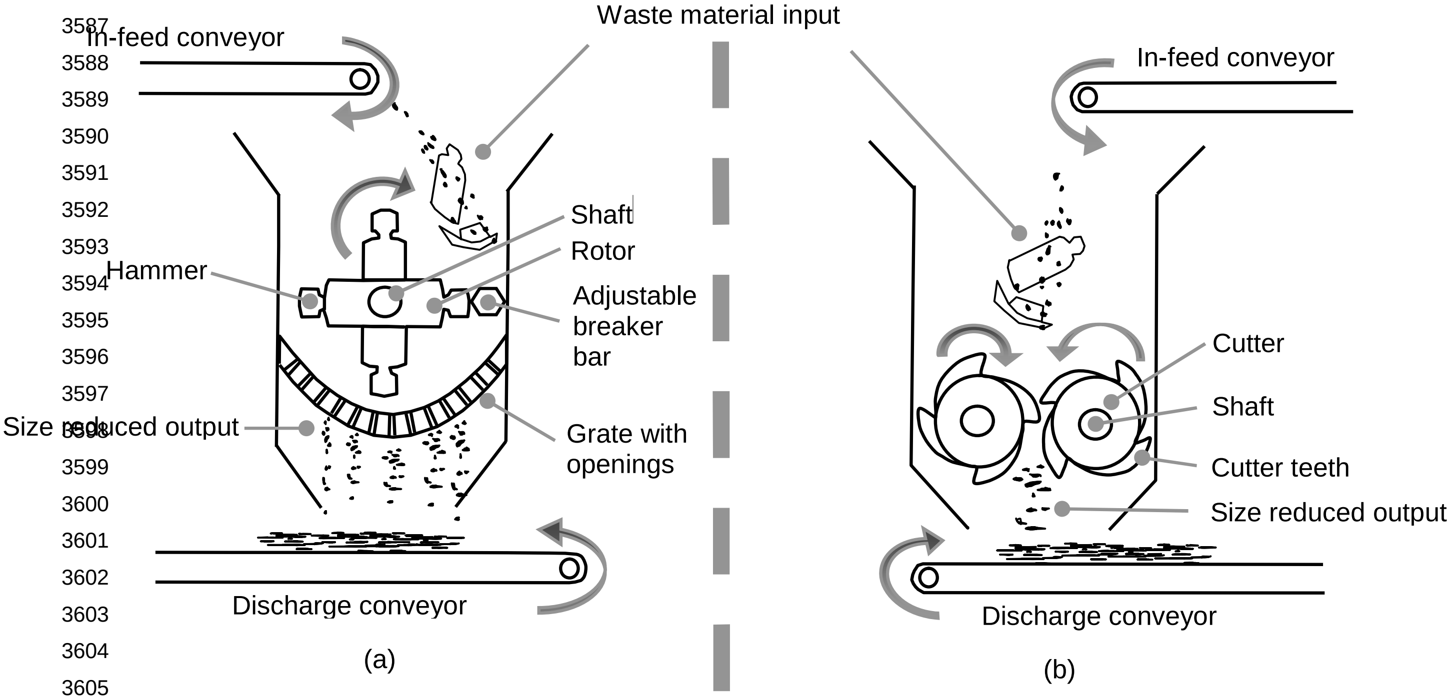


FIGURE 5 Schematic diagrams and operation principles for certain typical comminution equipment in MSW: (a) hammermill; (b) rotary shear. Adapted from Tchobanoglous et al.[63]

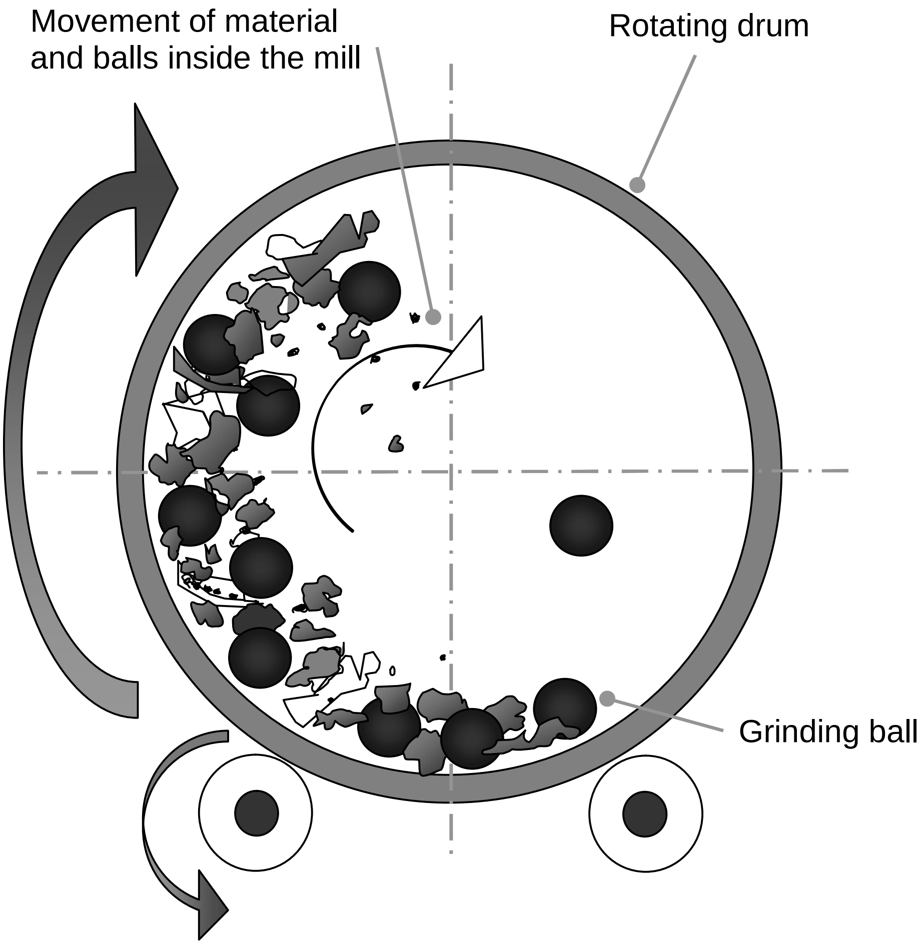


FIGURE 6 Schematic diagram of a vertical section of a ball mill, demonstrating its operating principle: as the drum rotates at a low speed around its horizontal axis the grinding balls in contact with the drum walls are lifted by the centrifugal force. At a certain point they lose contact and fall (cascade), impacting on the materials. Adapted from Faculty of chemical technology. University of Split[104] and Suryanarayana [105]

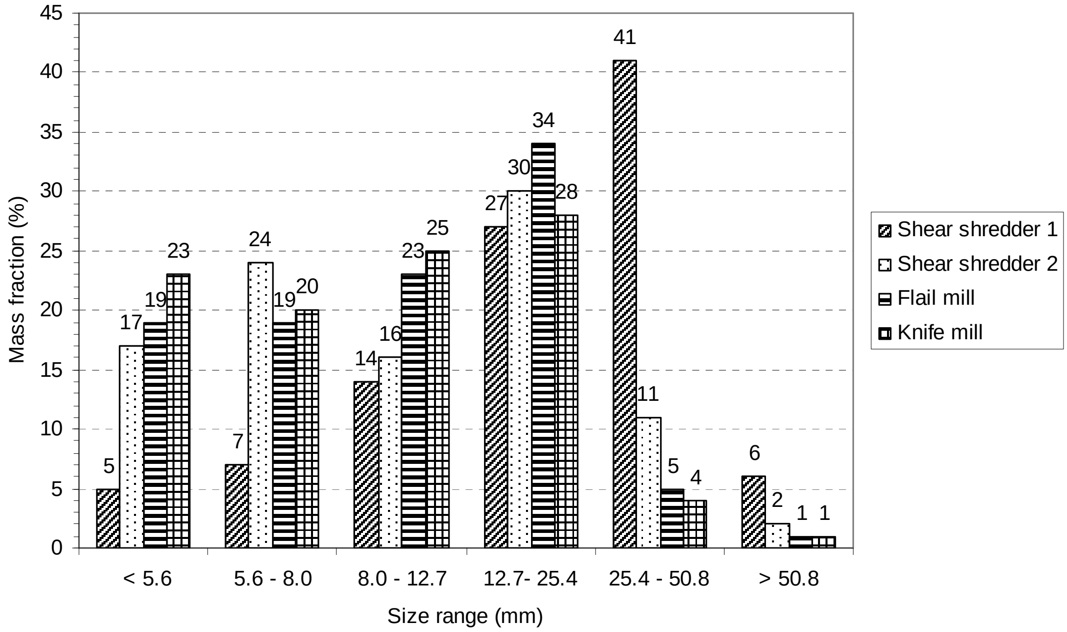
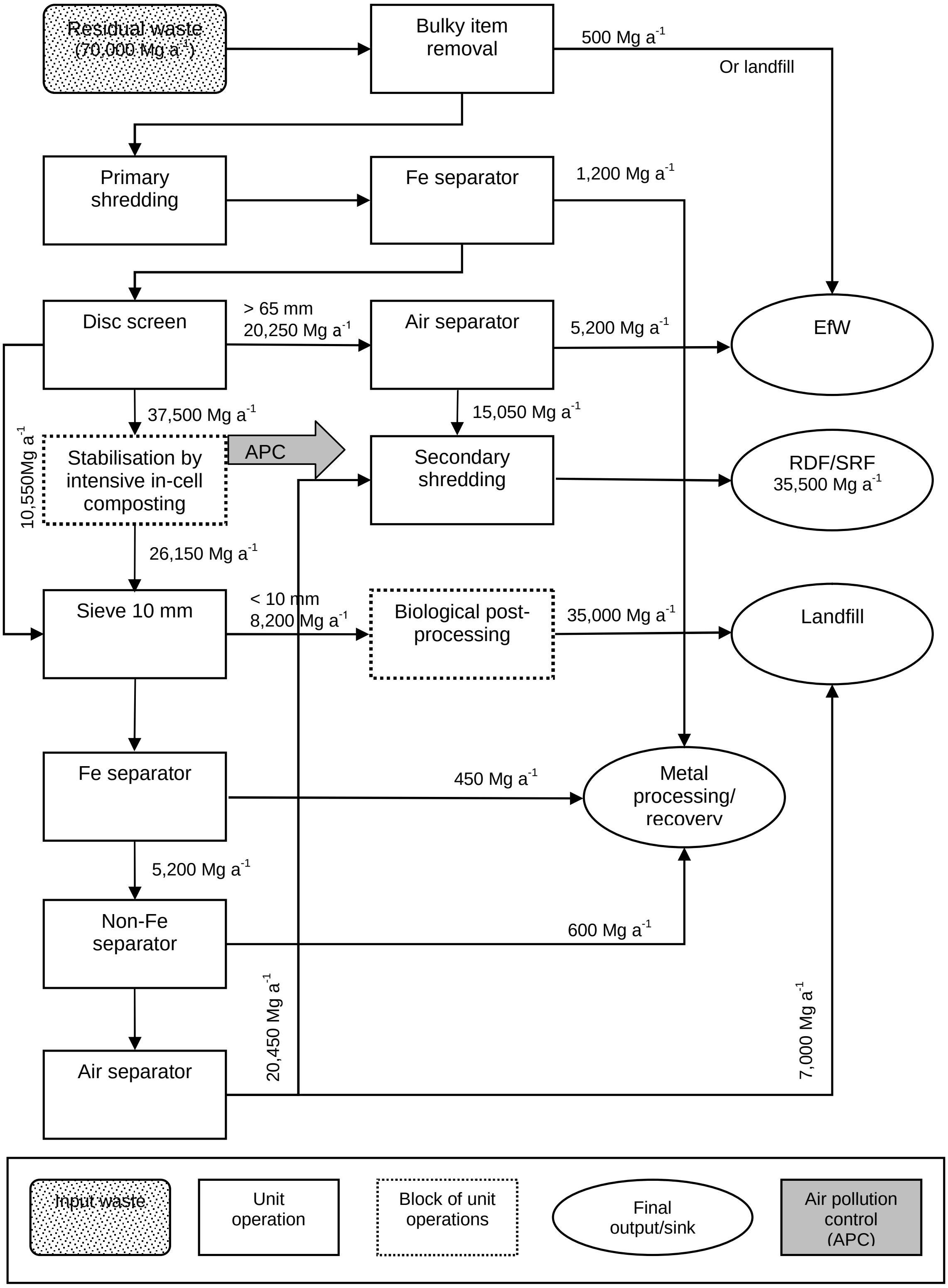


FIGURE 7 Secondary comminution of SRF, before pelletising, by different types of size reduction equipment; comparative results for the mass distribution of the shredded output. Data from Jackson[111], cited in Porteous[67]


Residual waste (70,000 Mg a-1)
Bulky item removal
500 Mg a-1
Or landfill
Primary shredding
Fe separator
1,200 Mg a-1
Disc screen
> 65 mm
20,250 Mg a-1
Air separator
5,200 Mg a-1
EfW
37,500 Mg a-1
15,050 Mg a-1
10,550Mg a-1
Stabilisation by intensive in-cell composting
APC
Secondary shredding
RDF/SRF
35,500 Mg a-1
26,150 Mg a-1
Sieve 10 mm
< 10 mm
8,200 Mg a-1
Biological post-processing
35,000 Mg a-1
Landfill
Fe separator
450 Mg a-1
Metal processing/ recovery
5,200 Mg a-1
Non-Fe separator
600 Mg a-1
20,450 Mg a-1
7,000 Mg a-1
Air separator
Input waste
Unit operation
Block of unit operations
Final output/sink
Air pollution control (APC)

3635

FIGURE 8 Simplified flow-chart and mass balance of the Nehlsen bio-drying MBT plant in Stralsund, Germany. Adapted from Breuer[89]

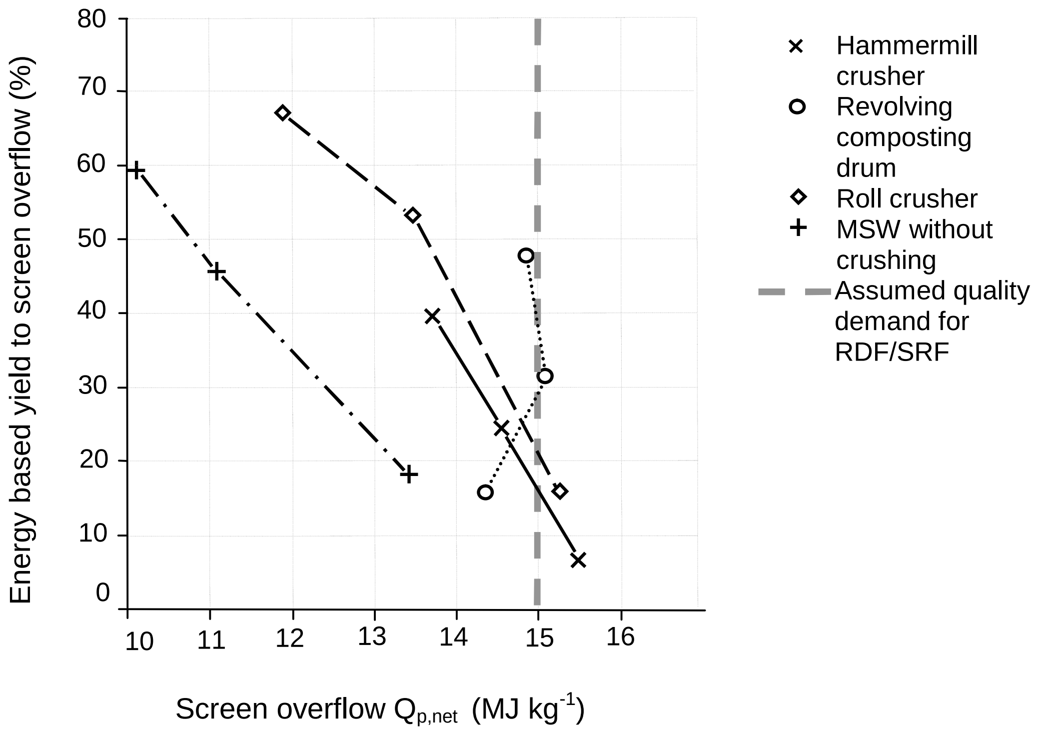


FIGURE 9 Effect of comminution and screening on the relationship of net calorific value $O_{p,net}$ and the energy based yield to the screen overflow, for different aperture sizes. Data points within each series from top to bottom correspond to the screen overflow product using 40, 80 and 150 mm apertures. Data form the MBT plant at Quarzbilchl, Germany. Redrawn from Soyez and Plickert[59]

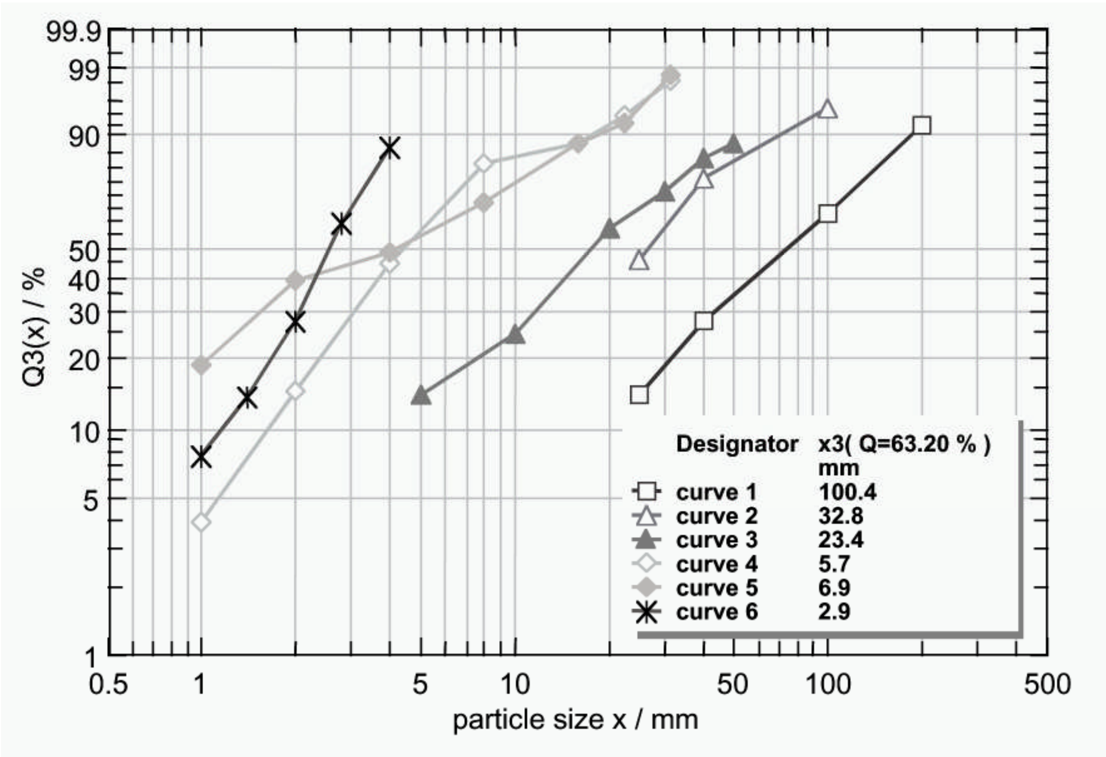


FIGURE 10 Cumulative mass fractions reporting at the screen undersize for various types of pre-treated domestic waste. Curves: (1) feed material; (2) comminution and drum screen at 100 mm; (4) and (5): ball-mill and 40 mm trommel underscreen; (6) ball mill-trommel and separation <5 mm organic-rich fraction. Characteristic particle size $d_{63.2}$ values are provided (63.2% ^{w}/w total mass smaller in size). From Koch et al.[145], with permission

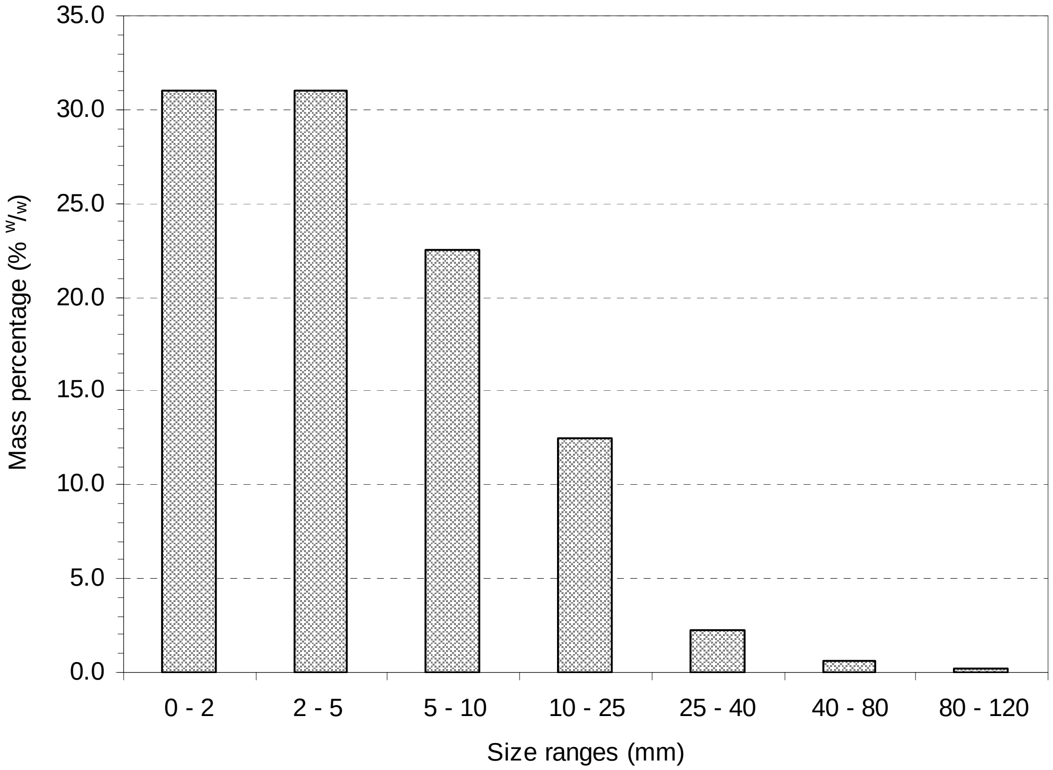


FIGURE 11 Histogram of cumulative mass of the organic fraction of German residual domestic waste after comminution in a Loesche-Hese cascade mill. Data from Koch et al.[106]

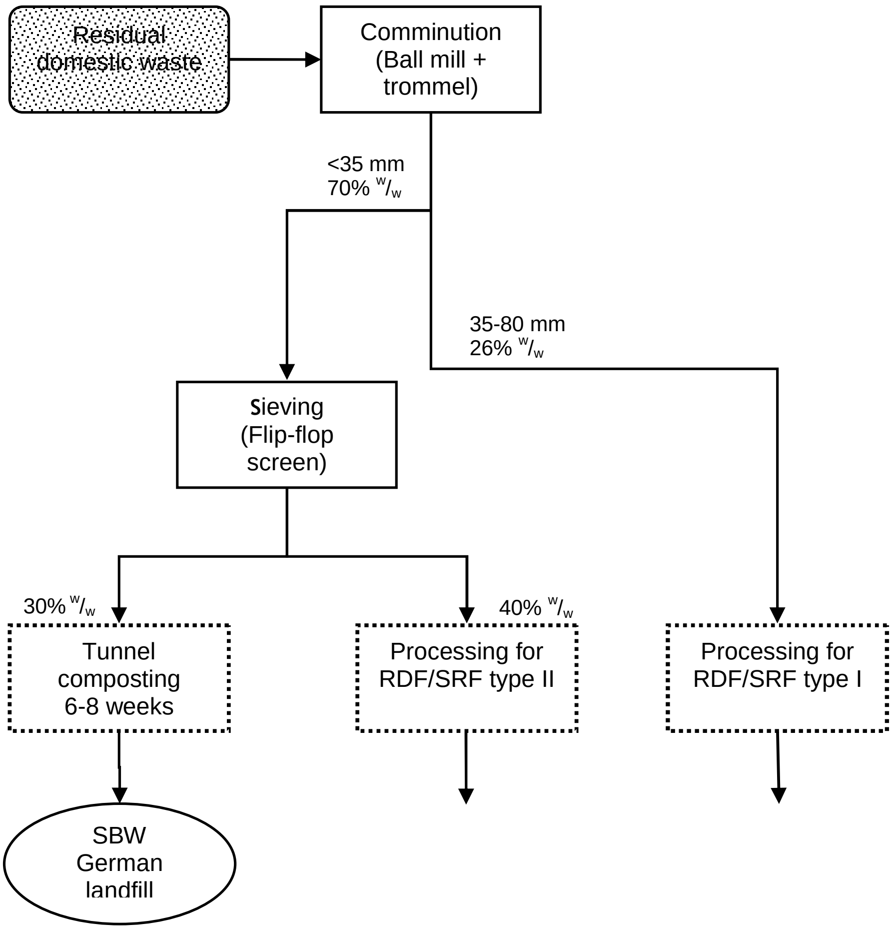


FIGURE 12 Mass balance for MBT process using Hese ball mill with flanged trommel.

SWB: stabilised bio-waste. For legend refer to FIGURE 8. Data form Koch[109]

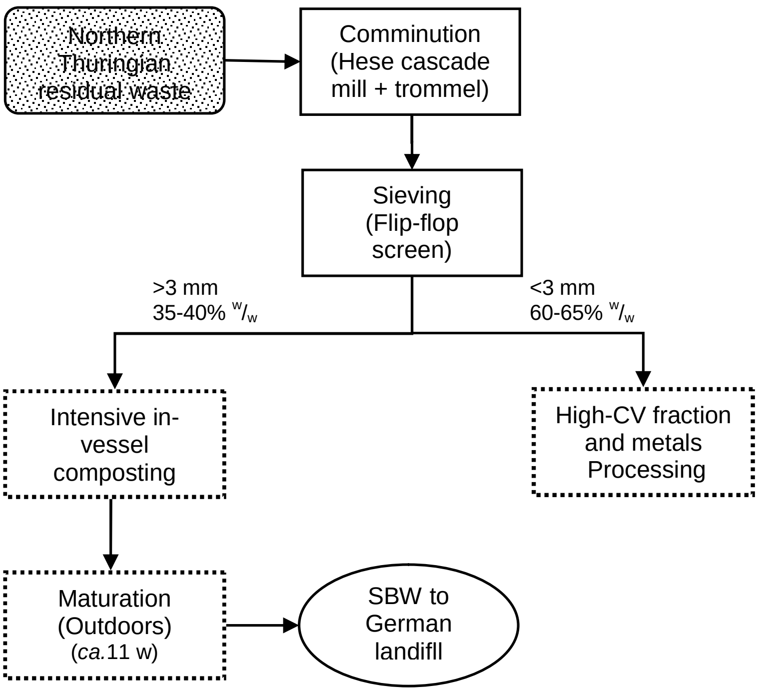


FIGURE 13 Mass balance data from the Brandenburg Recycling Park, using a Hese ball mill. SWB: stabilised bio-waste. For legend refer to FIGURE 8. Data from Schade-Dannewitz[108]

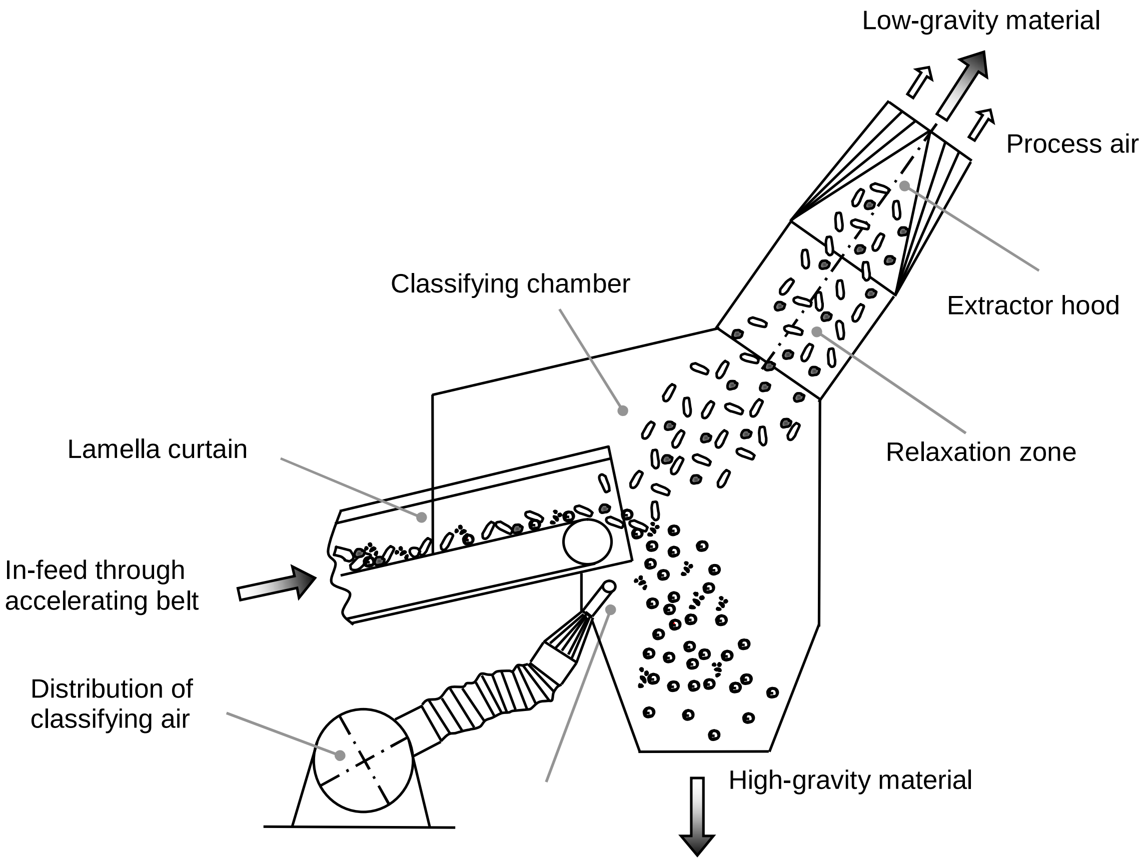


FIGURE 14 Schematic diagram showing the operating principle of a cross-flow air separator with pneumatic transport of the low-gravity material. Redrawn from Timmel[65]

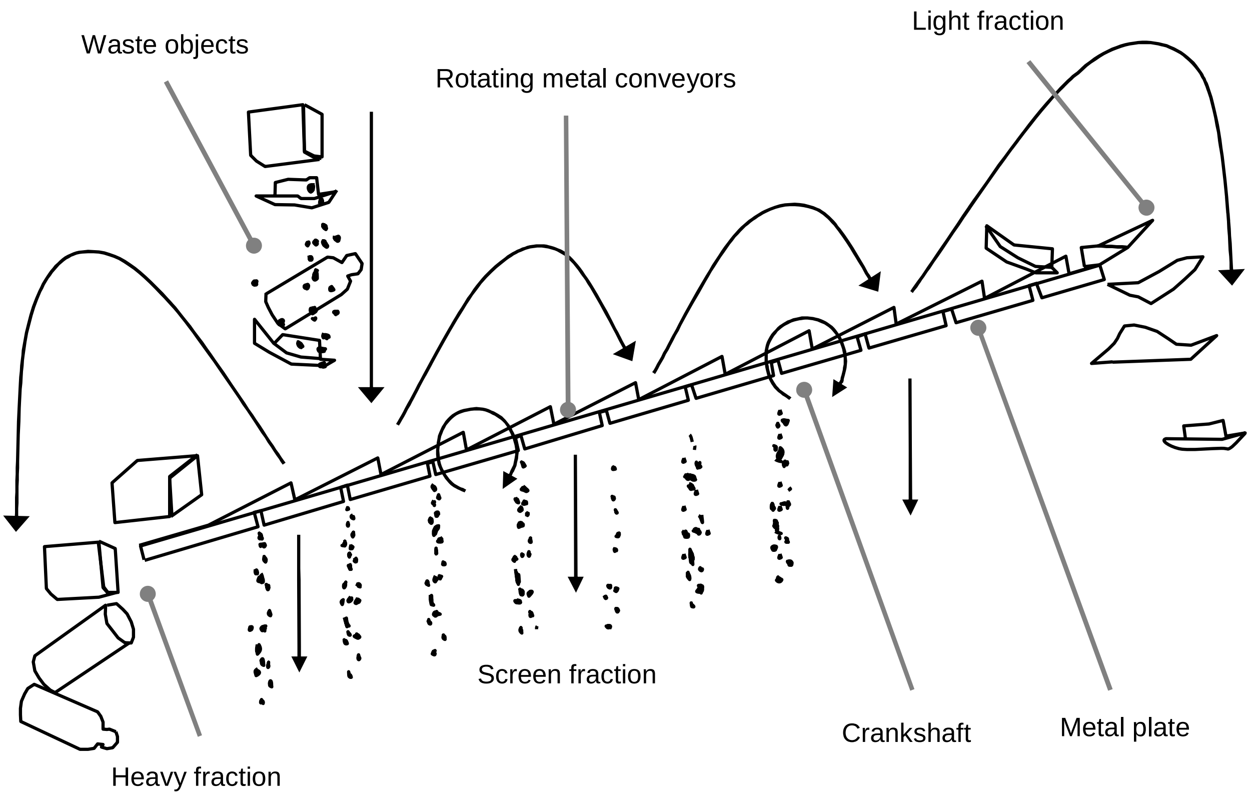


FIGURE 15 Schematic diagram showing the operating principle of a ballistic separator: (1) waste objects drop onto conveyor; (2) rotating metal conveyors follow an eccentric circular movement; (3) light fraction is carried upwards: e.g. paper, corrugated cardboard, plastic sheets and bags (4) heavy fraction rolls down: e.g. bottles, metals, hard plastics; (5) screen fraction falls through: e.g. sand, discarded food. Adapted from Mitsubishi Rayon Engineering[161]

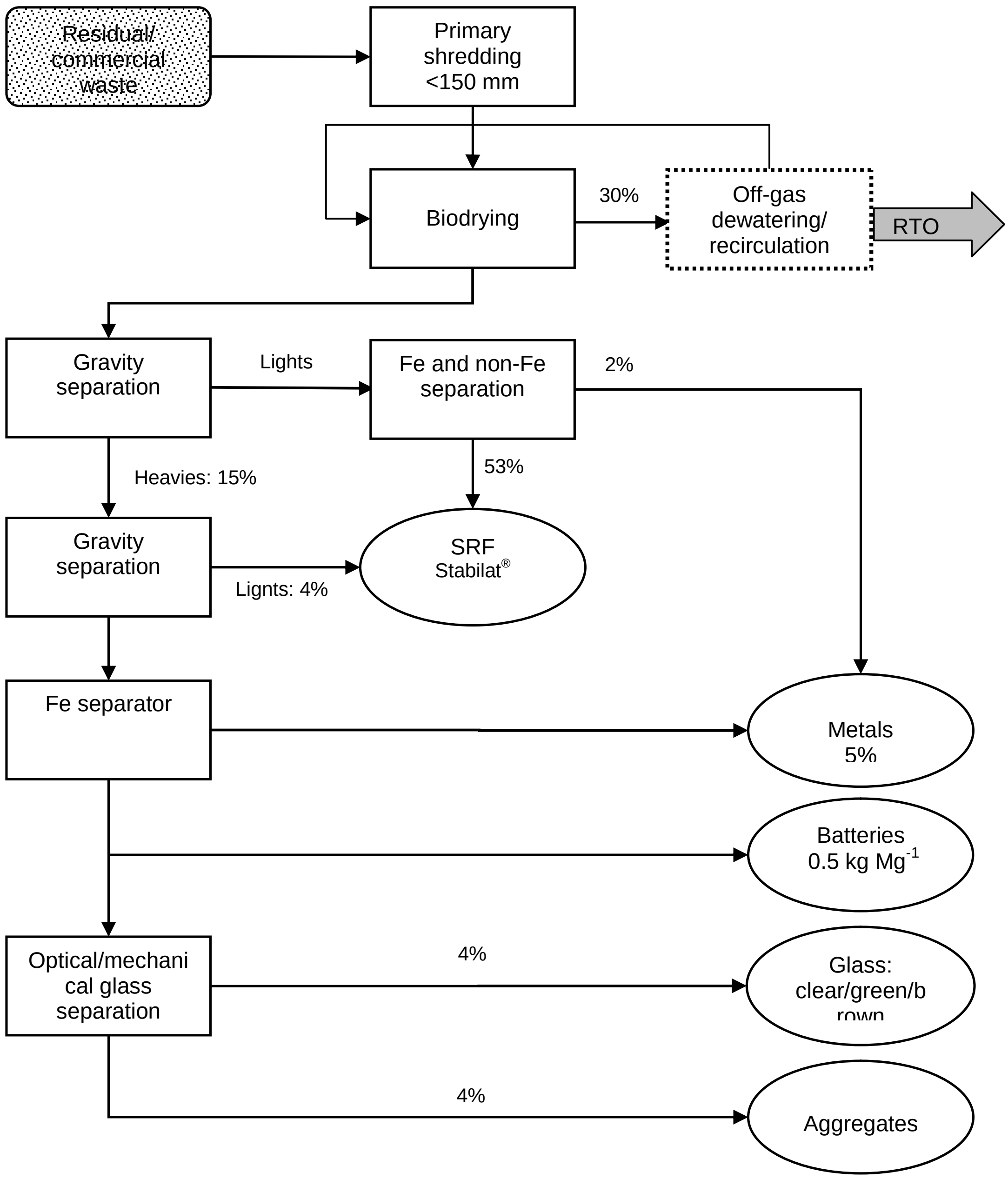


FIGURE 16 Simplified flow-chart and indicative mass balance of the Herhof biodrying MBT plant at the Rennerod and Asslar sites. RTO: regenerative thermal oxidation. For legend refer to FIGURE 8**.** Adapted from Diaz et al.[232]

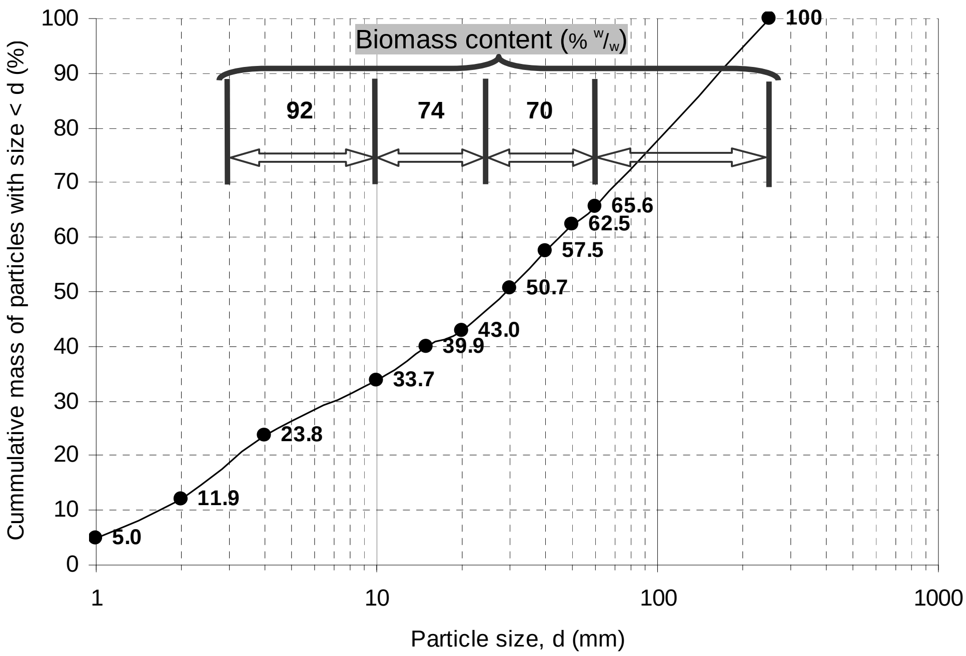


FIGURE 17 Particle-size distribution by sieve analysis of Herhof SRF (Stabilat®). Fractions with particle size lower than 60 mm exhibit high biomass content. Redrawn from Wengenroth[168]

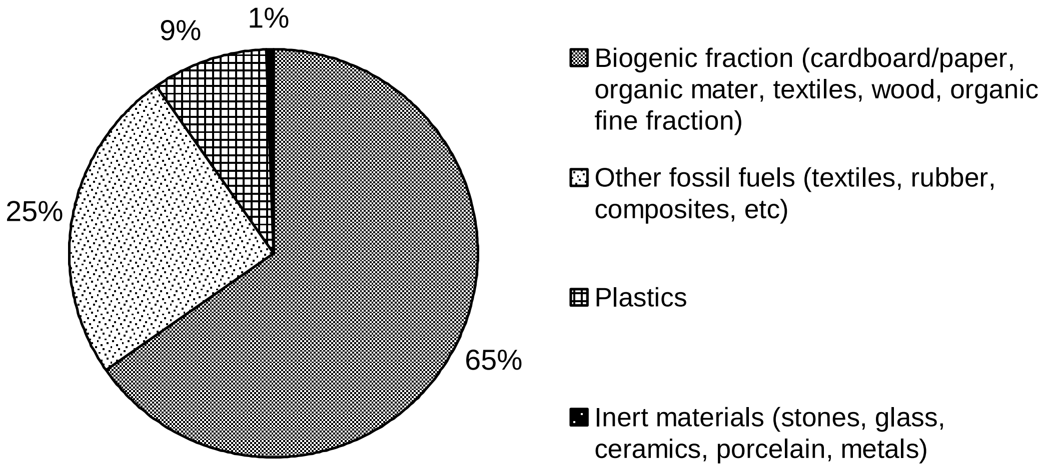


FIGURE 18 Composition of Herhof SRF (Stabilat®). Data from Herhof Environmental[218]

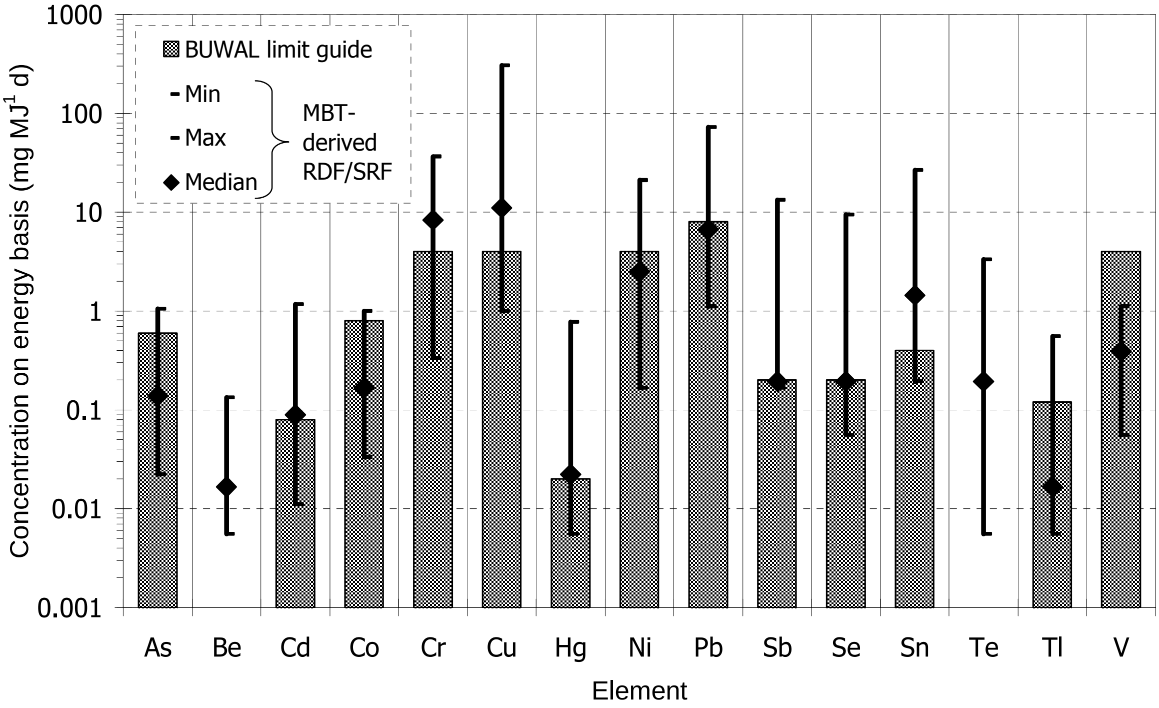


FIGURE 19 Energy-based concentrations of trace elements in RDF produced in early MBT plants, presented on logarithmic scale. Comparison with the 1998 limit guidance concentrations of the Swiss Agency for the Environment, Forrest and Landscape (BUWAL). A $Q_{p,net}$ of 18 MJ kg^{-1} has been assumed to convert values from mass basis to energy basis. Redrawn from Rotter et al.[49]

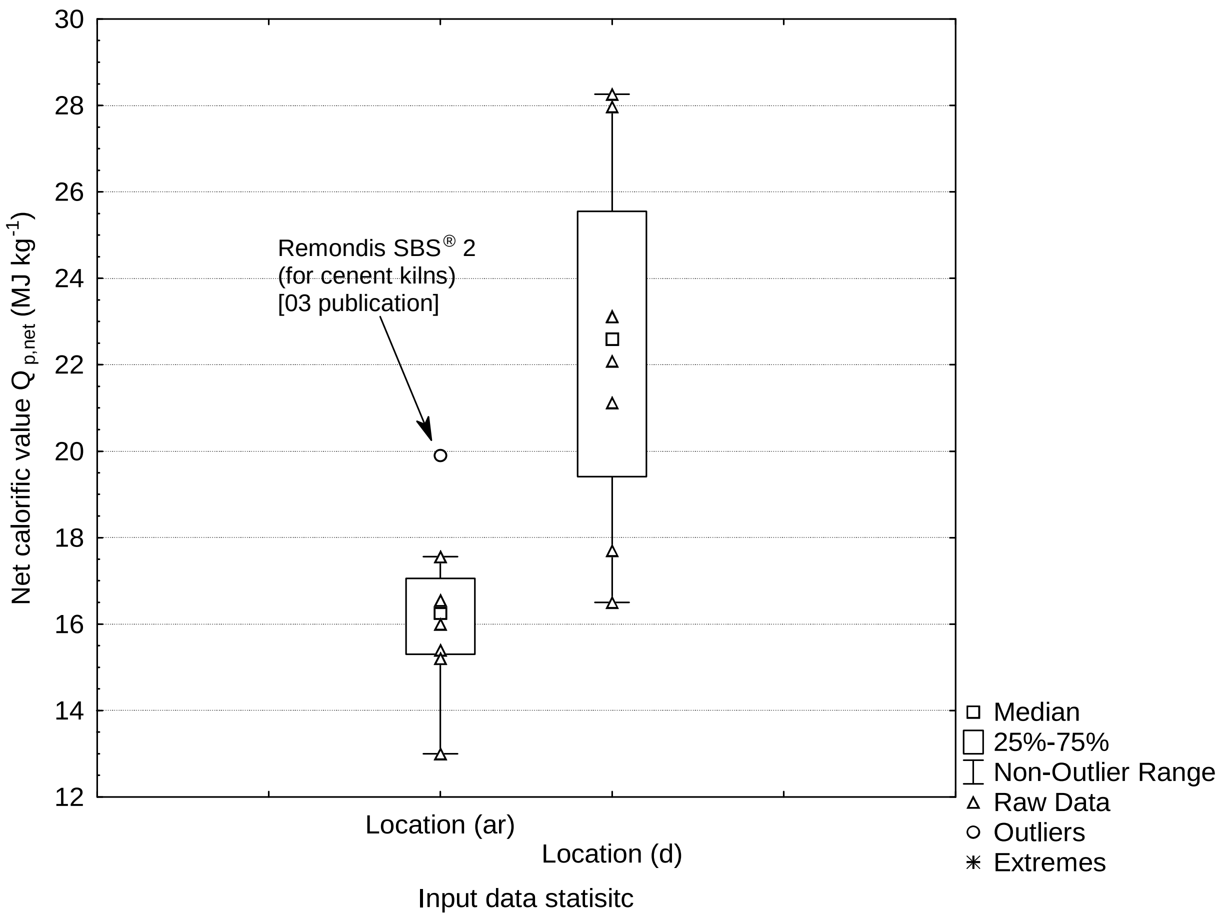


FIGURE 20 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of the of location values of net calorific value $Q_{p,net}$, expressed on an as received (ar) and dry (d) basis. Box-plot conventions: (1): lower and upper lines of the boxes denote the 25th and 75th percentiles; (2) lower outlier limit and upper outlier denoted by whiskers define the non-outlier range, i.e. range of values that defined as is the range of values that do not differ form the median more than the 25th or 75th percentile plus 1.5 times the interquartile range (height of box) (3) extreme values, presented as asterisks, exceed the 75th percentile plus 3 times the interquartile range.

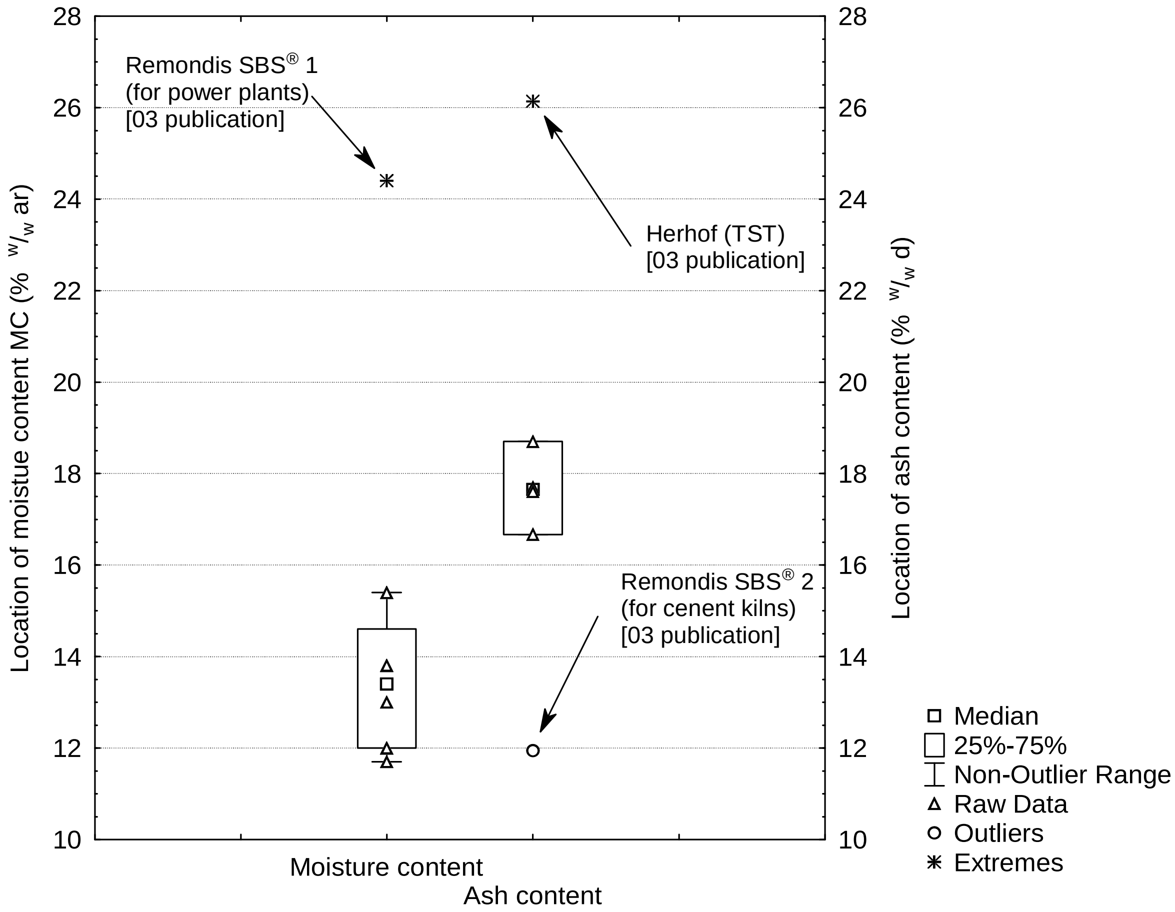


FIGURE 21 Results of descriptive statistical analysis on MBT-derived SRF data: 1. Location values of moisture content MC expressed on an as received basis (ar); and 2. Location values of ash content expressed on a dry basis (d). For box-plot conventions see FIGURE 20.

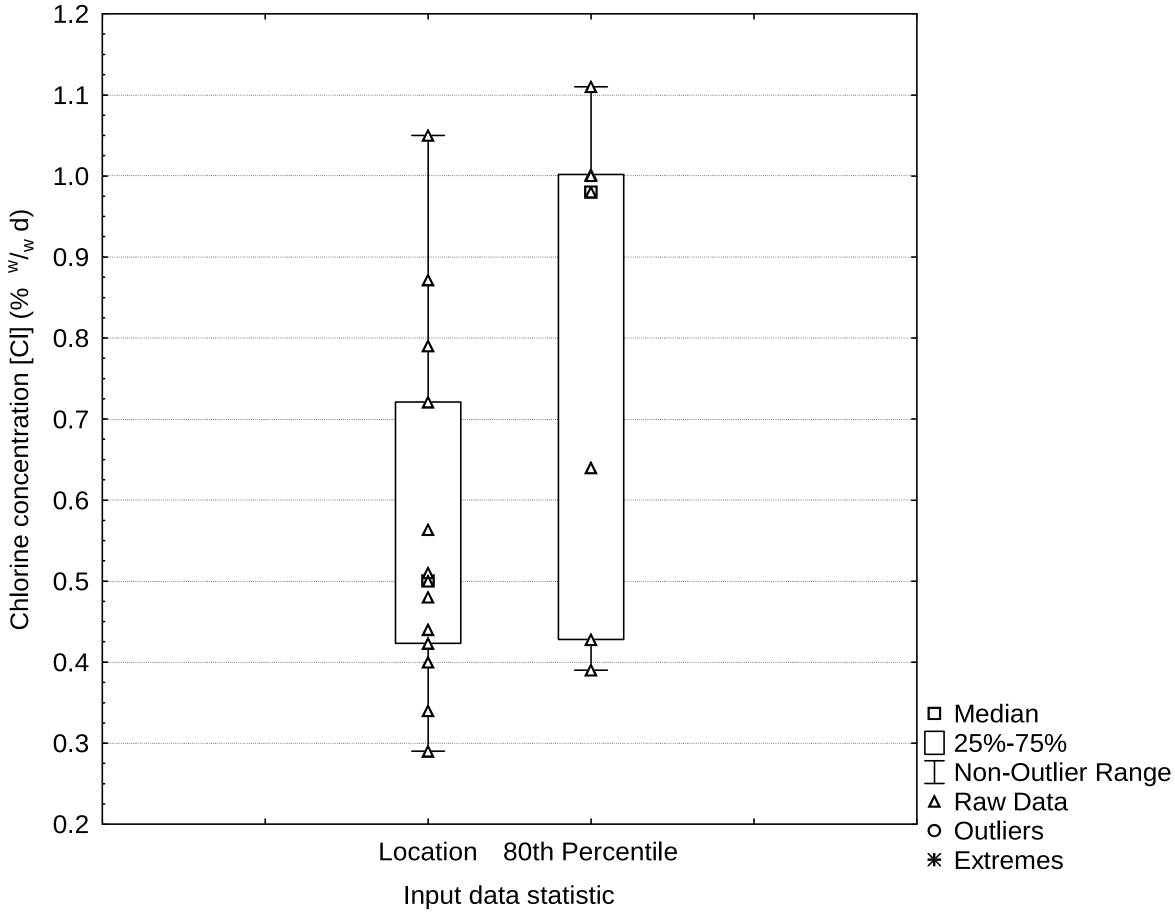


FIGURE 22 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location and 80th percentile values of chlorine concentration [Cl], expressed on a dry basis (d). For box-plot conventions see FIGURE 20.

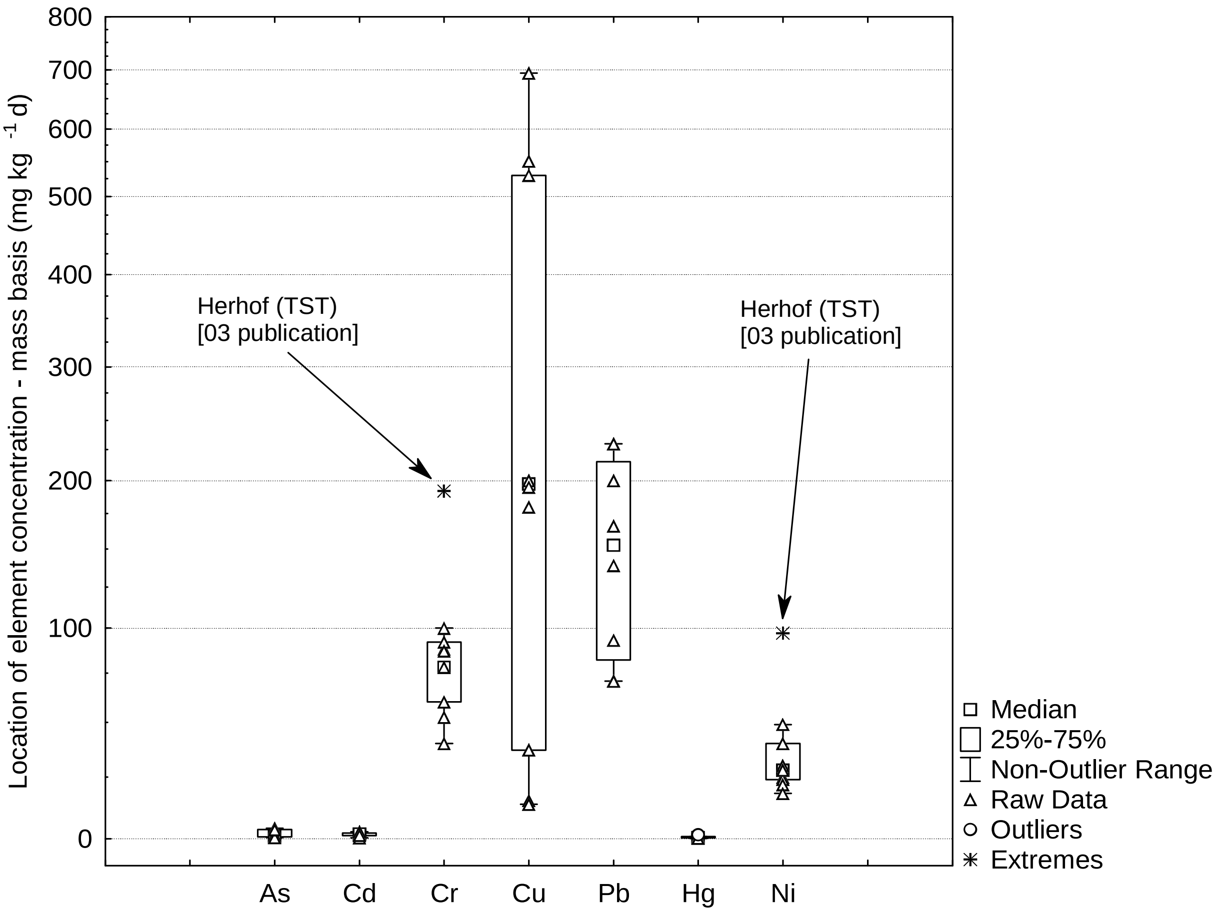


FIGURE 23 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location of concentration of trace elements, expressed on a dry basis (d). The As, Cd and Hg are further compared in FIGURE 24 using a suitable axis scale. For box-plot conventions see FIGURE 20.

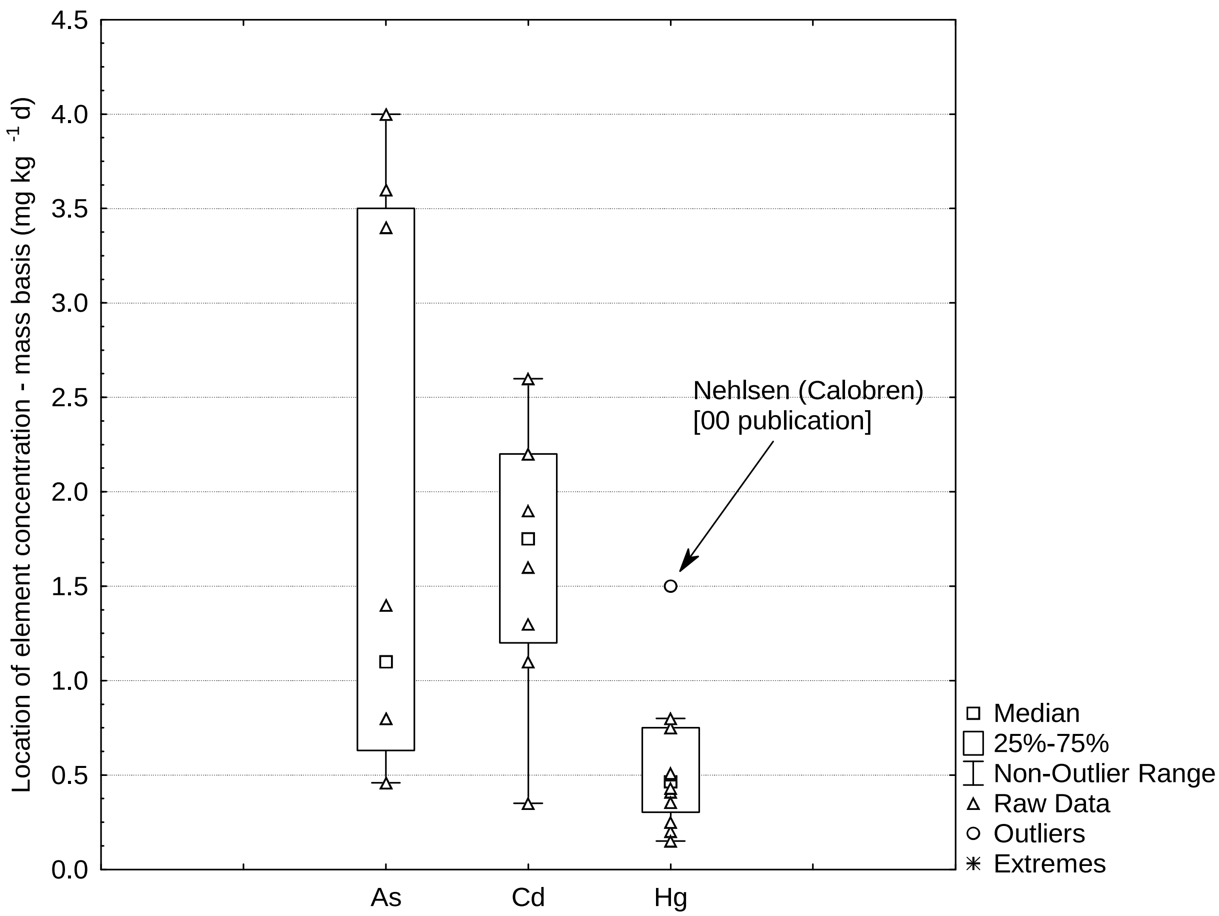


FIGURE 24 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location of concentration of certain trace elements, expressed on a dry basis (d). See FIGURE 23 for comparison with more elements. For box-plot conventions see FIGURE 20.

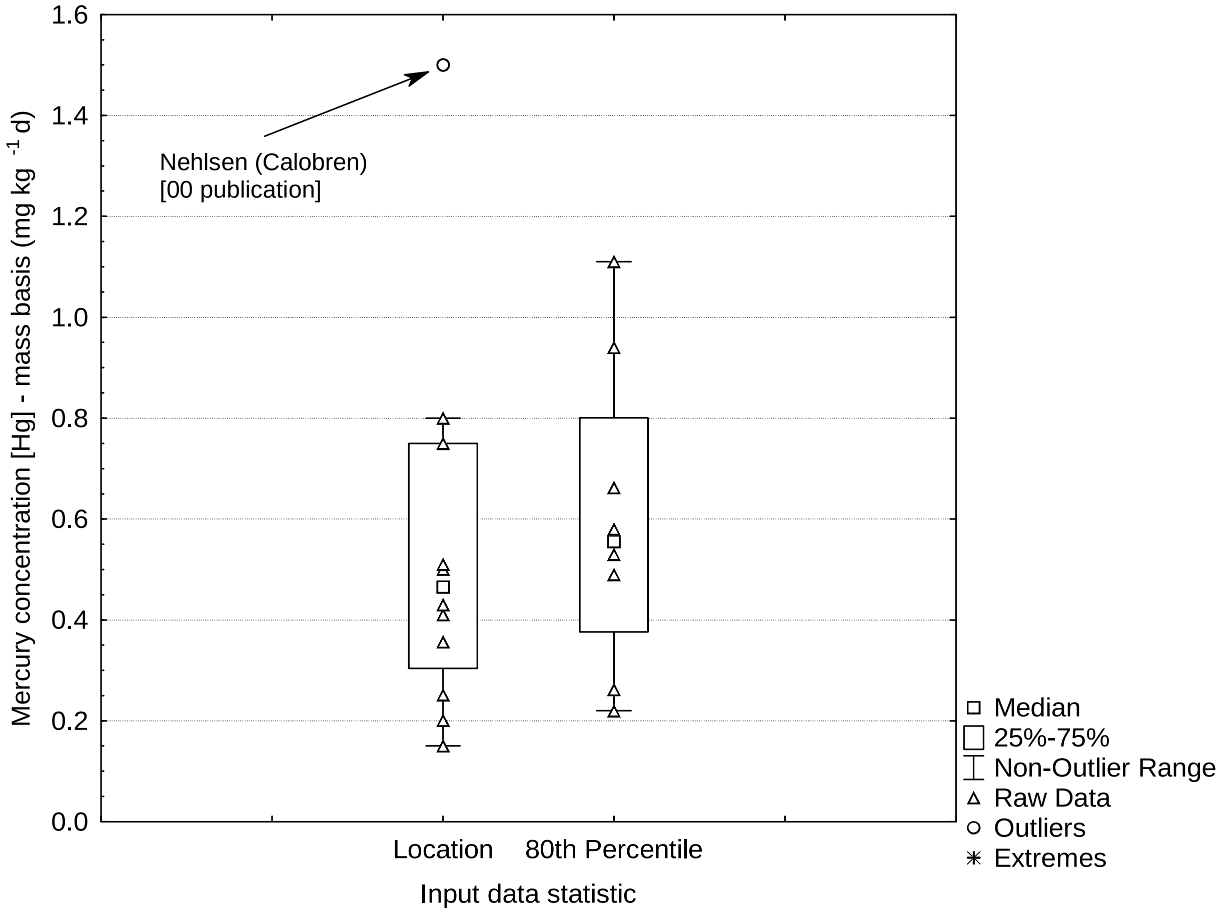


FIGURE 25 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location and 80th percentile values of mass-based mercury concentration [Hg], expressed on a dry basis (d). For box-plot conventions see FIGURE 20.

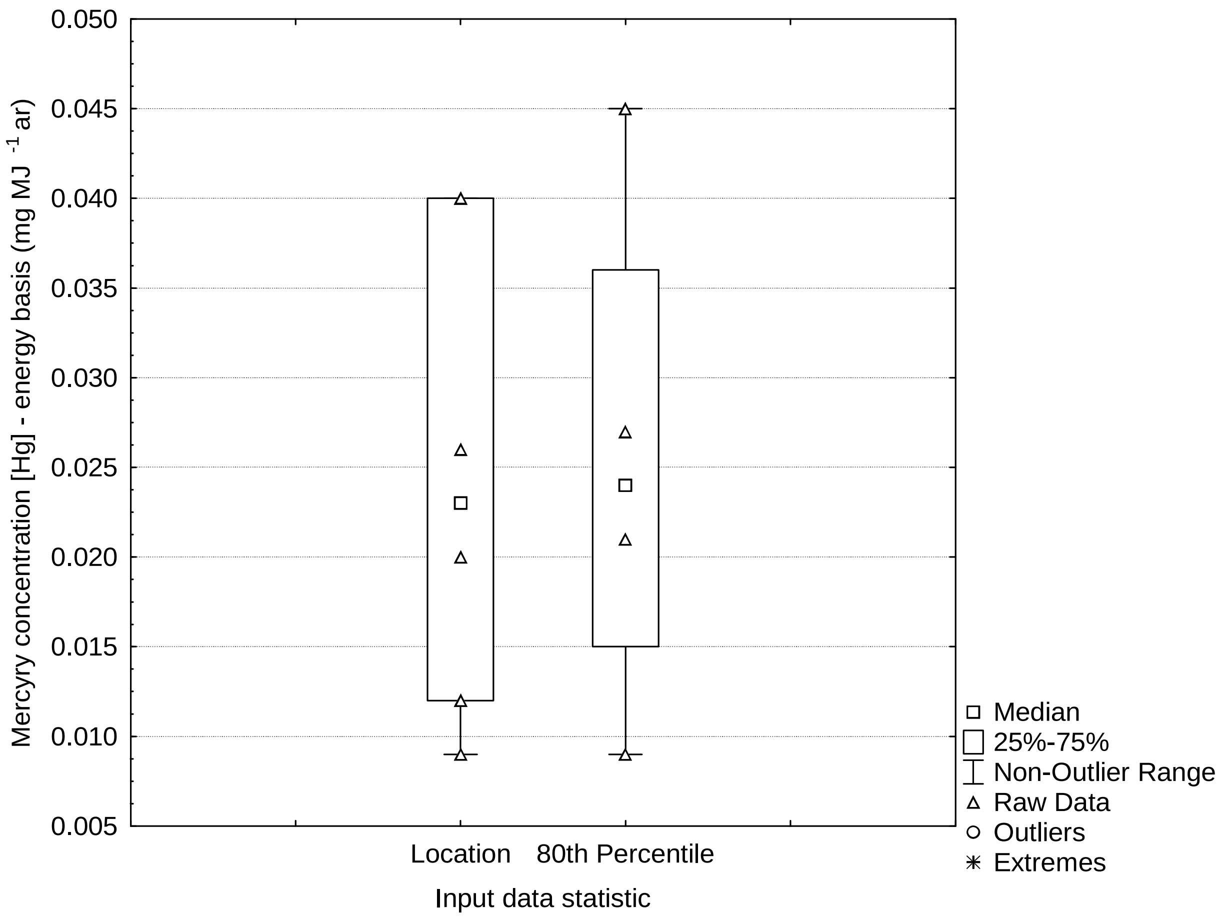


FIGURE 26 Results of descriptive statistical analysis on MBT-derived SRF data: comparison of location and 80th percentile values of energy-based mercury concentration [Hg], expressed on an as received basis (ar). For box-plot conventions see FIGURE 20.

TABLES

TABLE 1 Main bioconversion reactors commonly used in MBT plants

Main bioconversion reactor	Sub-category	Description
Aerobic composting	Tunnel	Long enclosed chambers, operated as either continuous or batch flow, some with mechanical agitation
	In-vessel/enclosed halls	Materials are composted on the floor of an enclosed building (hall), usually contained in long beds, i.e. windrows or series of parallel bays or tunnels
	Continuously agitated bays	Rows of long rectangular beds where material is enclosed between two walls and is continuously agitated by turning machines – continuous flow
	Maturation	Maturation stage, usually without aeration or agitation
Biodrying		Use of heat released during aerobic decomposition, supported by controlled aeration, to dry and partially biostabilise waste
Percolation		Washing with water within a reactor to transfer organic material into the liquid phase
Anaerobic digestion	Wet single-stage mesophilic	Use of anaerobic fermentation reactors, operated in a variety of modes
	Wet single-stage thermophilic	
	Dry single-stage mesophilic	
	Wet multi-stage mesophilic	
	Wet multi-stage thermophilic	

Adapted from: The Composting Association[60], Enviros[13], and Juniper[5]

TABLE 2 Potential outputs and uses for MBT processes

Type of output	Application
Compost-like outputs (CLO)	Food crops
(Soil conditioners, low-grade soil	Forestry
improver, etc)	Energy crops
	Improve soil structure and moisture retention in arid areas of poor soil quality
	Pasture land
	Horticultural applications
	Domestic gardens
	Verges and amenity land
	Landscaping during road construction and similar civil engineering projects
	Brown-field sites (contaminated land)
Waste-derived fuel (WDF)	Co-fuel for direct combustion in power plants (various technologies
Refuse derived fuel (RDF)	e.g. with pulverised fuel, fluidised bed, grate firing, etc)
Solid recovered fuel (SRF)	Fuel for indirect thermal recovery trough gasification and/or pyrolysis
Plastic-rich fraction	for use in power plants
	Co-fuel in bonding agent industries (e.g. cement kilns, lime and gypsum production, asphalt mixing, etc)
	Co-fuel in industrial boilers (e.g. iron and steel, paper industries)
	Fuel for a dedicated incinerator (e.g. fluidised bed)
	Fuel for a dedicated gasification/pyrolysis facility
	Co-fuel for an existing incinerator
Biogas applications	Produce electricity (and heat)
	Blend with landfill gas and/or syngas from waste gasification
	Produce a transportable fuel
Output intended for disposal options	Landfill daily cover
	Biostabilised residue, suitable for depositing in landfills
	Landfill cap
Digestate (liquor as fertiliser)	Liquid fertiliser
Liquor from dewatered digestate	Liquid fertiliser
Fibrous dewatered digestate	Potential as bulking agent or fuel
Ferrous metal	Secondary raw material
Non-ferrous metal (aluminium)	Secondary raw material
Aggregates	Construction and land-filling
Glass	Secondary raw material
Textiles, paper and light plastics	Potential as secondary material

Adapted from: Juniper[5], and Beckmann et al.[45]

[*] Unclear if it constitutes disposal or recycling by on-land application

TABLE 3 Indicative mechanical equipment currently used in MBT plants

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

Source of information: Juniper[5]

TABLE 4 General features and typical values of comminution equipment

Equipment	Rotation speed	Power	Through-put	Material processed	Output size
Hammermill shredder	700-3000 rpm	500-700 kW	20-30 t h^{-1}	Versatile, clay to leather or steel, can process very low density material	Pulverised
Rotary shear/shear shredder	60-190 rpm	100-800 kW		Tyres, refuse bags, bulky waste	25-250 mm
Flail mill				Card and paper	Coarse
Cascade/ball mill	*ca*. 10 rpm			Mixed and residual MSW	Coarse (35-80 mm) *
					Fine (<35 mm) *

Source of information: Tchobanoglous and Kreith [94], Pretz and Onasch[48], and Enviros[13]
* Ball mill coupled with trommel

TABLE 5 Indicative classification/separation equipment used in MBT plants

Processing type	Equipment	Operating principle
(Size) classification	Trommel (Drum sieve, Drum screen)	Tabular rotating screen, inclined slightly downwards, lifters help lift materials up
	Disc screens	Horizontal rotating bars across the screen, perpendicular to the material flow carry the material and bounce it into the air
Separation	Air classifiers *	Material is fed into a horizontal air stream: lighter is carried further/up and denser drops, based on density and aerodynamic properties. Advanced designs try to use mainly density properties or to include others, such as elastic
	Ballistic separators	Waste is fed to the middle of sloped vibratory screen, with under-flowing air stream that fluidises the bed: lights flow and heavies are transported by the vibrations, based on density and elasticity
Metal separation (Fe and non-Fe)	Magnetic separation of ferrous metals	Magnetic drums, over-band magnets and head pulleys are available. Magnets are either permanent or electromagnetic
	Eddy-current separation of non-ferrous metals	Application of electric field separates conductive from non-conductive materials. Systems with centric design are prevalent – systems with eccentric pole design are also available
Optical separation	Image detection devices	Picture analysis by sophisticated cameras and software
	Near-infrared detection (NIR) devices	Fast scanning spectrometer analyses identifies molecular structure; air nozzles blow selected items into bunkers; it enables separation based on chemical composition
	X-ray detection	Operates with transmission of X-rays: can distinguish between organic and inorganic materials (e.g. plastics and stones) and between light and heavy metals (e.g. Al and Cu)

Source of information: Tchobanoglous and Kreith[94], Pretz and Onasch[48], Enviros[13], and Kohaupt[112]
* Refer to TABLE 8 for detailed coverage

TABLE 6 Descriptors and formulas for the characterisation of the mechanical processing performance

Performance descriptor	Designation	Formula	Comments/references
Yield (mass basis) [of a product P_l]	$Y_m(P_l)$ or $Y(P_l)$	$Y\left(P_l\right)=\frac{m_{P_l}}{\sum_j m_{I_j}}$	mP_l : total mass of product P_1 mI : total mass of the input $\sum_i Y\left(P_i\right)=1$
Yield (energy basis) [of a product P_l]	$Y_e(P_l)$	$Y_e(P_l)=\frac{m_{P_l}\cdot LHV_{P_l}}{\sum_j m_{I_j}\cdot LHV_{I_j}}$	
Purity (or cleanness) [of product P_l in certain waste component(s) (CM)]	$C(CM)P_l$	$C(CM)_{P_l}=\frac{m(CM)_{P_l}}{m_{P_l}}$	$m(CM)P_l$: mass of a particular waste component (or set of components) (CM) in product P_l; mP_l : total mass of product P_1 $\sum_{(CM)} m(CM)_{P_l}=m_{P_l}$
Recovery [of a waste component (or set of components) (CM) into a product P_l]	$R(CM)P_l$	$R\left(CM\right)_{P_l}=\frac{m_{P_l}\cdot C(CM)_{P_l}}{\sum_j m_{I_j}\cdot C(CM)_{I_j}}$	$\sum_j m_{I_j}\cdot C(CM)_{I_j}=\sum_i m_{P_i}\cdot C(CM)_{P_i}$
Recovery [typical case of: one input I, two products (P_{CM} and P_{NCM}) and two sets of components (CM) and other-than-CM (NCM)	$R(CM)P_{CM}$	$R(CM)_{P_{CM}}=\frac{m_{P_{CM}}\cdot C(CM)_{P_{CM}}}{m_I\cdot C(CM)_I}=\frac{\left[C(CM)_I-C(CM)_{P_{NCM}}\right]\cdot C(CM)_{P_{CM}}}{\left[C(CM)_{P_{CM}}-C(CM)_{P_{NCM}}\right]\cdot C(CM)_I}$	

Performance descriptor	Designation	Formula	Comments/references
Total effectiveness [according to Rietema[113]]	E	$E(CM,NCM)_{I,P_{CM},P_{NCM}} = \left\| \frac{m_{P_{CM}} \cdot C(CM)_{P_{CM}}}{m_I \cdot C(CM)_I} - \frac{m_{P_{CM}} \cdot C(NCM)_{P_{CM}}}{m_I \cdot C(NCM)_I} \right\|$ $E(CM,NCM)_{I,P_{CM},P_{NCM}} = \left\| \frac{m_{P_{NCM}} \cdot C(CM)_{P_{NCM}}}{m_I \cdot C(CM)_I} - \frac{m_{P_{NCM}} \cdot C(NCM)_{P_{NCM}}}{m_I \cdot C(NCM)_I} \right\|$	Single overall performance descriptor. Satisfies the full list of the requirements proposed by Rietema[113]. Note that no single parameter can describe all performance aspects of a mechanical unit operation.
Total effectiveness [according to Worrell and Vesilind[115]]	E	$E(CM,NCM)_{I,P_{CM},P_{NCM}} = \left[\frac{m_{P_{CM}} \cdot C(CM)_{P_{CM}}}{m_I \cdot C(CM)_I} \cdot \frac{m_{P_{CM}} \cdot C(NCM)_{P_{CM}}}{mI \cdot C(NCM)_I} \right]^{1/2}$	Single overall performance descriptor. Not verified if it satisfies the full list of the requirements proposed by Rietema[113]. Note that no single parameter can describe all performance aspects of a mechanical unit operation.
Transfer coefficient (or transfer factor) [of substance (s) to product P_l]	$TC(s)P_l$	$TC(s)_{P_l} = \frac{m_{P_l} \cdot c_m(s)_{P_l}}{\sum_j m_{I_j} \cdot c_m(s)_{I_j}}$ and $TC(s)_{P_l} = \frac{c_m(s)_{P_l} \cdot m_{P_l}}{c_m(s)_I \cdot m_I} = MEC_m(s)_{P_l} \cdot Y_m(P_l)$	$\sum_i TC(s)_{Pi} = 1$
Material enrichment coefficient (mass basis) [of substance (s) from input I_j to the product P_l]	$MEC_m(s)P_lI_j$	$MEC_m(s)_{P_l,I_j} = \frac{c_m(s)_{P_l}}{c_m(s)_{I_j}}$	Concentrating, enrichment, MEC>1 Diluted, depletion, MEC<1
Material enrichment coefficient (energy basis) [of substance (s) from input I_j to the	$MEC_e(s)P_lI_j$	$MEC_e(s)_{P_l,I_j} = \frac{c_e(s)_{P_l}}{c_e(s)_{I_j}} = \frac{c_m(s)_{P_l} / LHV_{P_l}}{c_m(s)_{I_j} / LHV_{I_j}}$	$c_e = \frac{c_m}{LHV}$

Performance descriptor	Designation	Formula	Comments/references
product P_l]			
Grade efficiency (or selectivity) [of a narrow size range d_{NF} (portion of waste particulates of given size range) into a product P_l]	$G(d_{NF})P_l$	$G\left(d_{NF}\right)_{P_l} = \frac{m(d_{NF})_{P_l}}{\sum_j m(d_{NF})_{I_j}}$	Klumpar[114] Schweitzer[119]
Sharpness of cut [of a grade efficiency curve]	$k_{25/75}$	$k_{25/75} = \frac{d(G=25\%)}{d(G=75\%)}$	Klumpar[114] Wang et al.[120] Other percentages may be prove more relevant in a waste management application context

Table notation	Symbol	Description
Main symbols	*c*	Concentration of substance: i.e. c_m(s) mass based concentration of substance s
	C	Purity: mass fraction of waste component (or collection of components), i.e:
	E	*C*(S) or *C*(B)
	G	Total effectiveness
	k	Grade efficiency (or selectivity)
	m	Sharpness of cut (of a grade efficiency curve)
	MEC	Mass or mass flow rate
	R	Material enrichment coefficient
	TC	Recovery
	Y	Transfer coefficient (or transfer factor)
	LHV	Yield
		Lower heating value
Stream symbols	B	Combustible waste components
	CM	Component (or collection of components) in a stream: e.g. S or B
	I	Input stream
	NCM	Set of components other-than-CM
	NF	Narrow range fraction (portion of waste particulates that fall within a defined
	P	size range)
	s	Product (output stream)
	S	Substance (according to the definition of MFA, an element or chemical

Performance descriptor	Designation	Formula	Comments/references
		compound that is preserved through a process)	
		Waste component (or collection of components) containing substances of concern	
Indices	e	Energy basis of ratios	
	i	Running index of product stream	
	j	Running index of input stream	
	l	A certain product, a value of i	
	m	Mass basis of ratios	

Adapted from: Rotter et al.[49]

TABLE 7 Results on material flow management performance of size classification; overflow product stream intended to concentrate components suitable for RDF/SRF production in MBT plants

		Overflow product (OF)			Underflow product (UF)	
Set of waste components (CM)	In-feed material composition C(CM)I (% $^{w}/_{w}$)	Yield to overflow product $Y(P_{OF})$ (% $^{w}/_{w}$ unit operation input)	Recovery of CM to OF $R(CM)P_{OF}$ (% $^{w}/_{w}$)	Purity of OF in CM $C(CM)P_{OF}$ (% $^{w}/_{w}$)	Recovery of CM to UF $R(CM)P_{UF}$ (% $^{w}/_{w}$)	Purity of UF in CM $C(CM)P_{OF}$ (% $^{w}/_{w}$)
Unit operation input		64 (56 % $^{w}/_{w}$ plant input) [a,*] n.r. (47 % $^{w}/_{w}$ plant input) [a,**] 28.3 [b] n.r. (36 % $^{w}/_{w}$ plant input) [c,***] n.r. (26 % $^{w}/_{w}$ plant input) [c,†] n.r. (26+40 % $^{w}/_{w}$ plant input) [c,††] 61 [d]				
Paper	23.6 [d]	80 [d]			80 [e]	
Paper and card				15.1 [f] 34.56 [g,†††] 39.98 [g,*†] 24.93 [g,*†*]		5.5 [f] 8.08 [g,†††] 7.08 [g,*†] 8.56 [g,*†*]
Plastics - body				6.6 [f]		1.3 [f]

Set of waste components (CM)	In-feed material composition	Overflow product (OF)			Underflow product (UF)	
		Yield to overflow product	Recovery of CM to OF	Purity of OF in CM	Recovery of CM to UF	Purity of UF in CM
	C(CM)I	*Y*(P_{OF})	*R*(CM)P_{OF}	*C*(CM)P_{OF}	*R*(CM)P_{UF}	*C*(CM)P_{OF}
	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)
shaped						
Plastics - foil shaped				8.9 [f]		2.0 [f]
Plastics	3.6 [d]	61 [d]	8-10 [h]		33 [e]	
Ferrous metals	4.5 [d]	39 [d]		4.9 [f]		1.8 [f]
Non-ferrous metals	0.4 [d]	0 [d]		0.5 [f]		0.5 [f]
Aluminium	0.3 [d]	8 [d]				
Ash						
Wood	5.7 [d]	78 [d]		5.2 [f]		1.1 [f]
Textiles	15.9 [d]	80 [d]		18.8 [f]	4 [e]	1.1 [f]
Diapers				22.5 [f]	80 [e]	2.9 [f]
Rubber	0.4 [d]	30.5 [d]				
Glass	18.5 [d]	1 [d]				
Stone	3.9 [d]	0 [d]				
Food	2.0 [d]	73.5 [d]				
Yard waste	5.6 [d]	11 [d]				
Organics				2.5 [f]		5.8 [f]
OFMSW				8.26 [g,†††]	97 [e]	24.01 [g,†††]
				5.22 [g,*†]		44.67 [g,*†]
				11.90 [g,*†*]		37.99 [g,*†*]
Fines	15.8 [d]	3 [d]				
Rest > 40 mm				15.0 [f]		6.7 [f]
Rest < 40 mm				0.0 [f]		71.1 [f]

[a] Rotter et al.[49]: All values % $^{w}/_{w}$ ar of initial input waste. Pilot scale testing. For residual, uncomminuted waste. Input after bulky item removal (1% $^{w}/_{w}$ input).
Relevant specific notes:
[*] Urban waste input: 56% suitable for SRF of plant input: removal upstream: 1% input bulky items and 7 % downstream metal separation
[**] Rural waste input: 47% suitable for SRF of plant input: removal upstream: 1% input bulky items and downstream metal separation
[b] Mueller et al.[152]: Drum screen at 100 mm, after hammermill comminution in the Linkenbach, aerobic stabilisation MBT plant treating residual domestic and commercial waste
[c] Koch[109]: MBT plant. SRF yields as % $^{w}/_{w}$ of plant input. Relevant specific notes:
[***] Plant configuration: pre-crushing, Fe and non-Fe metal separation, underflow <100 mm to biostabilisation by composting
[†] Plant configuration: as above, screening at 40 and 100 mm: +40-100 to composting biostabilisation, -40 fraction to AD

[††] Plant configuration (FIGURE 12): cascade mill flanged with trommel, flip-flop screening, underflow to tunnel composting with continuous agitation

[d] Hasselriis[61]: Non-MBT, historical data, shown for comparison purposes. All values d. MSW processed through a primary trommel, operated at nominal throughput at former Recovery I test plant, the US. Variation between runs was reported, maximum for the food, rubber, leather, textiles, wood and yard waste and lowest for fines (<6.4 mm), glass and stones. Paper and plastics showed low variation

[e] Koch[109]: Outukumpu-Hese cascade mill flanged with trommel two stage screening at 40 mm and 80 mm. Results for <40 mm undersize.

[f] Pretz and Onasch[48]: Drum screen at 60 mm, with squared holes, used for enrichment of OFMSW in the underflow and combustibles in the overflow. No information on composition of input and materials and methods of the research.

[g] Silvestri et al.[151]: Residual MSW Province of Trento, Italy, after source segregation of recyclables including kitchen and green waste with 42% effectiveness, affected by tourist activities. Comminution in hammermill and screening at 80 mm in trommel, with the objective of optimal concentration of the OFMSW in the underflow for subsequent aerobic stabilisation and direct landfill disposal of the overflow. Relevant specific notes:

[†††] Trento, treatment landfill site

[*†] Zuclo, treatment landfill site

[*†*] Iscle di Taio, treatment landfill site

[h] Koch[107]: MBT plant. Hammermill shredding followed by screening at 50 mm, overflow to RDF production, underflow to AD.

TABLE 8 Air separators (air classifiers) for SRF production in MBT plants

Type of air separator	Separation principle	In-feed type and flow line point applicable to	Particle size range (mm)	Materials separated	Air load (kg_{waste} m^{-3} classifying air)	Comments
Zig-zag classifier	Cascade, baffled-column of cross-flow separators	High CV fraction from residual waste	10-40	Low-gravity material is carried by the air current upwards and has then to be separated. High-gravity items repost to the chute downwards	0.4-2.0	Relatively well studied, proven effective for various cases, such as construction waste and cable scrap Relatively small maximum feed size, but good separating effectiveness In the high-gravity chute an air-knife can separate more streams [a] Other type of baffled-column classifiers are the stacked V-shaped [b]
Cone classifier	Multiple cross-flow separation	High CV fraction from bio-dried or thermally dried waste. (including re-sorting of the high-gravity material with pneumatic processing tables)	3-40		0.3-0.8	Relatively small maximum feed size Secondary air-classification can be added at each separation stage to increase the effectiveness

Cross-flow separators with pneumatic transport of the low-gravity material		High CV fraction separation: (1) relatively low CV requirement	60-110		0.2-1.0	Capable of separating bigger in-feed particles than cone and zig-zag separators and suitable for a more complex material mix
		High CV fraction separation: (2) relatively high CV requirement:	110-220			
		Pre-separation of high CV stream with subsequent re-sorting of the low gravity fraction and/or the low-gravity fraction	60-300			
Cross-flow separators without pneumatic transport of the low-gravity material		(1) Cleaning of metal fraction produced during residual waste processing (separation of entrained film, paper, and textile pieces) (2) Removal of films from the screen overflow of the first classifying stage (3) Production of high CV fraction from biodried waste,	 >200 Indicative ranges: 10-65 and 65-250 or 15-35 and 35-85	Rotating drum version (1) high-gravity material chute: high-gravity items fall directly into it; plus items like glass and ceramics that fall initially against the rotating drum and report to either chute depending on contact time. (2) Low-gravity materials (textiles, cardboard) are transported through the rotating drum.		Suitable for simple separation applications. For enhanced effectiveness a second downstream drum and blower nozzle can be applied to the intermediate-gravity material
Impact classifier	Cross-flow air separation with sorting based additionally on elastic behaviour of particles	High CV fraction form residual waste comminuted in semi-autogenous mill	3-40 or 40-80	(1) Low-gravity material fraction: directly report the low stationary settling rate items (e.g. plastic film, paper) and through a belt the high-gravity, medium stationary settling rate, soft, deformable items (e.g.	0.2-0.8	Increased effectiveness for low-gravity material separation *

				cardboard packaging and textiles) (2) High-gravity, medium stationary settling rate, hard, dimensionally stable particles (e.g. bricks, pieces of concrete) report to high-gravity material discharge	
Bench belt separator	Cross-flow air separation with sorting based additionally on elastic behaviour of particles.	High CV fraction form coarse residual waste fraction, low requirements for fuel product	60-300	(1) High-gravity material discharge: directly report the large pieces of waste of high density (e.g. sheet metal packing); and roll to it the compact pieces (e.g. stones)	n.r.
		High CV fraction from commercial waste	0-60	(2) Low-gravity material belt: deformable and/or flat pieces (e.g. drink cartons) and low terminal settling velocity items through the settling chamber	

Source of information, if not mentioned otherwise: Timmel[65]
[a] Hasselriis[61]
[b] Tchobanoglous and Kreith[94]
[*] Not stated if yield or purity
CV: calorific value
n.r.: not reported

TABLE 9 Results on material flow management performance of air classifiers (ACs); low-gravity product stream intended to concentrate components suitable for RDF/SRF production in MBT plants

		Low-gravity product (LG)			High-gravity product (HG)	
Set of waste components (CM)	In-feed material (I) composition C(CM)I (% $^{w}/_{w}$)	Yield to LG product $Y(P_{LG})$ (% $^{w}/_{w}$ unit operation input)	Recovery of CM to LG $R(CM)P_{LG}$ (% $^{w}/_{w}$)	Purity of LG in CM $C(CM)P_{LG}$ (% $^{w}/_{w}$)	Recovery of CM to HG $R(CM)P_{HG}$ (% $^{w}/_{w}$)	Purity of HG in CM $C(CM)P_{HG}$ (% $^{w}/_{w}$)
Unit operation input		>70 [a,*] 40 [b]				
Combustibles				60-99 [c]		
Paper			<1-99 [c]			
Paper and card	50.7 [d]		66.6 [d]	73.7 [d]		27.1 [a]
Plastics	11.8 [d]		85.2 [d] 1-65 [c]	11.8 [d]		1.5 [a]
Paper and plastics			85-99 [e]	55-80 [e]		
Ferrous metals	19.3 [d]		2-50 [e]	0.1-1 [e] 1.1 [d]	98.0 [d]	38.0 [d]
Non-ferrous metals	3.2 [d]		45-65 [e]	0.2-1 [e] 0.1 [d]	99.1 [d] 85-99 [c]	6.6 [d]
Fines			80-99 [e]	15-30 [e]		
Ash			45-85 [e]	10-35 [e]		
Wood	4.7 [d]		13.1 [d]	1.6 [d]		7.8 [d]
Textiles	14.7 [d]		32.2 [d]	11.6 [d]		17.8 [d]
Glass	0.4 [d]			0 [d]	100.0 [d]	0.7 [d]
Vegetable matter	0.8 [d]			0.1 [d]	90.0 [d]	0.5 [d]

[a] Pretz and Onasch[48]: General estimate for cross-flow ACs operated with partial air-recirculation (up to 30 %) and density of load <35 g m_{AIR}^{-3} h^{-1}. Related specific notes:
[*] Mainly: plastic foil, thin-body type plastics and dry paper.
[b] Rotter et al.[49]: All values % $^{w}/_{w}$ ar of initial input waste. Pilot scale testing. For residual, uncomminuted waste. Input after bulky item removal, screening at 30 mm and ferrous metal separation. Three-stage (30-80 mm; 80-150 mm; 150-200 mm) air-knife (knife plate and rotating drum) AC, urban waste.
[c] Vesilind[122]: Non-MBT, historical data, shown for comparison purposes. The non-ferrous metal is aluminium only. Varying in-feed properties and operating mode affect performance.
[d] Data from Flitton[159], cited in Porteous[67]: Non-MBT, historical data, shown for comparison purposes. Results on a conical rotating AC designed by Newell-Dunford Engineering. In-feed of overscreen product after screening at 25 mm of possibly comminuted commercial waste.
e Hasselriis[61]: Non-MBT, historical data, shown for comparison purposes. Review of seven commercial references in the US, of horizontal, vertical and vibratory inclined AC types, fed with varying mixed MSW. Generally operated to a typical range of air/solids ratio of 2-7. Values given as “typical” ranges, not statistically defined. No detailed description for the “fines” and “ash” set of components.

3980

TABLE 10 Results on material flow management performance of ballistic separation; low-gravity product stream intended to concentrate components suitable for RDF/SRF production in MBT plants

		Low-gravity product (LG)			High-gravity product (HG)			Screenings product (SRC)		
Set of waste components	In-feed material (I) composition	Yield to LG product	Recovery of CM to LG	Purity of LG in CM	Yield to HG product	Recovery of CM to HG	Purity of HG in CM	Yield to SRC product	Recovery of CM to SCR	Purity of SRC in CM
(CM)	C(CM)I	Y(P_{LG})	R(CM)P_{LG}	C(CM)P_{LG}	Y(P_{HG})	R(CM)P_{HG}	C(CM)P_{HG}	Y(P_{SRC})	R(CM)P_{SCR}	C(CM)P_{SCR}
or property	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)
Overall input		76.9 [a] 31.8 [b] 36.4 [c] *ca*. 45 [e] *ca*. 45 [d]			13.1 [a] 6.4 [b] 11.5 [c]			10.0 [a] 61.8 [b] 52.2 [c]		
Paper and card [a]	17.0		91.1	20.1		6.9	9.2		2.2	3.5
Plastics [a]	9.4		78.6	9.6		16.2	11.7		5.2	5.2
Films [a]	8.8		97.2	11.2		1.4	1.0		1.4	1.4
Textiles and shoes [a]	8.3		85.3	9.3		14.7	9.1		0.0	0.2
Composites [a]	6.9		75.0	6.8		21.4	11.0		3.6	2.3
Sanitary products [a]	18.4		97.3	23.3		2.3	3.4		0.3	0.4
Wood [a]	3.9		42.9	2.1		46.0	13.7		11.1	4.2
Organics [a]	7.6		50.8	5.0		8.9	5.2		40.3	30.9
Glass [a]	0.1		0.0	0.0		0.0	0.0		100.0	1.3
Minerals [a]	5.6		23.1	1.7		53.8	22.8		23.1	12.6
Metals [a]	4.2		63.8	3.5		31.9	10.2		4.3	2.1
Others [a]	6.0		78.6	6.1		5.1	2.1		16.3	10.0
Fines <8 mm [a]	3.7			1.3			0.5			26.1
Net calorific value * $Q_{p,net}$ (MJ	11.2 [a]	12.1 [a] 11.0 [b]			9.2 [a]			6.6 [a]		

		Low-gravity product (LG)			High-gravity product (HG)			Screenings product (SRC)		
Set of waste components	In-feed material (I) compositio n	Yield to LG product	Recovery of CM to LG	Purity of LG in CM	Yield to HG product	Recovery of CM to HG	Purity of HG in CM	Yield to SRC product	Recovery of CM to SCR	Purity of SRC in CM
(CM)	C(CM)I	$Y(P_{LG})$	$R(CM)P_{LG}$	$C(CM)P_{LG}$	$Y(P_{HG})$	$R(CM)P_{HG}$	$C(CM)P_{HG}$	$Y(P_{SRC})$	$R(CM)P_{SCR}$	$C(CM)P_{SCR}$
or property	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$ unit operation input)	(% $^{w}/_{w}$)	(% $^{w}/_{w}$)
kg^{-1} ar)		11.0 [c]								

[a,b,c] Mueller et al.[152]: Two-step ballistic separator with a horizontally set of first level of paddles in the aerobic stabilisation MBT plant treating residual domestic and commercial waste at Linkenbach, Germany, tests in November 2002. Waste component categories as defined there.

[a] Input: overscreens of drum screen at 100 mm, after hammermill comminution; both ballistic separator paddle levels peroration at 45 mm.

[b] Input: upstream hammermill comminution. Both paddle levels at 75 mm.

[c] Input: upstream hammermill comminution. Both paddle levels at 45 mm

[d,e] Rotter et al.[49]: All values % $^{w}/_{w}$ ar of initial input waste. Pilot scale testing. Ballistic separation with peddle perforation at 40 mm.

[d] Input: urban residual uncomminuted waste after bulky item removal, overflow of screening at 30 mm and ferrous metal separation (calculated value, supposing 11% $^{w}/_{w}$ of initial residual waste input removed through bulky item and metal separation).

[e] Input: urban residual uncomminuted waste after bulky item removal and ferrous metal separation (calculated value, supposing 11% $^{w}/_{w}$ of initial residual waste input removed through bulky item and metal separation).

[*] Not yield: absolute NCV values in input and outputs of unit operation

TABLE 11 Existing and provisional national and trade quality assurance/quality control systems and standards for RDF/SRF in Europe

Country	Legislation/Trade standard	Description and implementation	Reference
Austria	Ö-norm	Joint project launched in 2001 to produce a similar to the German BGS standard. In 2002 founding of association for quality assurance.	European Recovered Fuel Organisation[31] Schulz-Ellermann[33]
Flemish region of Belgium	Standard developed by the European Association of Waste Thermal Treatment Companies for Specialised Waste (EURITS)	Produced by EURITS and adopted by the Flemish region of Belgium; criteria for substitute fuels for co-combustion in cement kilns. Values resulted from calculations based on certain assumptions. Refer to the publication for details. Criticised as too strict by the cement industry, especially for the calorific value threshold.	European Association of Waste Thermal Treatment Companies for Specialised Waste[188] Gendebien et al.[32] Juniper[5]
Finland	SFS 5875 national standard by Finish Standards Association (FSF)	Based on Finnish separate waste collection system of dry high calorific fractions and specific-target waste processing; created to stimulate SRF market development; extensive co-combustion application in boilers for district heating (CHP); covers whole supply chain, i.e. separation, transport and processing; defines three classes and monitoring of seven parameters – additional ones may be added on contractual agreement; required analytical methods are the International Standards Organisation (ISO) standards for solid mineral fuels; self-monitoring, independent supervision and approval procedures are not identified – provisions of standardisation institute may apply; producer-client agreement on sampling and QC. The standard boosted the use of SRF as a substitute fuel; criticised for absence of control requirements.	Finish Standards Association[191] Cuperus and van Dijk[173] European Recovered Fuel Organisation[31] Schulz-Ellermann[33] Wilén et al.[34]
Germany	2001 RAL-GZ 724-lebel for SRF Quality and test instructions by the Quality Association for Secondary Fuel and Recycled Wood (BGS) German Institute for Quality	Initially developed in 1999 by trade organisation BGS and adopted in 2001 by German standard organisation PAL for cement industry and power plants to fulfil the criteria of GZ 724. Establishes a quality label; input oriented, defines two classes: (1) MSW fractions and (2) specific waste, all non-hazardous according to European Waste Catalogue (EWC); no additional diversification with specific intended uses; constitutes of various stages for both internal monitoring and external, independent inspection: (1) initial inspection of	German Institute for Quality Assurance and Certification[192] Cuperus and van Dijk[173] Flamme[186]

Country	Legislation/Trade standard	Description and implementation	Reference
	Assurance and Certification (RAL)	production process and product quality by authorised institution to verify capacity for QA, (2) continuous self-monitoring including proximate and ultimate analysis of RDF, individualised sampling plan per plant and regular external control including sampling and analytical determination reporting to BGS, (3) re-inspection. On 30-04-2005 six plants were producing *ca*. 180,000 Mg a^{-1} quality assured RDF, out of which three from MSW fractions. Issue with duplicate monitoring (production plant and internal by end-users) leading to conflicting RDF quality accounts.	
Italy	UNI 9903 Ministerial Decree (5-2-98) Dlgs 152/2006	Introduced in 1992 to regulate the Italian “non-mineral” RDF (CDR); specifies RDF classes, sampling and analytical requirements; storage, transportation and documentation aspects are briefly addressed. Introduced new values for chemical-physical properties and CDR (normal quality SRF) and CDR-Q (high-quality SRF).	European Committee for Standardisation[30] Schulz-Ellermann[33] Zanotta[193]
Netherlands		Pre-normative activity for standardisation, research conducted for European Standardisation Organisation (CEN).	Schulz-Ellermann[33] Cuperus et al.[194]
Norway	Specifakationen	Applies to bio-fuels.	Schulz-Ellermann[33]
Sweden	SS 18 71 xx “Specialbränsle A” and “Lattbränsle”	Suite of specifications for bio-fuel and peat. Specifications for secondary fuels used in cement kilns, two classes.	European Committee for Standardisation[30] Gendebien et al.[32] Schulz-Ellermann[33]
Switzerland	Guideline specifications for cement kilns developed by the Federal Office for Environment, Forest and Landscape (BUWAL)	Two classes; developed with two main objectives: (1) no increase of the entire emission load from the production of cement, and (2) no enrichment of the pollutants in the clinker product.	Kost et al.[52] Rotter et al.[49]
UK	Substitute fuels protocol (SFP)	Industry voluntarily agreement for cement and lime kilns. SFP revised edition published by the Environment Agency (EA) on February 2005. Developed without consideration of MBT-derived RDF/SRF.	Environment Agency[195]

Adapted from Schulz-Ellermann[33]
QC: quality control

TABLE 12 Overview of limit values for existing European SRF quality standards

		Country								
		Germany [186]		Finland [34,*]			Italy			EURITS / Flemish region of Belgium [188 ††,]
Parameter	Units	Median	80^{th} percentile	Class I	Class II	Class III	Standard quality (CDR) (2006) [193]	Standard quality UNI 9903 (1998) [190]	High quality UNI 9903 (1998) [190]	Cement kilns
Ash content	% $^{w}/_{w}$ d	***					<15	<20	<15	5 **
Moisture content MC	% $^{w}/_{w}$ ar	***					<18	<25	<15	
Net calorific value $Q_{p,net}$	MJ kg^{-1} ar	***,†					>20	>15 min value	>19 min value	>15
Aluminium (metallic) (Al)	% $^{w}/_{w}$ ††			†††	* †	* †*				
Antimony (Sb)	mg kg^{-1} d	50 †* †	120 †* †							
Arsenic (As)	mg kg^{-1} d	5 †* †	13 †* †				<5	<9		
Beryllium (Be)	mg kg^{-1}									<1
Bromine (Br)/Iodine (I)	% $^{w}/_{w}$									<0.01
Cadmium (Cd)	mg kg^{-1} d	4 †* †	9 †* †	<1.0	<4.0	<5.0	<3	<7 Hg+Cd	<1 Hg+Cd	
Chlorine (Cl)	% $^{w}/_{w}$ d	***		<0.15	<0.5	<1.5	<0.7	<0.9% ar	<0.7% ar	<0.5
Chromium (Cr)	mg kg^{-1} d	125 †* †	250 †* †				<70	<100		
Cobalt (Co)	mg/kg d	6 †* †	12 †* †							
Copper (Cu)	mg kg^{-1} d	350 †* †	** †				<50 soluble	<300 soluble	<50 soluble	
Fluorine (F)	% $^{w}/_{w}$									<0.1
Lead (Pb)	mg kg^{-1} d	190 †* †	** †				<100 volatile	<200 volatile		
Manganese (Mn)	mg kg^{-1} d	250 †* †	500 †* †				<200	<400		
Mercury (Hg)	mg kg^{-1} d	0.6 †* †	1.2 †* †	<0.1	<0.2	<0.5	<1			<2
Molybdenum (Mo)	mg kg^{-1} d									20
Nickel (Ni)	mg kg^{-1} d	80 †* †	160 †* †				<30	<40		

Nitrogen (N)	% $^{w}/_{w}$ ††			<1.00	<1.50	<2.50				0.7
Sum potassium and sodium (K+Na) ††*	% $^{w}/_{w}$ d			<0.2	<0.4	<0.5				
Sulphur (S)	% $^{w}/_{w}$ ††			<0.20	<0.30	<0.50	<0.3 d	<0.6 ar		0.4
Sum HM	mg/kg d	1049	2460					<1040	<350	
Thalium (Tl)	mg kg^{-1} d	1 †* †	2 †* †							<2
Vanadium (V)	mg kg^{-1} d	10 †* †	25 †* †							
Zinc (Zn)	mg kg^{-1}									500
As,Se,(Te),Cd,Sb #	mg kg^{-1}									10
V,Cr,Co,Ni,Cu,Pb,Mn,Sn #	mg kg^{-1}									200

* Decimal points denote the necessary precision of detection. Classification limits apply to a volume of SRF ≤1000 m^3 or to the volume produced or delivered during one month

** Excluding: Ca, Al, Fe, Si. Arbitrary value

*** These process-specific parameters should be documented for the purposes of QA/QC: limits specified by each particular end-user contract apply

† Both MJ kg^{-1} d and MJ kg^{-1} ar should be reported

†† Values result from calculations based on certain assumptions. Refer to publication for details. Necessary basis of report (ar or d) not stated

††† Metallic Al is not allowed, but accepted within the limits of reporting precision (0.01)

* † Metallic Al is removed/minimised by source-separation and by the SRF production process

* †* Metallic Al content is agreed separately

†* † German values apply to the high-calorific value fractions derived from municipal waste. HM content values are valid as from a NCV of ≥16 MJ kg^{-1} d. For calorific values falling below, the above-mentioned values need to be accordingly lowered linearly; an increase is not allowed

** † Definition only on the basis of a reliable dataset from the SRF production process

††* Total content (K+Na) of water-soluble and ion-exchangeable proportion

Limit values apply to each of the metal separately

HM: heavy metals

QA/QC: quality assurance/ quality cont

TABLE 13 CEN classification codes for SRF

Property category	Classification property	Units	Statistic *	Classes				
				1	2	3	4	5
Economy	Net calorific value $Q_{p,net}$ **	MJ kg^{-1} ar	Mean	≥25	≥20	≥15	≥10	≥3
				1	2	3	4	5
Technology Cl: important in corrosion, slugging and fouling of boilers	Chlorine (Cl)	% $^{w}/_{w}$ d ***	Mean	≤0.2	≤0.6	≤1.0	≤1.5	≤3.0
				1	2	3	4	5
Environment Hg: volatile trace element of concern	Mercury (Hg)	mg MJ^{-1} ar	Median †	≤0.02	≤0.03	≤0.08	≤0.15	≤0.5
			80^{th} percentile †	≤0.04	≤0.06	≤0.16	≤0.30	≤1.0
				1	2	3	4	5
Environment Cd: volatile trace element of concern ††	Cadmium (Cd)	mg MJ^{-1} ar	Median †	<0.1	<0.3	<1.0	<5.0	<15
			80^{th} percentile †	<0.2	<0.6	<2.0	<10	<30

Adapted from: van Tubergen et al.[190], European Committee for Standardisation[58], and European Committee for Standardisation [196]

* Specified sampling, sample preparation, analytical methods and statistical analysis apply. Classification to be based on at least 10 consecutive data points, collected in a reasonable tine according to sampling plans. For Hg specific rules apply, according to number of assays taken

** Net calorific value (NVC) $Q_{p,net}$ is the same as lower heating value (LHV) $H_{u.}$

*** Dry reporting basis (d) selected for arbitrarily, because most existing data available in such from for Cl.

† The higher classification stemming from each of the two statistics specifies the class

†† Proposed classes for Cd were not included in the final proposal of CEN

TABLE 14 Properties for sufficient characterisation of WDFs according to end-use specifications

Property category	Properties
Chemical	Content of combustible matter
	Content of non-combustible mater (ash and moisture content)
	Content of H, C, O, N, (elemental analysis)
	Trace elements of concern ("heavy metals" or "minor elements")
	Major elements: Cl, P, S
	Content of combined fixed C
	Content of volatile constituents
Mechanical	Density of the combustible and non-combustible matter
	Bulk solids properties (bulk density, and angle of repose, flowability)
	Grindability
	Particle size distribution
	Storage properties (biological stability, sanitisation) and dispersability (fluidity)
Calorific	Heating value and calorific value
	Specific minimum air requirement
	Specific minimum flue gas requirement
	Adiabatic combustion temperature
	Thermal capacity, thermal conductivity and temperature diffusivity
Reaction kinetics	Ignition and burnout behaviour
	Corrosion potential
	De-volatalisation [a]

Source of information, if not mentioned otherwise: Beckmann and Thomé-Kozmiensky[36]
[a] Hilber et al.[198]
WDFs: waste-derived fuels

TABLE 15 Quality parameters for SRF according to end-use

SRF quality parameter	Type of end-use (co-combustion)								
	Cement kiln	Power plants					Fluidised bed combustors		Industrial firing uses
		Gasification and pulverised coal power plant	Pulverised coal power plant	Hard coal DBB power plant	Hard coal WBB power plant	Brown coal (lignite) power plant	FCB	FCB (with AC)	
SRF preparation form and storage requirements [a]	1. Bales: Shredding (fluff) Covered storage 2. Soft pellets: Covered storage 3. Hard pellets: Simple crushing Covered storage	1. Bales: Shredding (fluff) Covered storage 2. Soft pellets: Covered storage 3. Hard pellets: Simple crushing Covered storage Pulverisation	1. Bales: Pelletising Storage Pulverisation 2. Soft pellets: Covered storage 3. Hard pellets: Covered storage			Soft pellets [b]	1. Bales: Shredding (fluff). Covered storage 2. Soft pellets: Covered storage 3. Hard pellets: Covered storage		
Bulk density [c]	Range: 0.24-0.35 $Mg\ m^{-3}$	Range: 0.24-0.35 $Mg\ m^{-3}$	Range: 0.24-0.35 $Mg\ m^{-3}$	Range: 0.24-0.35 $Mg\ m^{-3}$	Range: 0.24-0.35 $Mg\ m^{-3}$	Range: 0.24-0.35 $Mg\ m^{-3}$			Range: 0.15-0.25 $Mg\ m^{-3}$
Particle size	*ca.* 25-50 [e,*] Median 30 [e] <25 mm [c]	*ca.* 10-25 [e,*,**] Median 20 [e,**] <25 mm [c]	*ca.* 10-25 [e,*,**] Median 20 [e,**] <25 mm [c]	*ca.* 10-25 [e,*,**] Median 20 [e,**] <25 mm [c]	*ca.* 10-25 [e,*,**] Median 20 [e,**] <25 mm [c]	*ca.* 10-25 [e,*,**] Median 20 [e,**] <25 mm [c]	*ca.* 10-150 [e,*] Median 50 [e,***]	*ca.* 10-150 [e,*] Median 50 [e,***]	Depending on thermal recovery technology:<300 mm grate systems <80 mm

	Type of end-use (co-combustion)								
	Cement kiln	Power plants					Fluidised bed combustors		Industrial firing uses
SRF quality parameter		Gasification and pulverised coal power plant	Pulverised coal power plant	Hard coal DBB power plant	Hard coal WBB power plant	Brown coal (lignite) power plant	FCB	FCB (with AC)	
				<20 mm [b]	<20 mm [b]	<25 mm [b]			fluidised bed systems Length of longest particles <300 mm [b] Range: 50-80 mm [c]
Feeding system				Pneumatic [b]	Pneumatic [b]	Mechanically by conveyor belt [b]			Alkali metals <5% in the remaining ashes [b]
Cl content	Kiln without by-pass [b,†]: Mean 0.5-1.0% $^{w}/_{w}$ ar Max1-3.0% $^{w}/_{w}$ ar Kiln with by-pass: Max *ca.* 3% $^{w}/_{w}$ ar [b,†] Wet process kiln: Max 6 % $^{w}/_{w}$ ar [b,†]			In general <1% $^{w}/_{w}$ (depending on S content) [b] Mean 0.6% $^{w}/_{w}$ d [b,† ††] Max 1.3 % $^{w}/_{w}$ d [b,†††]	In general <1 % $^{w}/_{w}$ (depending on S content) [b] Mean 1.1% $^{w}/_{w}$ d [b,†††] Max 2.5% $^{w}/_{w}$ d [b,†††]	In general <1% $^{w}/_{w}$ (depending on S content) [b] Mean 0.5% $^{w}/_{w}$ d [b,†††] Max 0.6/1.0% $^{w}/_{w}$ d [b,††,†††]	Mean 0.4% $^{w}/_{w}$ ar [b,***,†,††] Max 0.5/0.8/1.4% $^{w}/_{w}$ d [b,***,††]	Mean 0.4% $^{w}/_{w}$ ar [b,***,†,††] Max 0.5/0.8/1.4% $^{w}/_{w}$ d [b,***,†,††]	Median <0.85% [b]
Hg CEN	1,2,3,4			1,2	1,2	1,2,3	1	1,2,3,4	

SRF quality parameter	Type of end-use (co-combustion)								
	Cement kiln	Power plants					Fluidised bed combustors		Industrial firing uses
		Gasification and pulverised coal power plant	Pulverised coal power plant	Hard coal DBB power plant	Hard coal WBB power plant	Brown coal (lignite) power plant	FCB	FCB (with AC)	
classification classes potentially acceptable (median) [b]									
Cd CEN classification classes potentially acceptable (median) [b]	1,2,3,4			1,2,3	1	1,2	1,2	1,2,3,4,5	
Net calorific value	5/10-12/22 MJ kg^{-1} ar [d,*†] Median 21 MJ kg^{-1} [e] Range 15-23 MJ kg^{-1} [e,*]	Central trend value [e,*]: Median 17 MJ kg^{-1} Range 16-19 MJ kg^{-1} Minimum value [e,**]: Median 14	Central trend value [e,*]: Median 17 MJ kg^{-1} Range 16-19 MJ kg^{-1} Minimum value [e,**]: Median 14 MJ	>20 MJ kg^{-1} [b] Mean 13.5 MJ kg^{-1} ar [d] Range 11-18 MJ kg^{-1} ar [d] Central trend value [e,*]: Median 17 MJ kg^{-1} Range 16-19 MJ kg^{-1} Minimum value [e,**]:	>20 MJ kg^{-1} [b] Mean 17 MJ kg^{-1} [d] ar Range 13-22 MJ kg^{-1} ar [d] Central trend value [e,*]: Median 17 MJ kg^{-1} Range 16-19 MJ kg^{-1} Minimum value [e,**]:	>11 MJ kg^{-1} [b] Mean 13.5 MJ kg^{-1} ar [d] Range 11-18 MJ kg^{-1} ar [d] Central trend value [e,*]: Median 17 MJ kg^{-1} Range 16-19 MJ kg^{-1} Minimum value [e,**]: Median 14	Mean 13.5 MJ kg^{-1} ar [d] Range 11-18 MJ kg^{-1} ar [d] Median 14.5 MJ kg^{-1} [e,***] Range 6-18 MJ kg^{-1} [e,***]	Mean 13.5 MJ kg^{-1} ar [d] Range 11-18 MJ kg^{-1} ar [d] Median 14.5 MJ kg^{-1} [e,***] Range 6-18 MJ kg^{-1} [e,***]	

SRF quality parameter	Type of end-use (co-combustion)								
	Cement kiln	Power plants					Fluidised bed combustors		Industrial firing uses
		Gasification and pulverised coal power plant	Pulverised coal power plant	Hard coal DBB power plant	Hard coal WBB power plant	Brown coal (lignite) power plant	FCB	FCB (with AC)	
		MJ kg^{-1} Range 11-17 MJ kg^{-1}	kg^{-1} Range 11-17 MJ kg^{-1}	Median 14 MJ kg^{-1} Range 11-17 MJ kg^{-1}	Median 14 MJ kg^{-1} Range 11-17 MJ kg^{-1}	MJ kg^{-1} Range 11-17 MJ kg^{-1}			
Ash content [b]				Low	Low	Can be high			
Contrary materials [b]				Fe and non-Fe free No 3-D particles	Fe and non-Fe free[3] No 3-D particles	Fe and non-Fe free			Metallic Al <5% in the remaining ashes

[a] Glorius et al. [40]

[b] Ibbetson and Wengenroth[181]: For calorific values not stated: (1) if gross or net; nor (2) the basis (ar/d/daf).

[c] Breuer[89]: General SRF production specification (common for both cement kilns and power plants)

[d] van Tubergen et al. [190, 196]: Safety margin exists for all Hg and Cd classes and 100% fuel substitution is assumed in calculations. Actual air emissions will be determined also by raw fuel properties, fuel mix, and transfer coefficients of each specific technology. For hard coal WBB power plant conservative calculations apply, because of limited database. Relevant specific notes:

[*†] Mean values; there is no maximum value for NCV if used in clinker kiln

[†] Cl specification depends on the composition of the input: e.g. K, Na content

[††] The maximum values vary for different companies. Mean and max. values are close for a specific end-user

[†††] The Cl-concentration of the total fuel mix should be kept <0.2-0.4% to prevent high temperature corrosion. The maximum allowable Cl % (depends on the design and materials chosen): Netherlands (usually) 0.2%; UK 0.4% (plants are designed for coal with a high Cl content)

[e] Eckardt and Albers [46]: Data from end-user requirements. Basis for calorific values not stated (ar/d/daf). Relevant specific notes:

[*] Readings from graph.

[**] General category of power plants

[***] General category for FBC mono-combustion

AC: activated carbon used as absorbent

CEN: European Committee for Standardisation

DBB: dry bottom boiler pulverised coal, dry ash

FBC: Fluidised bed combustor
WBB: wed bottom boiler pulverised coal, molten slag

TABLE 16 Quality standards for SRF use in cement kilns

Parameter	EURITS/Flemish region of Belgium [188,*]	Switzerland [32]	UK industry specification [5]	Remondis SBS 2 [31,**]
Ash content	5% $^{w}/_{w}$ d ***			< 20% d
Moisture content MC				<20%
Net calorific value $Q_{p,net}$	>15		23-29 MJ kg^{-1} ar	18-23 MJ kg^{-1} d
Antimony (Sb)		0.2 mg MJ^{-1} ar	<50 ppm	<120 mg kg^{-1} d
Arsenic (As)		0.6 mg MJ^{-1} ar	<50 ppm	<13 mg kg^{-1} d
Beryllium (Be)	1 mg kg^{-1}			<2 mg kg^{-1} d
Bromine (Br)/Iodine (I)	0.01% $^{w}/_{w}$			
Cadmium (Cd)				<9 mg kg^{-1} d
Chromium (Cr)		4.0 mg MJ^{-1} ar	<200 ppm	<250 mg kg^{-1} d
Chlorine (Cl)	0.5% $^{w}/_{w}$		<0.2% $^{w}/_{w}$ d	1.2 mg kg^{-1} d
Cobalt (Co)		0.8 mg MJ^{-1} ar	<100 ppm	12 mg kg^{-1} d
Copper (Cu)		4 mg MJ^{-1} ar	<600 ppm	<1000 mg kg^{-1} d
Fluorine (F)	0.1% $^{w}/_{w}$			
Lead (Pb)		8 mg MJ^{-1} ar	< 500 ppm	<400 mg kg^{-1} d
Manganese (Mn)				<500 mg kg^{-1} d
Mercury (Hg)	2 mg kg^{-1}	0.01 mg MJ^{-1} ar	<20 ppm	<1.0 mg kg^{-1} d
Molybdenum (Mo)	20 mg kg^{-1}			
Nickel (Ni)		4 mg MJ^{-1} ar	<50 ppm	<160 mg kg^{-1} d
Nitorgen (N)	0.7% $^{w}/_{w}$			
Selenium (Se)				<5 mg kg^{-1} d
Sulphur (S)	0.4% $^{w}/_{w}$		<0.3% $^{w}/_{w}$	<0.8 mg kg^{-1} d
Sum Cadmium+Thallium (Cd+ Tl)		0.08 mg MJ^{-1} ar	<4 ppm	
Sum Flourine+Bromine+Iodine (F+Br+ I)			<0.5	
Sum HM				
Sum Sb+As+Cr+Co+Cu +Pb+Mn+Ni+Sn+V			<1800 ppm	
Tellurium (Te)				<5 mg kg^{-1} d
Thallium (Tl)	2 mg kg^{-1}			<2 mg kg^{-1} d
Vanadium (V)		0.12 mg MJ^{-1} ar	<50 ppm	<26 mg kg^{-1} d
Zinc (Zn)	500 mg kg^{-1}			
As,Se,(Te),Cd,Sb †	10 mg kg^{-1}			
V,Cr,Co,Ni,Cu,Pb,Mn,Sn †	200 mg kg^{-1}			

* Values result from calculations based on certain assumptions. Refer to publication for details. Necessary basis of report (ar or d) not stated

** Internal standard for the German organisation Remondis; applies to SRF produced from mixed MSW; values for element concentrations determined after microwave digestion of the SRF matrix by aqua regia acid solution mixture

*** Excluding: Ca, Al, Fe, Si. Arbitrary value

† Limit values apply to each of the metal separately

TABLE 17 Comparison of CO_2 emissions of various fossil fuels and Herhof SRF (Stabilat®)

Fuel	Calorific value (MJ kg^{-1})	Total CO_2 emissions (g CO_2 kg^{-1})	Total CO_2 emissions factor (g CO_2 MJ^{-1})	Percentage of regenerative energy (% energy)	Specific fossil CO_2 emissions (g CO_2 kg^{-1})	Specific fossil CO_2 emissions factor (g CO_2 MJ^{-1})
Lignite	8.6	955	111	0	955	111
Hard coal	29.7	2762	93	0	2762	93
Fuel oil	35.4	2620	74	0	2620	74
Natural gas	31.7	1775	56	0	1775	56
SRF (Stabilat®)	15.0	1060	71	66.8	354	24

Wengenroth[168]

TABLE 18 Background information on data-series used for the statistical evaluation of the MBT-derived European RDF/SRF

Case number	Data series name (including data period or year of publication)	Country	Type of MBT process	RDF/SRF type/ trademark	Type(s) of available statistic	Other background information	Assumptions - limitations	References
1	Herhof (TST) PR2 [1999 publication]	Germany	Biodrying	Trocken stabilat® (TST) or Stabilat®	Mean (arithmetic)	Data from peer-reviewed publication (PR2)	Calorific value assumed net (ar) Cl assumed ar	Heering et al. [164]
2	Herhof - Asslar plant [2001 publication]	Germany	Biodrying	Trocken stabilat® (TST) or Stabilat®	Mean (arithmetic)		Calorific value assumed net (ar) Cl assumed ar	Heering [235] cited by Gendebien et al. [32]
3	Nehlsen (Calobren) [1999-2003 data]	Germany	Biodrying	Calobren®	Mean Median 80^{th}-P	Data coverage: 10/99-06/03) - use in cement kiln	Calorific values assumed net	Juniper [5]
4	Nehlsen (Calobren) [2000 publication]	Germany	Biodrying	Calobren®	Mean		Calorific value assumed net (ar) Cl assumed ar	Zeschmar-Lahl et al. [236] cited by Gendebien et al. [32]
5	Eco-deco - Montanaso plant [2002-04 data]	Italy	Biodrying	Eco-deco SRF	Mean Median Standard deviation		As received (ar) net calorific values were transformed to dry (d) values following the CEN formula – leading to much higher d values that the ones originally reported Cu: soluble	Juniper [5]

Case number	Data series name (including data period or year of publication)	Country	Type of MBT process	RDF/SRF type/ trademark	Type(s) of available statistic	Other background information	Assumptions - limitations	References
							Pb: volatile	
6	Herhof (TST) PR1 [2003 publication]	Germany	Biodrying	TST®	Mean	Data from peer-reviewed publication (PR1)		Niederdränk et al. [215]
7	Remondis (SBS 2: for cement kilns) [2003 publication]	Germany	Mechanical sorting of high CV fraction in MBT	Recofuel / SBS® 2	Median 80th-P	More than 10 data points		van Tubergen et al. [190]
8	Remondis (SBS 1: for power plants) [2003 publication]	Germany	Mechanical sorting of high CV fraction in MBT	Recofuel / SBS® 1	Median 80th-P	More than 10 data points		van Tubergen et al. [190]
9	Herhof (TST) Renerod plant [2003 data]	Germany	Biodrying	TST®	Median 80th-P	Based on 70 samples		Juniper [5]
10	Eco-deco - Lacchiarella plant [2003-04 data]	Italy	Biodrying	Eco-deco SRF	Mean Median Standard deviation		As received (ar) net calorific values were transformed to dry (d) values following the CEN formula – leading to much higher d values that the ones originally reported Cu: soluble Pb: volatile	Juniper [5]

Case number	Data series name (including data period or year of publication)	Country	Type of MBT process	RDF/SRF type/ trademark	Type(s) of available statistic	Other background information	Assumptions - limitations	References
11	Biodrying – TAUW data [2005 publication]	The Netherlands	Biodrying	n.a.	Mean Median 80th-P Standard deviation	Independent investigation (Site D)	Sampling plan limitations	Cuperus et al. [194]
12	Herhof (TST) - [2005 publication]	Germany	Biodrying	TST®	Median 80th-P	More than 10 data points		van Tubergen et al. [190]
13	MBT - high CV fraction - TAUW data [2005 publication]	The Netherlands	Mechanical sorting of high CV fraction in MBT	n.a.	Mean Median 80th-P Standard deviation	Independent investigation (Site A)		Cuperus et al. [194]
14	Italian SRF average [2005 publication]	Italy	Average including cases of biodrying and mechanical sorting of high CV fraction	Average of TST® (Herhof /Fusina) Eco-deco SRF and Pirelli®	Median 80th-P	More than 10 data points	Cu: soluble Pb: volatile	van Tubergen et al. [190]
15	Herhof – Vesta Fusina plant [2006 data]	Italy	Biodrying	TST®	Mean		Dry basis assumed for ash content	Paoli et al. [234]

TABLE 19 Results on statistical analysis of MBT-derived RDF/SRF data-series

			Output statistic					Data quality			
Input data property and statistic	Designation of relevant property	Units	Max	Q3 (Upper quartile)	Median	Q1 (Lower quartile)	Min	Number of data series[*]	Medians-Means[**]	*CV* (Coefficient of variation) (%)	Equivalent, hypothetical CEN classification
Location of moisture content	MC	% $^{w}/_{w}$ ar	24.4	14.2	13.4	12.0	11.7	8	5-3	28.8	
Upper limit (80th percentile) of moisture content	MC	% $^{w}/_{w}$ ar	31.5	n.a.	19.8	n.a.	15.1	4	n.a.	28.8	
Location of ash content		% $^{w}/_{w}$ ar	28.3	25.1	21.1	18.2	17.6	7	4-2	25.3	
Location of net calorific value ar	Qp,net	MJ kg^{-1} ar	19.9	16.8	16.3	15.4	13.0	8	5-3	13.1	CEN class for hypothetic SRF with same median value: 3
Location of net calorific value d	Qp,net	MJ kg^{-1} d	28.3	24.33	22.60	20.27	16.50	8	6-2	18.8	
Upper limit (80th percentile) of net calorific value d	Qp,net	% $^{w}/_{w}$ ar	37.22	n.a.	26.47	n.a.	18.62	5	n.a.	25.7	
Location of chlorine	[Cl]	% $^{w}/_{w}$ d	1.05	0.72	0.50	0.42	0.29	13	9-4	40.0	CEN class for hypothetic SRF with same mean value: 2
Upper limit (80th percentile) of chlorine	[Cl]	% $^{w}/_{w}$ d	1.11	1.00	0.98	0.53	0.39	7	n.a.	36.9	
Location of sulphur	[S]	% $^{w}/_{w}$ d	0.40	0.33	0.24	0.20	0.18	6	3-3	32.9	
Location of arsenic	[As]	mg kg^{-1} d	4.0	3.4	1.1	0.7	0.5	8	4-4	78.6	
Location of cadmium	[Cd]	mg kg^{-1} d	2.6	2.2	1.8	1.2	0.4	8	4-4	47.3	
Location of chromium	[Cr]	mg kg^{-1} d	192	90	78	60	40	11	6-5	49.8	
Location of copper	[Cu]	mg kg^{-1} d	694	448	198	73	14	10	6-4	95.9	
Location of lead	[Pb]	mg kg^{-1} d	230	208	152	88	71	8	0-8	48.3	
Location of mercury	[Hg]	mg kg^{-1} d	1.50	0.75	0.43	0.33	0.15	12	9-3	71.4	

(mass basis)											
Upper limit (80th percentile) of mercury (mass basis)	[Hg]	mg kg^{-1} d	1.11	0.80	0.53	0.38	0.22	7	n.a.	51.1	
Location of mercury (energy basis)	[Hg]	mg MJ^{-1} ar	0.040	0.037	0.023	0.014	0.009	6	5-1	53.6	CEN class for hypothetic SRF with same median and 80th P value: 2
Upper limit (80th percentile) of mercury (energy basis)	[Hg]	mg MJ^{-1} ar	0.045	n.a.	0.024	n.a.	0.009	4	n.a.	47.7	
Location of nickel	[Ni]	mg kg^{-1} d	97	40	28	24	18	9	4-5	66.4	
Upper limit (80th percentile) of CEN SRF sum of “heavy metals”	[Σ(Sb,As,Cd,Cr, Co,Cu,Pb,Mn,Hg ,Ni,Tl,V)]	mg kg^{-1} ar	1025	n.a.	795	n.a.	581	4	n.a.	23.5	

* Number of data entries that were used to calculate the related statistics affecting their reliability

** To estimate the location median values were used if available, otherwise arithmetic means: this column provides the exact numbers: depending on the skewness of the initial statistic of a certain property, use of means instead of medians could mean overestimation on the median output location (if the property is positively skewed, as is typical for waste) or vice versa.

n.a.: not available

4124
4125