MATERIAL EFFICIENCY IN MANUFACTURING

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Developments, industrialization and mass production have triggered rapid increase of raw material consumption and great volumes of industrial waste, while industrial waste management infrastructure has not been developed with the same pace. One mean in striving for industrial waste management is the management of process materials. This paper introduces the performance measure sorting rate for each segment of waste material, along with a method for sorting analysis to help improving overall material efficiency and industrial waste management. The results revealed that more than 50% of combustible bins' content could be separately segregated as plastic, wood, paper, cardboard and bio-degradable.

Keywords: material efficiency, industrial waste management, waste segregation

1. INTRODUCTION

During last decades global population and our living standard have increased dramatically, leading to product demand growth and correlated increase of manufacturing activities. Developments, industrialization and mass production have triggered rapid increase of raw material consumption and great volumes of industrial waste. Much of the extracted resources and materials as well as majority of products end up as waste. The majority of waste further ends up in landfill and in incinerators while contaminating land, water and air. Hence, industrial waste is a key factor when assessing the sustainability of a manufacturing process or a company and improvements of industrial waste management are imperative if even annual production levels are to remain at its current.

One mean in striving for industrial waste management is the management of residual material. During the time, capacity of raw material extraction, manufacturing and product consumption has increased, whereas similar developments in infrastructure and returning flows of resources and materials into their environmental origins or new cycles has not been developed with the same pace. Put it differently, recycling and reusing technologies and capacities has not improved as production technologies and capacities has been greatly improved during the decades. That being said, European Commission (2011) has already concluded resource efficiency as an absolute mean to secure growth and jobs in Europe by bringing major economic opportunities, improve productivity, drive down costs and boost competitiveness. Moreover, Mistra - Swedish foundation for strategic environmental research – in 2011 in a report called "Closing the loop: From Waste to Resource" has also pinpointed out the importance of more circular economy for Swedish industries. Implementing material efficiency in manufacturing directly result in cost and energy saving in transformation, transportation and disposal as well as reduction greenhouse gas emissions (Allwood et al., 2011, Peck and Chipman, 2007), which is also in line with European long-term visions for 60% carbon dioxide reduction and 80% greenhouse gas reduction by 2050. Current industrial waste management challenge is not only to reduce the amount of generated waste and decrease virgin material consumption, but also is to keep high quality grades of material in the industrial system; preferably to a degree where it is considered a by-product that can directly be utilized in another process or reused within its own loop and reduce the requirement of virgin material. Majority of manufacturing companies, which has metal as a primary product material, have a good command on metal segregating for recycling, whereas the segregation degree and recycling rate of process material/residual material such as foundry sand, process fluids, textiles and packaging material including hard and soft plastics, cardboard, paper etc. are much lower.

This paper aims to introduce the performance measure sorting rate for different segments of waste fractions along with a method to measure improvement potential of the sorting as a help to improve overall material efficiency and industrial waste management. This study is in line with legal standards and environmental management system requirements to monitor the total volumes of hazardous and non-hazardous waste as well as the total (external) cost for handling. In addition, different waste segments have different environmental impacts, thus segment performance ought to be monitored separately.

2. THEORETICAL BACKGROUND

Material efficiency has been defined by different scholars such as (Peck and Chipman, 2007) and (Worrell et al., 1997) and it has a close semantic characteristics to other sustainability concepts such as dematerialization, eco-efficiency and resource efficiency. A simple and practical definition however has given as "the ratio of output of products to input of raw materials" by Abdul Rashid et al. (2008). In addition, material efficiency is also considered as a complementary concept to energy efficiency in order to move towards manufacturing sustainability. As stated by Lilja (2009), taking life cycle approach in consideration *material efficiency* is a preferable approach in comparison with *waste prevention* and it should be substituted in close future, since first, it seems that the avoidance of waste is not a sufficient driving force for a transition in the consumption and production patterns and secondly, the materialization of *waste prevention* goal needs actions that are not alternatives for investments in waste recycling, waste recovery or final disposal.

There are arguments in the literature regarding whether or not there is a lack of material supply and will we run out of material in the future? This is basically dependent on future resource discovery and extraction against future demand and technologies (Allwood et al., 2011). Although it is not clear whether virgin material input is a constraint, waste generation and waste handling have been unquestionably argued as a major environmental issue for the future, even if annual waste generation levels remains at its current level. According to (IEA, 2008), material demand will be enhanced significantly and 140 billion tons of key resources per year are expected to be consumed by 2050. A study by Frostell (2006) also indicated that waste generation in the Europe will increase by 10-20% in 2020 in comparison to 2005. Material efficiency is not sensitive to definition and classification of waste since it is applicable in all stages of product life cycle. However, the right level of consumption in each stage (quantity) is difficult to determine. Having said that, one vital criticism against the material efficiency concept, is the fact that it does not include the prevention of negative impacts of waste (quality). Hence, material efficiency leads to less material consumption and waste generation, but decreasing the amount material consumption does not necessarily affect quality of the waste. Therefore, it does not take waste hazardousness/non-hazardousness and pure waste fraction segregation into consideration.

Different material have different environmental impacts, hence materials need to be prioritized base on their environmental as well as economic benefits. The main apprehension behind maturity of metal segregation and recycling in manufacturing industries are growth of demand and correlated quantitative shortage and scarcity of metals, growth of prices, high environmental pollution and carbon footprints for extracting and providing metals, China's domination of critical raw material, substitution difficulties and role of some metals as by-products during extraction are regarding metal and recycling (Norgate and Rankin, 2002). These facts have led metal waste management activities to be on higher stages of waste hierarchy i.e. reducing and recycling. On the other hand, the segregation degree and recycling rate of process material/residual material is still immature even in an environmental conscious country such as Sweden. According to (Allwood et al., 2011, Öko-Institut e.V, 2009) some current barriers in this regards might be: 1. Recycling technical challenges that deal with more mixed material (complexity) further along the process and production chain as well as new dissipative application, 2. Recycling economic challenges that embrace lack of infrastructure of waste collection due to expenditure of collection and sorting due to insufficiency of price incentive, 3. Recycling operational challenges include complexity of separation, lag between production and disposal.

According to definition of material efficiency – ratio of output to input – first equation can be concluded. However, figures regarding material input are not always clear in industries, which lead to the second equation.

Material efficiency = Product output / Material input   or
= product weight / Incoming material weight (1)

$$\text{Material efficiency} = \text{Product output} / (\text{Generated waste} + \text{Produced product}) \quad \text{or}$$
$$= \text{Product weight} / (\text{waste weight} + \text{product weight}) \; (2)$$

These criteria ought to be indexed per produced unit, per production or per tonnes of products, while it is possible to utilize cost equivalents or volume measures (Kurdve, 2008), for instance equation 3. Moreover, material efficiency is also related to economy and efficiency in economy is measured by money. Hence, equation 4 and 5 can be concluded as suggested by (Allwood et al., 2013).

$$\text{Material efficiency} = \text{Product value} / (\text{Waste cost} + \text{Product value}) \; (3)$$
$$\text{Materials required/Service provided} = \text{Materials required/Money spent} \times \text{Money spent/Service provided} \; (4)$$
$$\text{Physical material efficiency} = \text{Economic material efficiency} \times \text{Price of service} \; (5)$$

In addition to the overall material efficiency this study has used a segmentation of non-hazardous waste material into metals, inert and other/non-inert materials introduced in an earlier study (Kurdve, 2008). For each segment the portion of high quality sorted material is calculated as a segment sorting rate.

3. RESEARCH METHODOLOGY

The paper is mainly based on an empirical study, although a structured literature review on material efficiency and industrial waste management was carried out. The literature selection incorporated the key words "industrial waste management" and "waste sorting/segregation/separation" as well as their combination with "manufacturing". The literature search focused on papers addressing a situation similar to Swedish manufacturing industry; even though papers outside of this area tackling relevant problems in industrial waste management have been also included. Moreover, qualitative up-stream and down-stream search of references was performed. The empirical base for this paper relies on multiple case studies in different Swedish manufacturing companies involved in a project called Material Efficiency Management in Manufacturing (MEMIMAN), funded by Mistra. The overall purpose of the project is to identify the limiting factor for each determined waste fraction, and thereby enhance waste segregation and recyclability to help climbing up the waste hierarchy. Table 1 shows a brief description of case companies involved in this research.

Table 1. Overview of invovled companies.

	Volvo GTO	**Volvo CE**	**Alfa Laval**	**Scania**
Type	A remanufacturer of engines and components of trucks, buses and construction equipment	A manufacturer of construction equipment and industrial material handling	A manufacturer of products for heat transfer, separation and fluid handling	A manufacturer of heavy trucks, buses, and gearboxes and engines
Number of interviewees	11	10	3	20

To fulfil the objective of the research, multiple method research design (Saunders et al., 2009) was deployed using quantitative and qualitative approaches at data collection and data analysis stages. Empirical data collection for this study was performed through a multiple case study employing focused semi-structured interviews, document review and participant-observation (Yin, 2014) at all case companies. Semi-structured interviews was based on some predefined questions and open discussion if the interviewees wanted to explain more. Interviewees ranged from environmental coordinators and manufacturing engineers to plant manager, production manager and operators in order to capture a broad perspective of employees' viewpoints within manufacturing industries. In addition, findings through employing Waste Flow Mapping (WFM) (Kurdve et al., 2012) in the same case companies have been used to help identifying and analysing improvement potentials. Waste flow mapping and interviews were performed after each other in a very short time interval. The reason of employing waste flow mapping approach lies on previous reliable results that authors achieved when developing the approach. The other motivation lies on the positive feedbacks from case companies in utilizing WFM. In short, the WFM approach constitutes of different lean and green tools such as Green Performance Map, Eco-mapping, Value Stream Mapping, initial waste segment analysis and waste sorting analysis. However, not all findings and tools of the WFM approach were included in this study. The observation includes how involved manufacturing companies handle their industrial waste and by-products i.e. the way that waste fractions and/or segments are being segregated, transported, sold and recycled or reused in-house (if any) and what actors are involved in industrial waste management system in each company. The results afterwards, were compared and analysed to increase understanding and generalizability of empirical findings (Miles and Huberman, 1994). Underneath table illustrates an overview of the deployed research methodology.

Table 2. Overview of research methodology.

Literature review	Empirical Study		Data analysis
	Multiple case study	Waste Flow Mapping	
• Using keywords • Up-stream and down-stream search of references	• Focused semi-structured interview • Participant-observation • Document review	• Segment analysis • Eco-mapping • Waste Sorting analysis • Lean/go to Gemba	• Initial segment analysis • Detailed analysis of potential

4. EMPIRICAL FINDINGS

An initial overall segment sorting rate was calculated for the non-hazardous waste segment, in order to find how big portion of the material was sorted into high quality fractions as shown in Table 3. The segment sorting rates were calculated through dividing the segregated portion of each waste segment by the total waste generated of each segment including sorted and mixed.

$$\text{Segment sorting degree (\%)} = \Sigma \text{ sorted} / (\Sigma \text{ mixed} + \Sigma \text{ sorted})$$

Then a sorting analysis was made to investigate the potential to sort out even more high quality fractions from the mixed or low quality fractions. The initial segment analysis at all case companies (table 3) shows that the rate of sorting varies a lot between different companies and materials. Volumes of inert materials were low in the investigated operations and thus were omitted from further analysis.

Table 3. Overall segment sorting degree.

Segment sorting rate	Metals		Inert		Other/Non-inert	
	sorted	mixed	sorted	mixed	sorted	mixed
A	96%	4%	100%	0%	94%	6%
B	68%	32%	96%	4%	41%	59%
C	31%	69%	100%	0%	60%	40%
D	97%	3%	0	100%	57%	43%

Through eco-mapping and a following waste sorting analysis, waste bins from different operations were precisely examined in all case companies. For each analyzed bin, the contained waste was weighed to calculate the portion of different material fractions. Based on main waste fraction in case manufacturing companies – combustible, metal scrap, plastic (hard and soft), cardboard, hazardous materials, paper and wood - the analysis was carried out.

Initial observations showed that the majority of industrial waste fractions in all case companies are being sorted in accordance with local standards, although some wrong segregated fractions were observed; only few of them were rated as important. Some of the pure sorted bins were also contaminated with a wrong fraction/material. According to interviews and observations, the main reasons behind wrong waste segregation were technical problems and specific circumstances, inadequate information sharing, mistaken or invisible labeling, existence of different functions and actors, wrong bin location, weak 5S activities and unwillingness of operators to contribute due to lack of incentives or exhaustion and lack of visualization. As a result, more explicit standards, better communication and feedbacks, more cooperation from operation along with support and motivation are needed for improvement.

In a more detailed analysis through examining 23 waste bins and their contents, further results summarized in Table 4 were achieved. Numbers inside each cell represent the percentage of respective fraction in the respective bin. Looking at the table, in average only around 43% of the content in the combustible bins were materials that should be sorted as combustible and household wastes according to standards, and of this 16% could have been sorted as bio-degradable material. Around 26% of the materials were plastics, therefore, there is a great potential to sort out plastics with both economic and environmental benefits. Besides, approximately 8% and 6% of the content in the combustible and household bins were paper and cardboard, which could have been further sorted separately. Small portions of other types of waste including wood, tins, metal scraps, metal chips, coffee grounds and special waste (hazardous) were also found in the bins labelled combustible and household waste, which in average constitute a total of 17% of their content. Likewise, there are economic and environmental benefits to segregate mentioned materials from combustible bins.

Despite the errors found in some combustible bins, hazardous wastes were in general found to be treated appropriately with regards to internal rules and this is basically owing to legislation and legal reporting, which is case specific for Sweden and cannot be generalized globally or within Europe. It was also apparent that metal fractions were being handled appropriately and the reason behind the high degree of metal segregation has been already discussed in theoretical background; mostly economic benefits.

Table 4. Results from waste sorting analysis.

Type of bins	Plant A				Plant B						Plant C								Plant D				
	Combustible	Plastic	Combustible	Combustible	Combustible	Combustible	Metal scarps	Combustible	Combustible	Combustible	Combustible	Combustible	Combustible	Combustible	Household waste	Household waste	Combustible	Metal scarps	Combustible	Metal scarps	Combustible	Combustible	Combustible
Cardboard	27		11	8	3			36	1	3		4	8	17			13		23		1		
Metal scarps	12		6		2		94	7	1									99		98	1		5
Hard plastic		21		4	3	71		10	10		26	22					8		27		38	12	66
Soft plastic	3	73		4	40	17		4	4	1	67	8	22	28				0,2	4			25	
Hazardous material	4			3								35	54	32				0,4		2	35		
Household waste	24		8	20	28				3	94		20	4	3	10	91			31		2	13	8
Combustible	30	5	43	37	22	12	6	13	66	1	4	11	12	20	90	9	79	0,4	5		20	33	18
Paper		1	28	24	2			30	15	1	3								7		3	17	3
Wood			4																				
Landfill																			3				
Total Percentage	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total weight (kg)	3,7	4,5	5,1	3,8	16	8,1	325	12	7	25	2,3	8,3	1,1	1,2	1	3,5	2	144	38	95	7,8	1	3,4

5. DISCUSSION

Observations, initial segment analysis, and interviews, along with employing WFM, made it clear that improvement potential of industrial waste management systems are still high when it comes to waste segregation, particularly for non-productive material/residual material. Such improvements not only provide environmental benefits, but also economic advantages. In the first stage, manufacturing industries need to ensure correct segregation of their productive and non-productive material. Fortunately, productive material (mainly metals) and hazardous material are handled correctly, but non-productive materials such as packaging from assemblies are not separated in the most beneficial way. Thus, in addition to attempts for waste generation reduction, **avoiding blending and correct separation of different waste fractions is the first step** towards an effective industrial waste management system. Employees' awareness regarding correct sorting, economy/environment alignment and misalignment as well as sufficient education, monitoring and guidance by visualization are some enablers to success. Nevertheless, Shahbazi et al. (2014) revealed that individuals (general public, researchers and companies' employees) have an uncertain and different perceptions regarding environmental impact and economic benefits of common waste fractions in manufacturing industries. Results also disclosed a more unclear understanding of environmental benefits rather than economic for sorting industrial waste.

The next step will be to improve the value of waste fractions i.e. having more specific cost-effective fraction. Waste sorting analysis proves to be an effective practical tool to be utilized occasionally at manufacturing companies in order to check and examine the improvement opportunities. Depending on industrial operation and their residual and packaging material, more specific fractions can be added; for example mixed metals can be further divided into Aluminum, Galvanized steel, Casting Iron, Steel and Mixed Metal scrap. Generally, higher cost is associated with the mixed waste fractions compared to the pure segregated ones that often regain a larger portion of the original material value. The value differences correspond to the cost of separating or sorting valuable material from the mix (Kurdve et al., 2012). To illustrate improvement opportunities in further waste segregation of mixed metals, a performed waste sorting analysis on a random bin in one of the case companies is shown in the below pie chart (figure 1). As shown, only 28% of the bin is really mixed scrap, while for instance 34% is Cast-iron and 7% Aluminum, which ought to be separated as separate fractions.

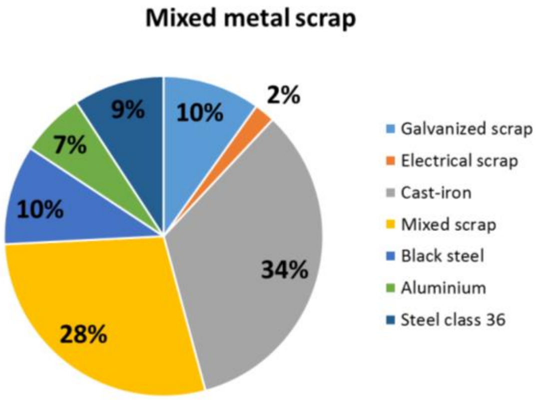

Fig. 1. Waste sorting analysis of the content of a mixed metal scrap bin.

Besides of metals, plastics can be also further segregated as Polystyrene (PS), Polyethylene (PE), Polyethylene terephthalate (PET), Polypropylene (PP) and Polytetrafluoroethylene (TPFE) and rubber. Below, in figure 2, pie chart demonstrates the proportion of existing plastics together in all performed sorting waste analysis. As is shown, 74% of plastics are Polyethylene (PE) and 11% Polyethylene terephthalate (PET), which could potentially be separated as improved/new fractions.

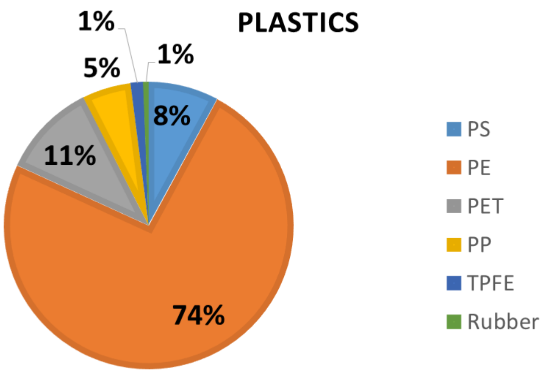

Fig. 2. Proportion of different types of plastics based on case studies.

A solution might be to separate the waste flows and monitor each segment in order to be able to understand each material flow and their final disposal stage as waste and to set relevant targets. Suggested by Kurdve et al. (2012), segments can be categorized into Metals, Inert materials, Other non-inert (Combustible), Fluid waste and Other Hazardous waste. Table 5 can be used for suitable performance measurement of material efficiency that (P) represents produced unit while (C) and (W) represent cost and weight respectively.

Table 5. Performance measurement for suggested segments.

	Segments	Examples	Segment sorting degree (%)	Weight per produced unit (ton/#)	Average segment treatment cost (SEK/ton)
Non-hazardous material	Metals	Aluminum, copper, steel, cast-iron	Σ sorted / (Σ mixed + Σ sorted)	$W_{(segment\ total)}$ / P	$C_{(segment\ total)}$ / $W_{(segment\ total)}$
	Others, non-inert, Combustible	Paper, cardboard, bio-degradable, wood, plastics	Σ sorted / (Σ mixed + Σ sorted)	$W_{(segment\ total)}$ / P	$C_{(segment\ total)}$ / $W_{(segment\ total)}$
	Inert materials	Sand, glass, waste to landfill	Σ sorted / (Σ mixed + Σ sorted)	$W_{(segment\ total)}$ / P	$C_{(segment\ total)}$ / $W_{(segment\ total)}$
Hazardous material	Fluid waste	Oil, chemical, solvents, glycol, emulsion	Not applicable	$W_{(segment\ total)}$ / P	$C_{(segment\ total)}$ / $W_{(segment\ total)}$
	Other Hazardous waste	Electronic waste, fluorescent, batteries	Not applicable	$W_{(segment\ total)}$ / P	$C_{(segment\ total)}$ / $W_{(segment\ total)}$

6. CONCLUSIONS

This paper highlights the crucial role of industrial waste management and material efficiency in industrial sustainable development, particularly with regards to residual material. In an effective and efficient industrial waste management, the value of non-productive material and their improvement potentials need to be included. Empirical results from multiple case study in different manufacturing industries in Sweden shows the improvement potential of further waste segregation to gain both economic and environmental benefits. In addition, determining different waste segments and relative fractions along with calculating material efficiency performance measurements including sorting rate, weight per produced unit and average segment treatment cost facilitate operational management as well as industrial waste management. These material efficiency performance measurements are also in line with legal and environmental management standards' requirements to keep waste flows under observation.

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