Title: A method and databases for estimating detailed industrial waste generation at different scales – with application to biogas industry development

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Abstract: In this study, a top-down method for constructing databases of industrial waste generation profiles is presented. The method employs routinely reported statistical data for economic activities, which enables simple data acquisition and ensures capture of changes in production processes and waste generation. Quantified waste generation profiles following the EWC nomenclature for 42 waste types were compiled into two EU databases, one for 12 sectors and the other for more than 200 industries. These were complimented with quantified factors on waste generation per employee for each sector. The relationship between amounts of waste generated and number of employees has been confirmed for each sector with statistical tests; this can be used to estimate waste quantities in other scenarios. The databases employ standard EU economic and waste nomenclatures, which are also similar to those used worldwide. Potential use scenarios include: evaluation of different geographic boundaries, such as industrial park, municipal, regional or national level; focus on expected types and quantities of waste generated by particular sectors and industries; or targeting particular types of wastes, the economic activities that produce them and the quantities generated. The latter scenario is illustrated in this paper by exploring potential for industrial symbiosis where waste streams from bio-based industries are used to produce biogas in the Västra Götaland region of Sweden. The developed method and databases could support the implementation of circular economy policies, including industrial symbiosis.

Keywords: Industrial Waste, Circular Economy, Waste Generation, Industrial Symbiosis

1. Introduction

The European Union has adopted an ambitious package to promote Circular Economy, aimed at fostering sustainable economic growth, generating new jobs and reducing environmental impacts. Part of the package establishes clear targets for waste reduction, including by waste re-use and industrial symbiosis (IS). Industrial wastes need to beaccounted and characterized in order to investigate their possible use as feedstock.

To establish an industrial symbiosis partnership, finding a partner firm for material exchange requires detailed data at company level (Chen and Ma, 2015). However, industrial waste data is often not available or may be difficult to obtain, either for confidentiality reasons or because it is time-consuming to collect (Jackson et al., n.d.). The task becomes even more challenging when the regional scale is considered, due to the large number of companies that need to be surveyed. On the other hand, application of IS at the regional scale has several advantages, including a greater variety of potential customers that may use the available resources (Jensen (2016), the provision of the volumes required to achieve economies of scale (Cutaia et al., 2015; Posch, 2004; Sterr and Ott, 2004), and ensured proximity between companies (Lombardi and Laybourn, 2012 Chertow and Ehrenfeld, 2012).

Krones has stated that different waste accounting methods have different degrees of policy relevance, depending on the policy objective. For instance, using bottom-up approaches, such as Industrial Facility Surveys, is appropriate if the aim is to minimise the environmental risks (Krones, 2016). This method can be applied to case studies in which the number of participants is not too large, for instance the case of eco-industrial parks, as the response rates may otherwise be low (e.g.:Ormazabal et al., 2016). Due to the large amount of data they require, bottom-up approaches are difficult to perform at the national and regional levels (C. Reynolds et al., 2016; Salhofer, 2000; Yost and Halstead, 1996). Additionally, the data collection is time-consuming, as it is based on questionnaires or surveys (Salhofer, 2000).

Top-down approaches, on the other hand, are a more appropriate choice where the aim is to support effective sustainable material management strategies (Krones, 2016). Top-down methods use available statistical data or other data sources to study and analyse a system. Waste Input Output tables (WIO) is one example of such an approach, in which financial information is coupled with physical waste statistics to link waste production to economic activities. However, this approach is mostly applied at country level. Some WIO have already estimated detailed industrial waste flows, including looking at desaggregation by industrial sectors or types of waste (C. Reynolds et al., 2016), (Salemdeeb et al., 2016). Other top-down studies have been performed for the waste flows of a particular substance, such as lead, food waste or plastics (Lee et al., 2012), (C. J. Reynolds et al., 2016) (Joosten et al., 2000), or a particular industrial activity. There are examples where WIO methodologies have been applied at the regional scale (e.g. (Yang et al., 2016)). Also hybrid models, in which bottom-up and top-down approaches are combined, have been applied at the regional level, using surveys to estimate average values for prediction of the total amount of waste produced in a region (ADAS 2009).

It is well known that gathering information from an industrial facility (i.e. the bottom-up approach) provides the most accurate picture on industrial wastes (Rhyner et al., 2017). Nevertheless, the collection of such data is time consuming, and often impossible for confidentiality reasons. The presented method addresses this gap by applying a top-down approach for constructing waste profiles databases for industries and sectors. To our knowledge, no similar methods or databases have been established for estimating waste generation so comprehensively and for possible application scales from single facilities to industrial parks, regions and entire countries. The method also offers several advantages stemming from the use of statistical data. By using frequently reported statistical data, the databases can be easily updated with the new releases of the data allowing for capturing modifications in the production processes and waste generation. The databases are also comprehensive, covering most economic sectors and industries. Moreover, the method provides highly detailed information following the EWC nomenclature for 42 waste types. It is important to note that the databases and other results of this study are based on the recent industrial waste statistics for the years 2012-2015. Also, a framework for identifying scenarios for industrial waste utilization for a given geographic region, based on the developed method and the databases, is suggested in this paper. For the purpose of illustrating this framework application, an example of bio-based industries in West Sweden and waste streams suitable for producing biogas has been developed.

2. Method

The framework suggested in this paper for identifying scenarios for industrial waste utilization is intended to be flexible and possible to adapt to the development priorities established for a given region. The framework includes 3 main components: the selection of development priorities to focus on, waste selection and characterization , and the industrial symbiosis identification (Figure 1). The development priorities are based on the needs and opportunities of the studied region (see section 2.1 Example for an example). These priorities determine which waste types are to be studied. The waste selection and characterization is made up of 4 steps. In Step 1, a list is produced, where the specified waste types are expressed in terms of waste categories within the standard waste nomenclatures. In Step 2, a characterization of wastes produced in the different economic sectors is made, using waste generation statistics and calculation of waste generation profiles by sector. Sectors that produce the wastes included in the list from Step 1 are selected for further analysis. In Step 3, detailed characterization of the waste generation of each industry within the selected sectors is carried out, allowing a refined selection of industries. Finally, in step 4, the expected quantities of waste produced by the industries selected in Step 3 are estimated, based on calculations of the waste intensity for each industry.

Additionally, more detailed waste criteria can be added to the developed databases, to allow identification of opportunities for industrial symbiosis. In this paper, the identification of potential industrial symbiosis for biogas production in a region in the west of Sweden is used as an example, as part of which the industries that generate suitable waste within the area, as well as the methane yield of the wastes were analysed.

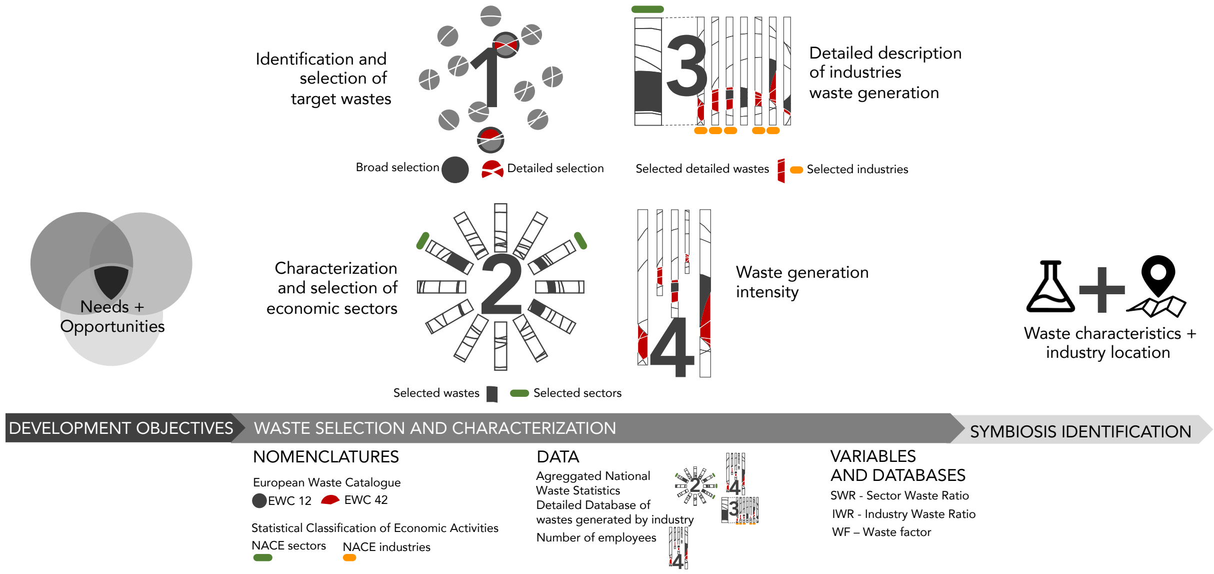

Figure 1 – Diagram of the framework

Nomenclatures

The flexibility of the method is ensured by using standard European Union (EU) nomenclatures. Additionally, correspondence tables relating EU nomenclatures to other worldwide nomenclatures are available. Wastes are classified according to the European Waste Catalogue (EWC), which covers 12 waste groups (further as EWC12), and further subcategories. The secondary category includes 42 waste groups (further as EWC42, see supplementary information Table 1 and 2 for a complete EWC list).

Industries are classified using the Statistical Classification of Economic Activities in the European Community nomenclature (NACE) Rev. 2, which covers more than 600 NACE codes, hereinafter defined as industries. As an example, industry 1711 refers to manufacturing mechanical or semi-chemical pulp companies. Industries can be aggregated into NACE sections (21). This study includes 3 sections namely; agriculture, forestry and fishery; mining, and manufacturing. Because the manufacturing section is very large, it has been further disaggregated into 10 subsections. This disagreggation is a common practice in Eurostat’s methodologies for waste reporting, which are defined in regulation (EC) No 2150/2002 of the European Parliament and of the council on waste statistics (Eurostat, 2008). The sections and subsections considered in this study are hereafter defined as sectors (see supplementary information Table 3). As an example, industry 1711 is included in the manufacture subsection C17-C18 (manufacture of paper and paper products).

Waste selection and characterization

The choice of development priority and determination of waste types to study (see section 2.1 Example) are followed by the selection and characterization of wastes available for industrial symbiosis in a given region. This process is composed of 4 main steps which are described below.

STEP 1. Identification and selection of target wastes

This step identifies the corresponding categories from the EWC12 and EWC42 nomenclatures for the wastes selected according to the development priorities. The identification is made by comparing the development priorities with the descriptions of the EWC12 and EWC42 categories (see supplementary table 1 for a complete list of the EWC categories). As an example, if metallic waste has been selected as the waste type, the EWC12 category ‘06 Metallic Wastes’ should be selected.

STEP 2. Characterization and selection of economic sectors

In the developed database for waste generation in industry sectors, waste generation profiles have been quantified for 12 economic sectors as the proportions (so called Sector Waste Ratio (S*WR*)) of EWC12 wastes they generate. The Sector Waste Ratio (S*WR*) was calculated as the share of waste *j* in relation to the total amount of waste from sector *k* in country *z* (*Equation 1*). The SWR was calculated for 28 European countries and for each of the EWC12 waste categories. Median and mean values, as well as higher and lower quartiles were calculated. Outliers were defined as values that were 1.5 times higher or lower than the upper or lower quartile. The results were visualised in boxplots, using R software (see Figure 3). As an example, the results from Equation 1 showed that the Manufacture of Furniture sector produces a mean of 22% of EWC12 category 06, Metallic Wastes, per ton of waste produced. To access the uncertainty in the estimates of the mean for each waste type, 95% confidence intervals (CI) were constructed by applying the bootstrap method on country level data (1000 samples) (Supplementary information table 4).

$$SWR_{jkz} = \frac{W_{jkz}}{\sum_{m=1}^{j} W_{jkz}} \qquad \textit{Equation 1}$$

SWR - Sector Waste Ratio in tons/tons
W – Amount of waste produced, in tons
j – Waste type, in this case primary category of EWC that includes 12 groups of waste (EWC12)
k –Sector
z - Country

Sectors with high S*WRs* for wastes identified in Step 1 were selected for further analysis. This analysis used Equation 1, but this time performed for the EWC 42 subgroups of wastes and the selected sectors (see Table 1). Again using the example of the Manufacture of Furniture sector, within the EWC12 category 06, Metallic Wastes, the most representative EWC42 is category 06.1, Ferrous metal waste and scrap, with a mean of 18% of the total mass.

STEP 3: Detailed description of the waste generation of different industries

In this step, industries (by NACE code) within the sectors identified in Step 2 were characterized. In particular, the developed waste generation profiles dabatase for industries includes the proportions of different wastes (by EWC42 category) generated by individual industries. The amount of each EWC42 waste type produced by each industry was divided by the total amount of waste produced within the same industry (Equation 2), here defined as Industry Waste Ratio (IWR). Data for wastes produced per industry in Portugal was used (further information about this data is available in Section 2.4 Data collection). The calculations were carried out for the four available years, 2012-2015, and average values were used. As an example, Industry 3101, representing Manufacture of office and shop furniture, produced an average of 39% of EWC42 06.1, Ferrous metal waste and scrap.

$$\overline{IWR}_{ji} = \frac{1}{t}\sum_{n=1}^{t}\frac{W_{jit}}{\sum_{m=1}^{j} W_{jit}} \qquad \textit{Equation 2}$$

IWR - Industry Waste Ratio in tons/tons
W – Amount of waste produced, in tons
i – Industry
j – Waste type, in this case secondary category of EWC, that includes 42 groups of waste (EWC42)
t – Available years

STEP 4. Waste generation intensity

To obtain an accurate estimate of the amount of industrial waste generated in a specific region is difficult, why the use of waste generation factors is common practice when waste intensity is calculated (Rhyner et al., 2017). Estimates can be performed using national data, available in Eurostat for 28 European countries. The datasets usually used to estimate the waste generation cover an entire sector, such as turnover or number of employees along with waste factors (SCB, 2014). The advantage of using number of employees is that this data is commonly available in a detailed listing and for different spatial scales (Salhofer, 2000). Therefore, the allocation of waste generation is done based on the assumption that it is correlated to the industries number of employees.

Consequently, the Waste Factor per employee (WF) reflects the total waste generated by a given sector within a country, in relation to the number of employees the sector has. The WF can be used to estimate the amount of waste produced by a sector in a given region, or by an individual company within the sector, assuming that companies from the same sector produce approximately the same quantities of waste per employee. Analysis of Variance (ANOVA) testing was used to evaluate the potential relationship between waste generation and number of employees, with the null hypothesis that this is false and the alternative hypothesis that the relationship exists. Subsequently, a regression line was fitted to the available data points, and the respective coefficient of determination (r^2) was calculated. The regression used was the log-log regression model.

Data collection for the Waste selection and characterization method

Data was obtained from official publications, as well as from different organizations and institutes. Below is a list of the data used for the method.

- For Sector Waste Ratios (*SWR*) calculation (Step 2), National waste statistics for 28 EU countries in 2014 were used (Eurostat, 2018a)[1]. The data is reported every second year. The data contained 12 sectors and 42 groups of wastes (EWC42 categories),which were later aggregated into EWC12 categories. This data is publicly available and presented by country, sector and type of waste produced (EWC42). The waste generation is attributed to both production and consumption activities. Major mineral wastes , such as mineral construction and demolition waste (EWC 12.1), other mineral waste (12.2, 12.3, 12.5), soils (12.6) and dredging soils (12.7) are not included in this data. According to Eurostat, waste generation excluding major mineral wastes reflects general trends more accurately than statistics on total

[1] Each state member performe data quality reports, which is available at: https://circabc.europa.eu/faces/jsp/extension/wai/navigation/container.jsp

waste, and also increases comparability across countries. Additionally, over 90% of mineral wastes come from the mining and construction sectors, which are subject to considerable fluctuation over time. The same data was used to calculate the Waste Factors (Step 4).

- Number of employees per sector for regions in the European Union, are used to calculate the Waste Factors (WF). The data is updated in an annual basis. (Eurostat, 2018b).
- The data used to calculate the Industry Waste Ratio (IWR) (by NACE code) was collected from the Portuguese Environmental Agency (APA). This data is collected by APA under the Portuguese regulation Decree-Law nº 73/2011, which makes it mandatory for companies and operators to disclose information regarding waste generation and transfers on a yearly basis. The regulations apply to companies that: 1) have more than 10 workers, or 2) produce more than 1100 L of Municipal Solid Waste on a daily basis, or 3) produce any type of hazardous waste. The data was provided for 2012, 2013, 2014 and 2015. For each industry type, the data includes information on the waste types produced according to the List of Waste code and EWC code.

Example study: Waste feedstock for biogas production in the Västra Götaland Region

In this paper, an example from the Västra Götaland Region in Sweden is used to illustrate the developed framework. Västra Götaland is a coastal region in western Sweden, with approximately 1,670,000 inhabitants and a population density of 66/km^2 (SCB, 2017). The regional administrative system covers 49 municipalities, including the second largest Swedish metropolitan area, Gothenburg, home to approximately 60% of the region's and 6% of Sweden's population. Gothenburg is also home to the largest port in Scandinavia, which handles almost 30% of Sweden's foreign trade. A wide range of companies from different sectors, including shipping, agriculture, forestry and manufacturing, operate in the region (Lansstyrelsen, 2015).

The framework was applied to an industrial symbiosis example of biogas production from industrial biowaste. Biogas production is one of the development priorities defined by the local authorities in the Västra Götaland region. The region has set the ambitious target of raising the biogas production to 2TWh by 2020, from the current production of 0.329 TWh. To achieve this target, it is necessary to meet the national performance targets regarding biogas and biomethane production, Sweden's vision of a fossil free vehicle fleet by 2030, and the Swedish gas industry's vision of vehicle gas being made up of 100% biomethane by 2030, to be extended to 100% in the gas grid by 2050 (Backman and Rogulska, 2016). Additionally, it is also estimated that the required investment in biogas production will create 3,000 full-time jobs in the region (Västra Götaland Region, 2016). Finaly, the production of renewable energy, which includes biogas and methane, has been identified as an important sustainability strategy at both regional and national level in Europe.

Biogas is produced as a result of organic matter decomposition processes performed by bacteria in an anaerobic (in the absence of free oxygen) digestion process. In Sweden, most of the biogas is produced using sewage sludge from wastewater treatment plants (Biogasportalen, 2014). Industrial and agricultural by-products are also attractive resources for biogas production due to their high methane yield, and because they are typically generated in large volumes and concentrated in a single place, allowing for economies of scale and simplifying the logistics process (Lönnqvist et al., 2015; Angelidaki, 2002).

In order to identify industrial symbioses for biogas production, a set of extra criteria was added, one of them the methane yield. Wastes with high theoretical methane yield potential are more suitable for biogas production and should be prioritized. Based on available methane yield values (Murovec et al., 2015), a list of biogas Methane Yield representative values (MY) for each of the EWC42 categories was set up, which also includes the corresponding volatile solids (VS) and total solids (TS) values. Some categories have more than one representative waste, and therefore maximum and minimum methane yield potential values were calculated. This list was used to calculate the methane yield potential of a mix of different biodegradable wastes per ton of waste usually produced by an industry (i.e. Industry Methane Yield potential, IMY). The IMY for a given industry is calculated as shown in Equation 3.

$$IMY_i = \sum_{m=1}^{j} \overline{IWR}_{ji} \times MY_j \times VS_j \qquad \textit{Equation 3}$$

IMY - Industry Methane Yield potential in mL CH4/g-WS
IWR - Industry Waste Ratio in tons/tons as calculated in Equation 2
MY – Methane Yield representative values in mL CH4 / g VS
VS – Volatile solids in g/g-WS
i – Industry
j – Waste type, in this case secondary category of EWC, which includes 42 groups of waste (EWC42)

The potential Overall Methane Volume (*OMV*) for each of the industries operating in the region were calculated by multiplying the obtained *IMY*, by the *WF*, see (Step 4 of the method), and by the industries number of employees, as shown in Equation 4.

$$\mathrm{OMV}_i = IMY_i \times WF_k \times E_i \qquad \textit{Equation 4}$$

OMY - Overall Methane Yield potentials in m^3 CH4
IMY- Industry Methane Yield potential in mL CH4/g-WS as calculated in Equation 4
WF – Waste Factor in tons/employee as calculated in Equation 3
E – Number of employees
i – Industry
k - Sector

The OMV was also estimated for each of the facilities/companies operating in the region, using data on the geographic coordinates, industry type and company size (number of employees). The locations of the companies found to generate the most suitable wastes were mapped using QGIS software. In addition to the waste producers, biogas plants (the potential receivers of these wastes) were also mapped (Swedish Gas Association, 2016). A list of companies operating in the Västra Götaland Region was obtained from the Swedish Statistical Office (SCB). This data contained name, size (in number of employees), industry type and the geographical coordinates for each company with more than two employees. As a final step, it was possible to account the potential electricity generation from biogas production using the located wastes, converting the methane values in m^3 per year into TWh per year. The conversion was done using the lower heating value for methane, 36 MJ/m^3, and assuming there are no losses.

2.1. Additional assumptions

This method assumes that companies within the same industry use similar technologies in their industrial processes, and therefore produce similar types of waste. However, some industries can be considered broad, as they include more than one type of industrial plant or produce different products. It was also assumed that the proportions of the wastes generated within each sector and industry are similar across Europe.

The methane yield values for each waste category were estimated based on average values according to the literature. However, these factors may correspond to the best values of the experiments under optimal conditions, which may be different from the actual operational environment.

3. Results and discussion

Waste selection and characterization method

Step 1. Identification of target wastes

The use of the method is illustrated on an example of biogas production industry, which uses biodegradable feedstock, including waste. Step 1 of the method involved analysis of the EWC12 and EWC42 categories, in order to identify those containing biodegradable waste. Figure 2 shows the EWC12 and EWC42 categories selected for this study. Within EWC12, biodegradable waste was found in categories 5, 7, 9, 10 and 11. Category 9 (Animal and vegetable waste) includes only biodegradable wastes, whereas the other categories may also include other wastes (Figure 2). Category 5 (Healthcare and biological wastes) may include biodegradable waste, however this category was not considered, as the waste it produces has to be managed by specialised waste management companies. Category 10 (Mixed ordinary wastes) may also include biodegradable waste, however, it may also include a large proportion of other types of wastes, and was therefore not selected for further analysis. Figure 2 shows the EWC12 and EWC42 categories selected for this study (7, 9 and 11).

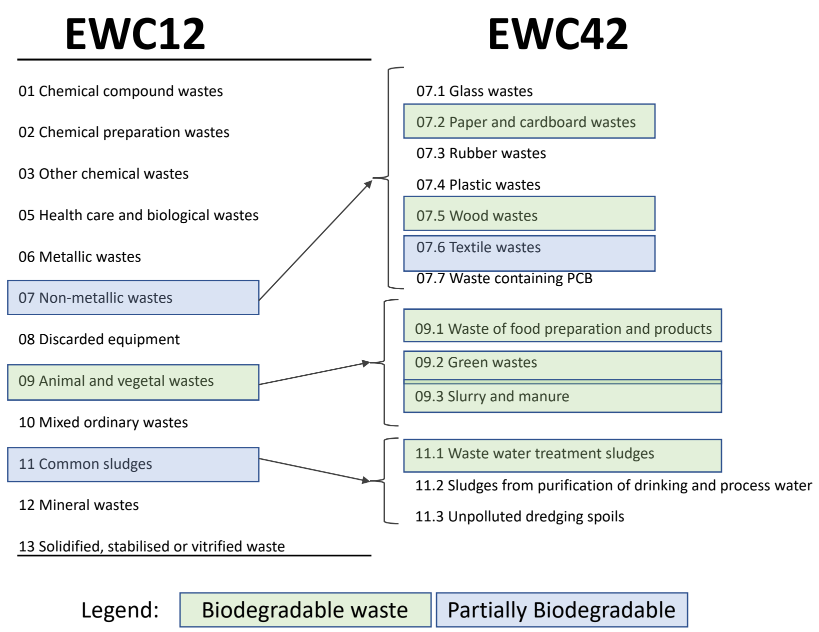

Figure 2: Biodegradable waste in EWC12, EWC 42

Step 2. Selection of economic sectors

Sectors generating relevant waste categories are selected by filtering the waste generation profiles database for sectors by the EWC12 and then by the EWC42 categories that were selected in Step 1. Sectors with the highest Sector Waste Ratios (SWR) for the relevant EWC categories are selected for further study. Figure 3 shows the quantified waste generation profiles as the SWR expected for the EWC12 waste types, in shares per ton of the waste generated by each sector (see supplementary information Table 4 for results including confidence intervals). Data for 2014 for 28 EU countries was used to calculate the SWR. Note that the results for the studied 28 EU countries are similar, as the values are centred around the median, and the values of the upper and lower quartiles are close to the median. There are some exceptions, such as the large variation in EWC12 categories 6 and 12, relating to the manufacture of basic metals. This variation may be due to differences in combustion technology, as the main waste products from EWC12 category 12 for this sector is combustion waste, such as ashes. In general, the calculated waste generation profiles are in line with results from other studies. As an example, in a study based on surveys from the UK, the waste generated by the food processing sector was made up of 66% animal and vegetable waste, 6% common sludge, 18% mixed waste, and 7% non-metallic waste (ADAS, 2009) – values very similar to the ones obtained in this study.

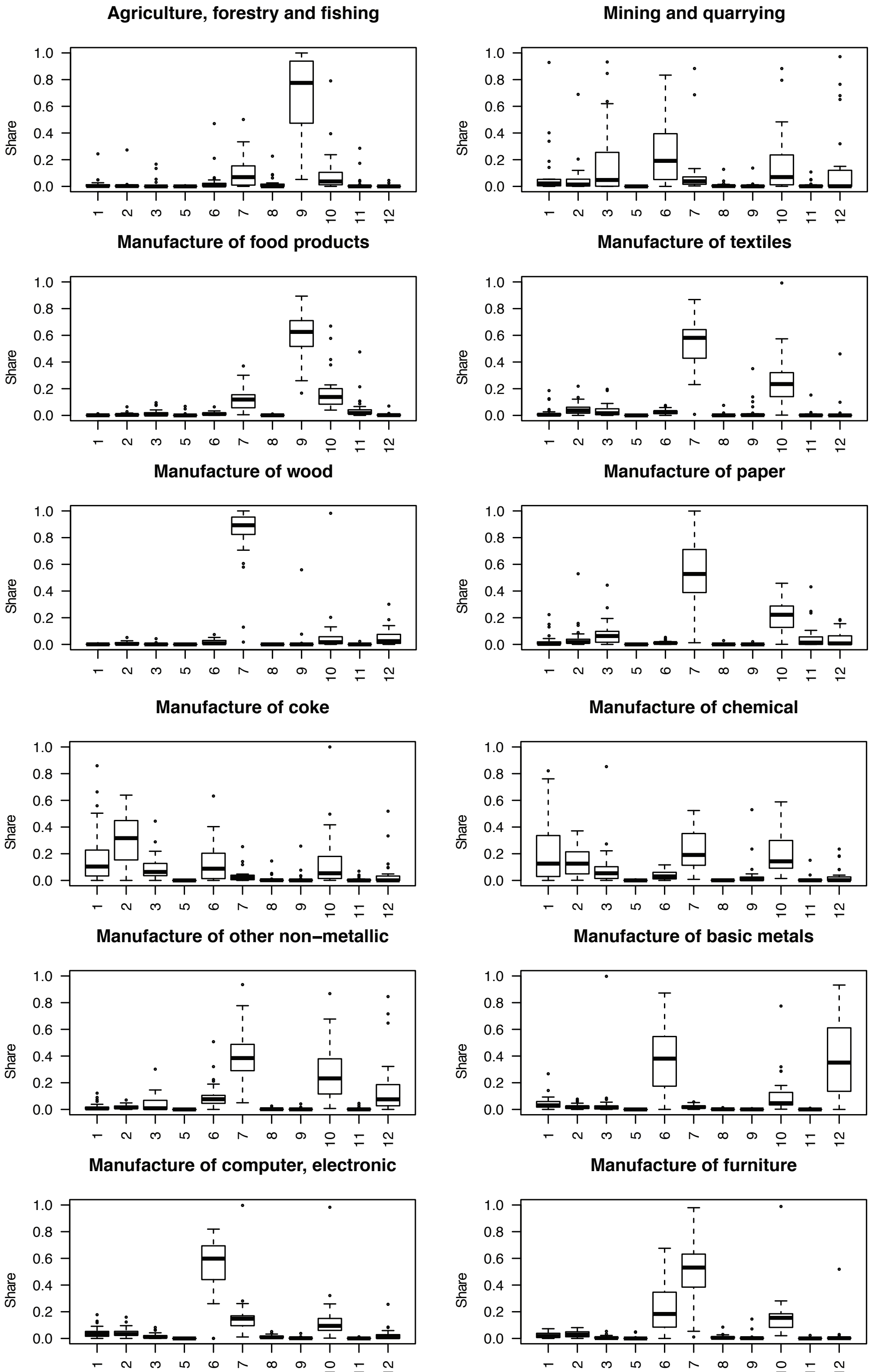

Figure 3 - Sector Waste Ratios (SWR) of all waste categories (EWC12)

By analysing the SWRs (see Figure 3) alongside the waste categories from Figure 2, it is possible to select sectors that produce biodegradable waste. EWC12 category 9 waste (Animal and vegetable waste) can mostly be found in the Agriculture sector (78%, median) and in the Manufacture of food products sector (63%, median) (Figure 2). Category 7 (Non-metallic minerals), includes biodegradable wastes such as sorted wood, paper and textiles. For each ton of waste produced, the Manufacture of wood sector generates approximately 89% of Category 7 waste, while Textile production, Manufacture of paper and Manufacture of furniture each generate approximately 53%. The sectors Manufacture of chemicals and Manufacture of other non-metallic minerals also generate large amounts of Category 7 waste. However, as is clear from the more detailed data for EWC42 (see full results in supplementary information figure 1), the waste generated here is non-biodegradable, and includes for example rubber and glass. Finally, Category 11 (Common sludges) waste is mostly generated within the sectors Manufacture of food products and Manufacture of paper.

Table 1 shows the shares of biodegradable EWC42 waste expected to be generated by 6 selected sectors. The Manufacture of paper and Manufacture of textile sectors generate the greatest share of EWC42 category 07.5 (Paper and cardboard wastes) while Manufacture of wood generates the most Wood wastes. The most common waste categories in the Agriculture and Manufacture of food sectors are EWC42 category 09.1 (Animal and food wastes), EWC42 09.2 (Green wastes), and EWC42 09.3 (Slurry and manure).

Table 1 – Waste Ratios (WR) of biodegradable waste categories (EWC42) for each ton of waste produced for selected NACE sections (that produce biodegradable waste)

NACE Section	Lowe Quartile, Median and Upper Quartile	07.2 Paper and cardboard wastes	07.5 Wood wastes	07.6 Textile wastes	09.1 Animal and food waste	09.2 Green wastes	09.3 Slurry and manure	11.1 Waste water treatment sludge's
Agriculture	Lower Quartile	0%	0%	0%	0%	2%	4%	0%
	Median	0%	1%	0%	2%	5%	42%	0%
	Upper Quartile	1%	3%	0%	9%	20%	76%	0%
Manufacture of food	Lower Quartile	2%	0%	0%	12%	15%	0%	1%
	Median	4%	0%	0%	28%	25%	1%	2%
	Upper Quartile	7%	1%	0%	40%	36%	5%	4%
Wood Production	Lower Quartile	0%	81%	0%	0%	0%	0%	0%
	Median	0%	87%	0%	0%	0%	0%	0%
	Upper Quartile	1%	95%	0%	0%	0%	0%	0%
Paper Production	Lower Quartile	17%	1%	0%	0%	0%	0%	0%
	Median	34%	3%	0%	0%	0%	0%	1%
	Upper Quartile	65%	17%	0%	0%	0%	0%	6%
Textiles	Lower Quartile	7%	1%	18%	0%	0%	0%	0%
	Median	12%	2%	31%	0%	0%	0%	0%
	Upper Quartile	15%	3%	45%	0%	0%	0%	0%
Furniture	Lower Quartile	2%	20%	0%	0%	0%	0%	0%
	Median	6%	36%	0%	0%	0%	0%	0%
	Upper Quartile	9%	49%	1%	0%	0%	0%	0%

STEP 3 - Industries' waste generation profiles

Industries within the selected sectors are studied further. In the developed waste generation profiles database for insdustries, industries' waste generation profiles are quantified by their shares of EWC42 categories wastes (Industries Waste Ratio – IWR, see Equation 2). Figure 4 shows the IWR of the selected biodegradable wastes by different industry codes (NACE) within the Manufacturing of food sector. As an example, 80% of the waste generated by industry 1011 (Livestock and slaughtering activities) is expected to be biodegradable waste, of which 65% belongs to EWC42 category 9.1 (Animal and food waste). Figure 4 also shows that food processing industries generate mostly animal (EWC42 9.1) and sludge waste (EWC42 11.1).

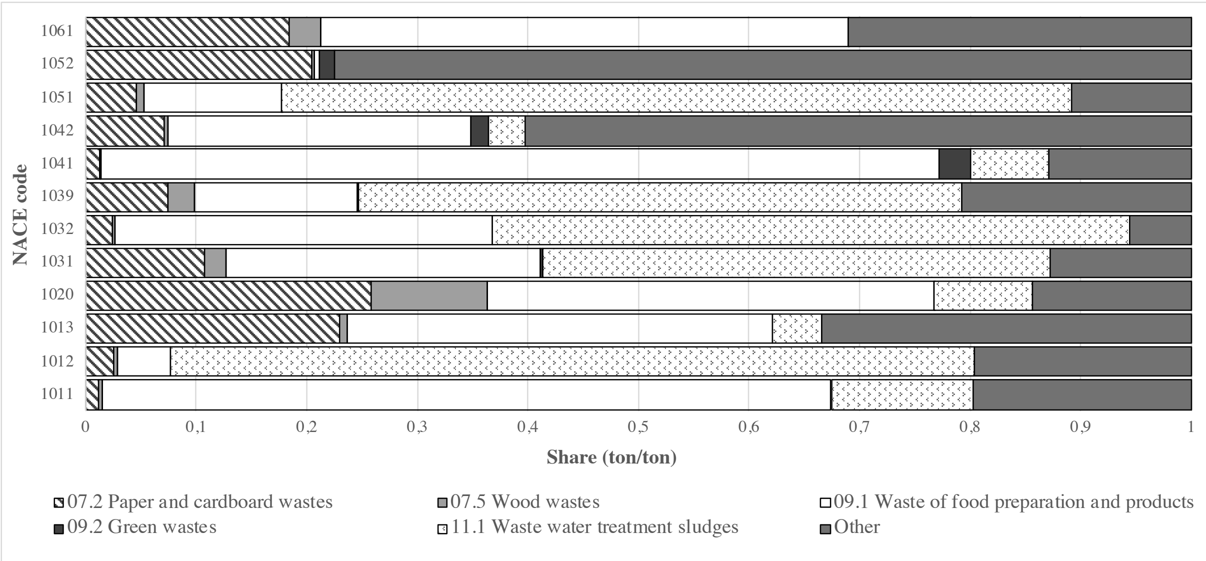

Figure 4 – Industries Waste Ratio (IWR) of industries generating biodegradable waste (EWC42). Note: none of the NACE industries presented in this figure produce waste belonging to category 9.3, why this category is not included in the figure.

STEP 4. Waste generation intensity

The Waste Factor per employee (WF) is used to estimate the amount of waste produced by a sector in a given region, or by an individual company within the sector (Equation 3). Figure 5 shows the expected WF factors for the total waste generated per sector, based on data for 28 EU countries. The results of the ANOVA tests showed that the effect of the number of employees on the amount of waste generated was statistically significant in every industry sector (as the p values for all relations are lower than 0.001). Also the log-log regression functions for each sector show a positive relationship between the number of employees and the total waste generation in tons, with r^2 values between 0.40 and 0.83. This confirms that it is reasonable to assume that the industrial waste generated by each industry is correlated to its number of employees. Yet, waste generation intensity is not only related to the number of employees, but also to other conditions, such as: environmental policy, legal instruments, economic instruments, enforcement/control, production processes, products, additive environment protection measures, waste prevention, recycling, disposal, logistics, etc. (Mertins et al., 1999). For the purpose of performing an initial approximation for waste prediction, the use of the number of employees data showed to be a good readily available option.

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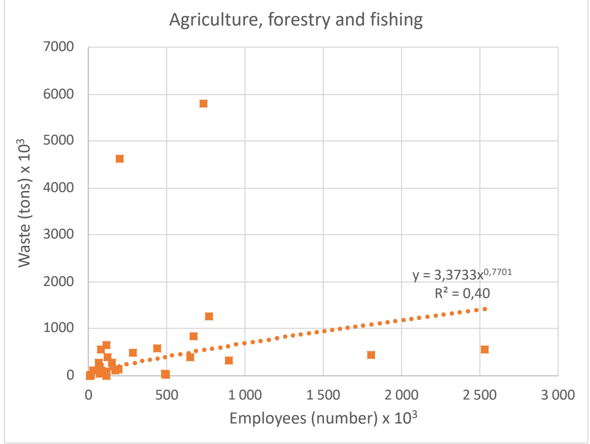
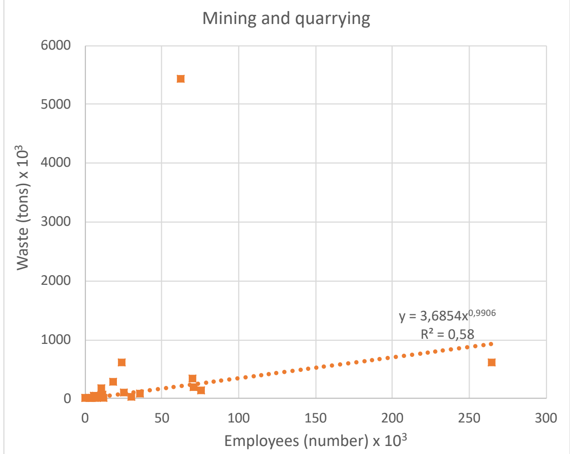
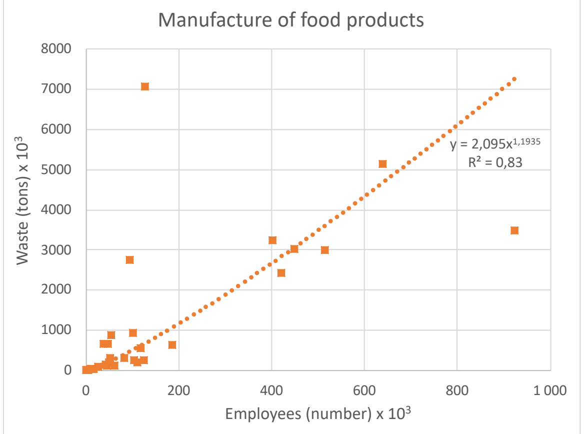


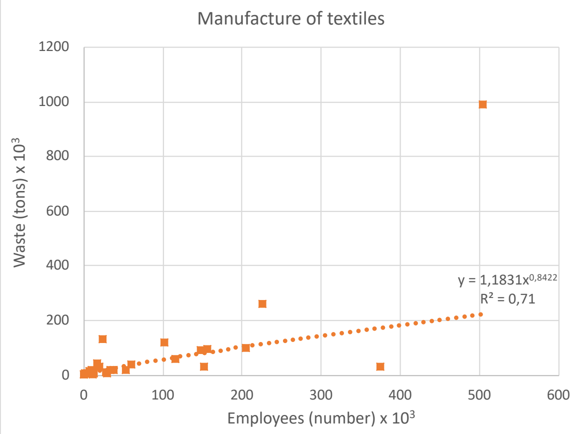
Agriculture, forestry and fishing
Waste (tons) x 10^3
Employees (number) x 10^3
0
1000
2000
3000
4000
5000
6000
7000
0
500
1 000
1 500
2 000
2 500
3 000
$y = 3,3733x^{0,7701}$
$R^2 = 0,40$



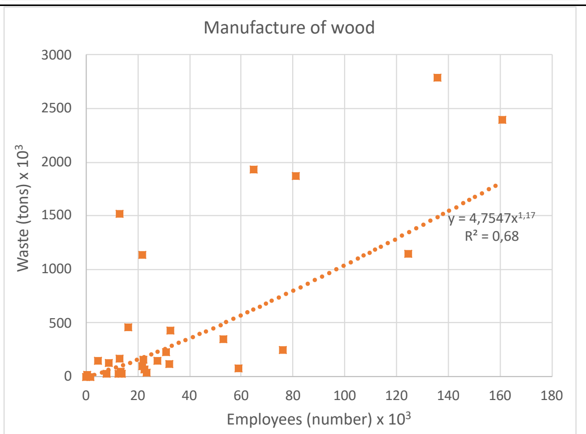
Mining and quarrying
Waste (tons) x 10^3
Employees (number) x 10^3
0
1000
2000
3000
4000
5000
6000
0
50
100
150
200
250
300
$y = 3,6854x^{0,9906}$
$R^2 = 0,58$



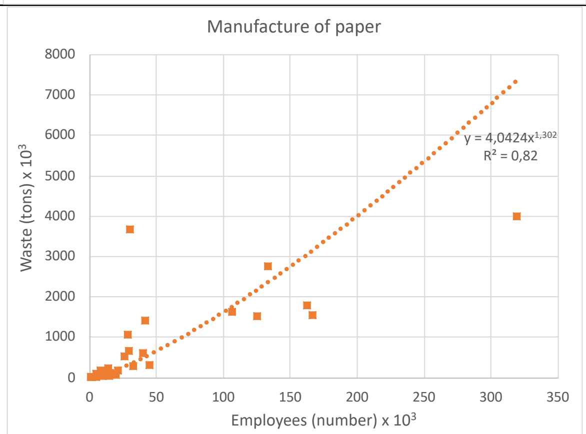
Manufacture of food products
Waste (tons) x 10^3
Employees (number) x 10^3
0
1000
2000
3000
4000
5000
6000
7000
8000
0
200
400
600
800
1 000
$y = 2,095x^{1,1935}$
$R^2 = 0,83$



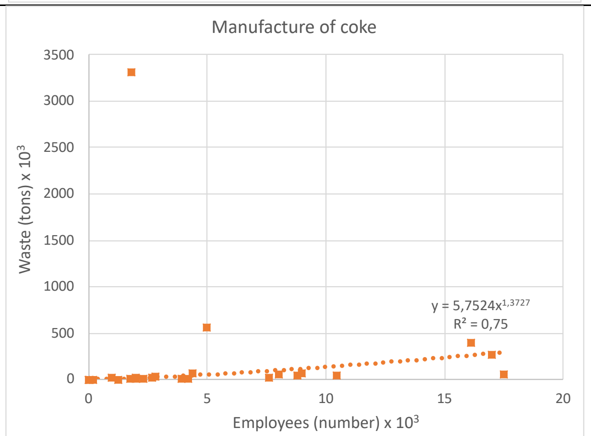
Manufacture of textiles
Waste (tons) x 10^3
Employees (number) x 10^3
0
200
400
600
800
1000
1200
0
100
200
300
400
500
600
$y = 1,1831x^{0,8422}$
$R^2 = 0,71$



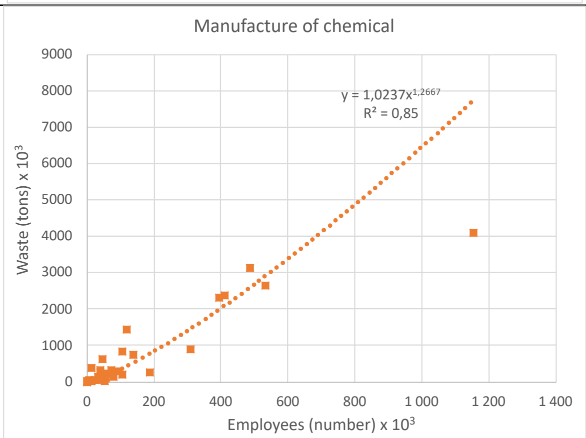
Manufacture of wood
Waste (tons) x 10^3
Employees (number) x 10^3
0
500
1000
1500
2000
2500
3000
0
20
40
60
80
100
120
140
160
180
$y = 4,7547x^{1,17}$
$R^2 = 0,68$



Manufacture of paper
Waste (tons) x 10^3
Employees (number) x 10^3
0
1000
2000
3000
4000
5000
6000
7000
8000
0
50
100
150
200
250
300
350
$y = 4,0424x^{1,302}$
$R^2 = 0,82$



Manufacture of coke
Waste (tons) x 10^3
Employees (number) x 10^3
0
500
1000
1500
2000
2500
3000
3500
0
5
10
15
20
$y = 5,7524x^{1,3727}$
$R^2 = 0,75$



Manufacture of chemical
Waste (tons) x 10^3
Employees (number) x 10^3
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
200
400
600
800
1 000
1 200
1 400
$y = 1,0237x^{1,2667}$
$R^2 = 0,85$

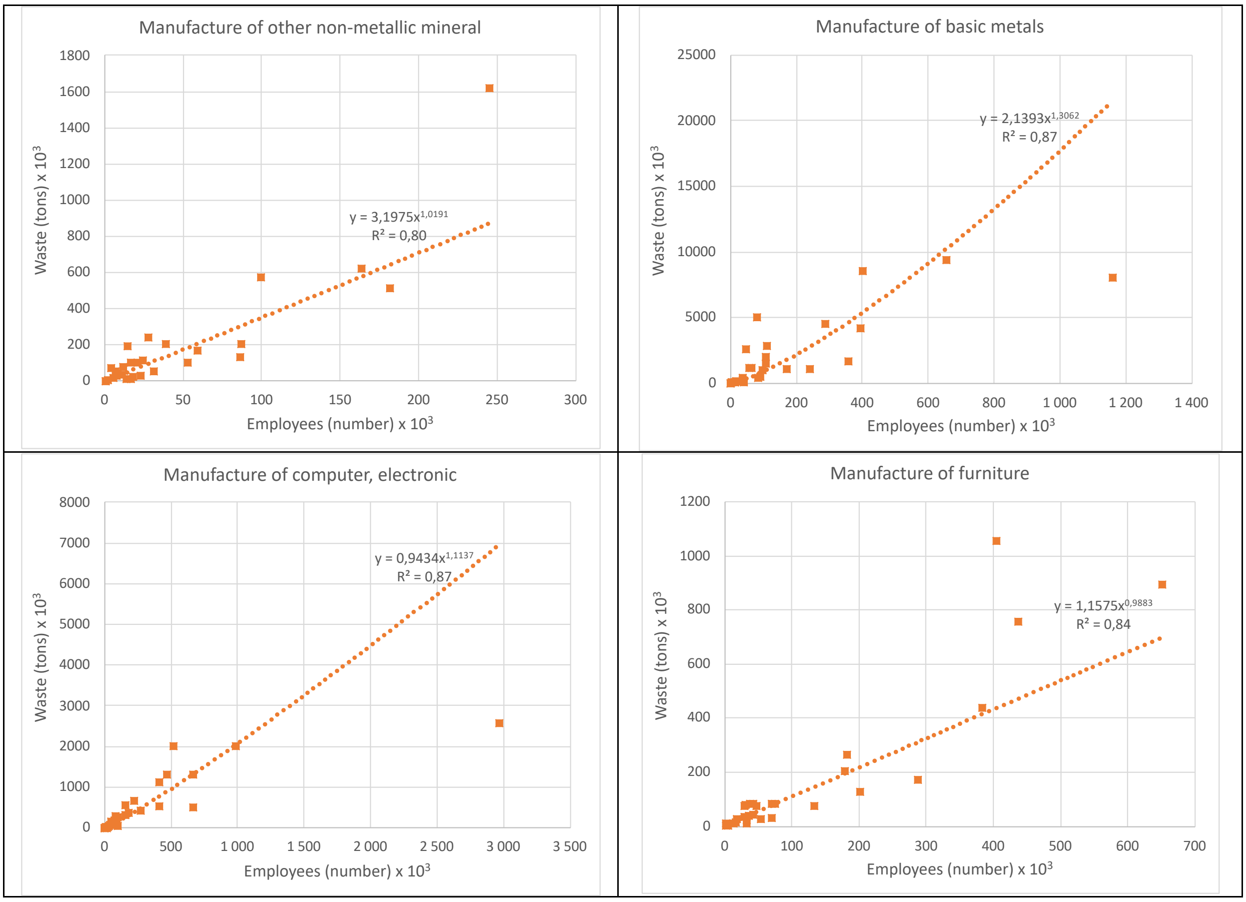


Figure 5 - Waste intensity per sector in Europe per employee

Production of Biogas example

Production of biogas using an anaerobic digestor is a complex chemical and biological process (Hamawand and Baillie, 2015). Factors to consider include the types of feedstocks to be used. For example, pig manure alone is a poor substrate due to excessive nitrogen content, but when combined with substances with high levels of organic carbon, such as straw, it becomes a very good feedstock (Gaworski et al., 2017). In fact, due to their high methane potential many of the industrial by-products can be used as "methane boosters" and added to other feedstocks (Wellinger et al., 2013). Table 2 shows the methane yields for some EWC42 waste categories, as well as minimum and maximum values for the group (Methane Yield representative values (MY)). Textile wastes are not included in Table 2 because no MY could be found in the literature. Furthermore, the biodegradability of textile waste is variable, as it may include non-degradable synthetic fibres. Waste category 09.1 (Animal and food waste) is the category with the highest MY and therefore a priority waste for the production of biogas.

Table 2 – Methane potential yield (MY) for each of the EWC42 biodegradable waste categories

EWC	EWC description	Representative waste	TS Dry weight	VS (g/g-TS)	VS (g/g-WS)	Methane potential mL/g VS	Methane Yield (mL/g wet basis)	Reference	Methane Yield (mL/g wet basis) Min	Methane Yield (mL/g wet basis) Max
07.2	Paper and cardboard wastes	Office Paper	0,.94				204	(Cruz and Barlaz, 2010)	70	251
		Newspaper	0.94				70	(Cruz and Barlaz, 2010)		
		Coated Paper	0.94				79	(Cruz and Barlaz, 2010)		
		Corrugated Containers	0.95				145	(Cruz and Barlaz, 2010)		
		Waste paper			0.82		251	(Sowunmi et al., 2016)		
07.5	Wood wastes	Wood shavings	0.80	0.95	0.76		16	(Steffen et al., 1998)	16	16
09.1	Animal and food waste	Apple pomace, fresh	0.20	0.98	0.20	416	81	Online European Feedstock Atlas basis version, 2018	49	824
		Fruit wastes	0.18	0.75	0.13	375	49	(Wellinger et al., 2013)		
		Poultry meat offals	0.94	0.87	0.81	570	464	Online European Feedstock Atlas basis version, 2018		
		Homogenized animal carcasses	0.35	0.92	0.32	1,140	365	(Steffen et al., 1998)		
		Food waste			0.24		122	(Sowunmi et al., 2016)		
		Animal fat (rendering plant)	0.90	0.92	0.82	1,000	824	(Steffen et al., 1998)		
		Pig slaughterhouse waste	0.51	0.49	0.25	580	144	(Rodríguez-Abalde et al., 2011)		
09.2	Green wastes	Garden wastes	0.75	0.90	0.68	400	270	(Steffen et al., 1998)	44	270
		Leaves	0.80	0.90	0.72	200	144	(Steffen et al., 1998)		
		Branches	0.70				44	(Cruz and Barlaz, 2010)		
09.3	Slurry and manure	Dairy manure	0.17	0.10	0.02	204	4	(Kafle and Chen, 2016).	4	83
		Horse manure	0.25	0.19	0.05	155	7	(Kafle and Chen, 2016)		
		Goat manure	0.82	0.64	0.52	159	83	(Kafle and Chen, 2016)		
		Chicken manure	0.68	0.48	0.32	259	83	(Kafle and Chen, 2016).		

		Swine manure	0.31	0.27	0,08	323	27	(Kafle and Chen, 2016)		
11.1	Waste water treatment sludge's	Waste water sludge	0.10	0.75	0,08	400	30	(Bayr, 2014)	0,2	30
		Paper pulp primary sludge	0.03	0.03	0,00	210	0,2	(Bayr, 2014)		
		Paper pulp secondary sludge	0.05	0.04	0,00	108	0,2	(Steffen et al., 1998)		

Combining the MY values from Table 2 with the Industries Waste Ratios (see Figure 4), the typical Industry Methane Yield (IMY) potential for each industry was obtained by applying Equation 3 (see results for industries with highest IMY-s in Table 3). The Overall Methane Volume (OMV) for each industry type was estimated as a product of IMY, waste intensity and number of employees. Manufacture of bread is the industry with the highest OMV. This industry generates large quantities of food waste, including bread and pastry products. Based on the data in Table 3, and assuming that there are no losses, the amount of biogas that could be produced from industrial wastes generated in the region is approximately a minimum of 0.103 and maximum of 0.590 TWh per year. When related to the goals established by the region, this would represent 25% of the defined target of 2.4 TWh.

Table 3 – Industrial activities that produce waste with higher methane yield potential in Västra Götaland region

NACE code	NACE Description	MIN Industry Methane Yield (IMY) (L/t-WS)	MAX Industry Methane Yield (IMY) (L/t-WS)	Total Waste Intensity (tons per year)	Min Overall Methane Volume (OMV) (m^3/year)	Max Overall Methane Volume (OMV) (m^3/year)
1071	Manufacture of bread; manufacture of fresh pastry goods and cakes	43,853	560,138	20,709	908,171	11,600,182
1812	Other printing	58,650	210,386	41,706	2,446,088	8,774,434
1011	Processing and preserving of meat	33,608	550,238	8,886	298,642	4,889,496
1020	Processing and preserving of fish, crustaceans and molluscs	39,775	402,293	10,585	421,024	4,258,331
1721	Manufacture of corrugated paper and paperboard and of containers of paper and paperboard	57,168	204,881	16,093	920,020	3,297,213
1085	Manufacture of prepared meals and dishes	28,022	291,202	9,197	257,706	2,678,072
1013	Production of meat and poultry meat products	35,207	376,529	6,022	212,005	2,267,310
1722	Manufacture of household and sanitary goods and of toilet requisites	16,155	73,100	27,255	440,292	1,992,331
1811	Printing of newspapers	62,924	225,957	7,124	448,254	1,609,655
1051	Operation of dairies and cheese making	10,873	135,137	10,547	114,672	1,425,263
1813	Pre-press and pre-media services	64,155	230,391	4,749	304,646	1,094,035
1089	Manufacture of other food products nec	39,565	455,239	2,396	94,783	1,090,579
1072	Manufacture of rusks and biscuits; manufacture of preserved pastry goods and cakes	30,758	241,242	4,490	138,109	1,083,212

Calculated Overall Methane Volume obtained for each of the NACE-code industries has a broad range due to the high heterogeneity of the expected methane yield for the detailed waste types within each of the EWC category. Waste ratios for these detailed waste types are not included in the statistics and therefore a MIN-MAX range of the methane yield (MY) is calculated for each of the EWC categories. This range is then used to calculate the OMV. Nevertheless, more precise results are easy to obtain for the selected region by removing some of the detailed waste types that are not expected to be present in the EWC categories of a specific NACE industry and therefore approximating better to the real detailed waste distribution and the corresponding EWC category's MY. As an example, it is not expected that within the NACE 1071 Manufacture of bread industry, "Slaughtering house wastes" can be generated within EWC category 09.1. Therefore, these wastes can be excluded, and new Overall Methane Volume values can be calculated.

The developed framework allows identification of those facilities whose waste generation could contribute the most to biogas production, which in turn makes it possible to identify municipalities with higher potential for biogas production. The results presented in Figure 6 show eleven municipalities within the Västra Götaland region, which have a higher potential for biogas production, including Gothenburg, Borås, Falköping, Lidköping, Skövde, Skara. Mariestad, Götene, Sotenäs, Möndal, and Kungälv. The map also shows the locations of the larger anaerobic digestion biogas plants, which are found in most of the municipalities with the highest OMV. This means that the distance between the waste owners and the potential receivers is probably not too high, an important factor for enabling an industrial symbiosis partnership (Golev et al., 2015). Currently, most of these plants use primarily waste of vegetable origin, and source-separated household waste (PURAC, 2018). It should be noted that the Gothenburg municipality, most populous in the region, and the surrounding municipalities currently do not have a large anaerobic digestor with the ability to process biodegradable urban and industrial waste. Therefore, the installation of an anaerobic digestor ought to be explored. The suggestion is that the anaerobic digestor should be located close to the natural gas pipeline, so that the produced biogas could be injected into the grid.

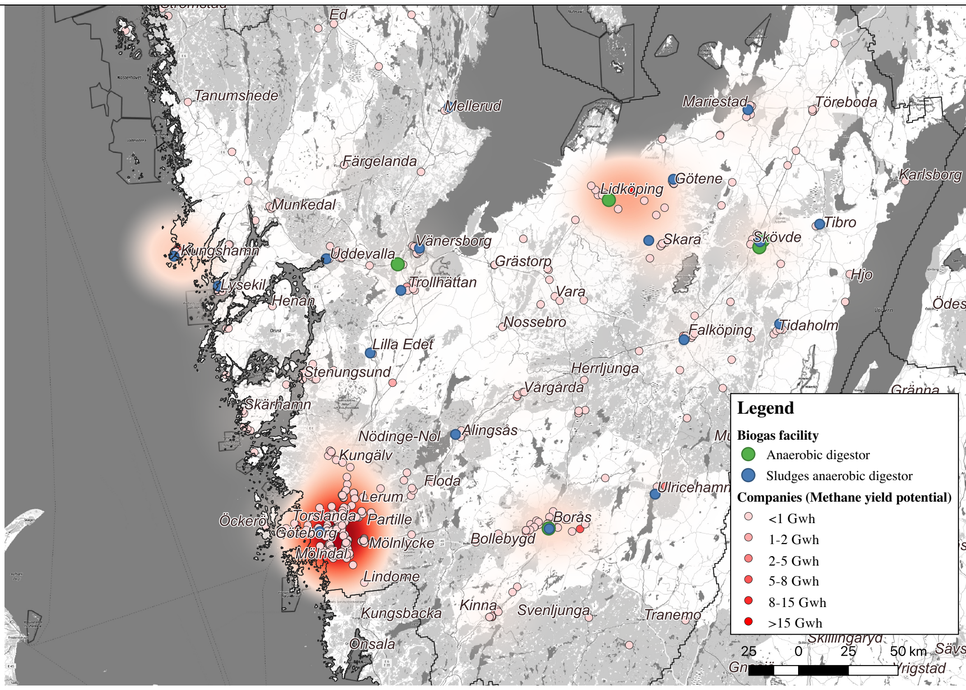


Figure 6 - Heat map

Method discussion

The developed method enables development of circular economy and industrial symbiosis plans by answering different questions through screening of the types and quantities of industrial wastes that are expected to be generated by industries. Indeed, according to Song et al., 2017, the first step to discover and plan industrial symbiosis involves the understanding and visualisation of material flows, which can be done using the entire framework developed in this study. The method allows a quick and easy estimation on the quantities and amounts of expected wastes in geographic areas such as a municipality, a region or a country. With such information, waste streams can be prioritized for circular economy (CE) actions according to their high quantity, content of non-renewable and/or valuable materials, environmental impact, available pathways for reuse, proximity to utilization facilities, etc. The method is versatile, allowing to be applied at different scenarios.

The first application scenario focuses on types of wastes, for instance investigating which industries or sectors can be expected to generate a given type of waste. This application is illustrated on the biogas example, with biodegradable waste as the target feedstock. In the example, facilities were prioritized not only based on the amounts and types of generated wastes, but also according to the waste's methane yield potential, as well as the location of the receiving facilities.

The second application scenario is through focusing on waste generation in selected economic sectors and industries. This application is useful to public sector actors, industrial branch organizations and companies. For example, if furniture manufacturing is an intense industry in a region, what types and quantities of waste can this industry be expected to generate? How can this waste be best utilized?

Another example could be when a new business that will use a specific waste type as a raw material is to be set up in a region. The method and the profiles databases presented here could be used to identify any industries already operating in the region that would be able to supply the sawdust and in such a way inform the decision about the business opportunities as well as an optimal location in which to establish the new business.

As exemplified in the scenarios, the study results should be seen as a starting point to prioritize either particular waste flows or sectors or industries. The results could be combined with bottom-up data to perform detailed studies of available CE actions including industrial symbiosis, upcycling, material and energy recovery, etc. Such a method application can be useful to researchers to identifying focus for in-depth investigation of CE/IS implementations and to public sector agencies for development of CE strategic plans and policies. For example, the estimated generation of industrial wastes within the area can be complemented with the facilities geographic location, as has been illustrated in the example developed in this article.

The top-down method for industrial waste estimation developed in this paper has several strengths. It is comprehensive, encompassing all the industry sectors and types of wastes. It is based on data acquisition from statistical offices publications, in contrast to the bottom-up approach where industries need to be interviewed. The method gives a possibility to easily update the data with new releases of the relevant statistics and in such a way captures changes in the production processes and waste generation.

The constructed sector waste profiles (Figure 3) are useful for identifying the focus for waste management in different sectors, which can be used by industrial branch organisations. Public sector actors can use sector waste profiles together with the waste intensity factors for determining which sector should be targeted for improved management of a certain type of waste. The validity of the method for estimating waste generation using waste factors per employee, developed in this paper, has been corroborated by the results showing a clear positive relation between the number of employees and the waste generation within each sector. The application of the waste factors is manifold, including easy comparison of companies´ waste flows with the European benchmark and for providing estimates on waste flows at different spatial scales. The statistical test results showed that whilst there is a relation between number of employees and waste generation in all sectors, correlation coefficients were stronger in some sectors than others. Consequently, waste generation estimates should be used with caution for those sectors where the correlation coefficient was lower. Waste generation factors were also calculated for 2004 and compared to the 2014 factors used in this study. The results showed no significant statistical differences between the values obtained with the 2004 and 2014 data, which suggests that waste generation factors are reasonably stable (see supplementary information figure 2).

An important contribution of the developed method to the IS research field and to IS implementation practice is adapting and enabling the use of the IS concept to municipalities and regions. By describing available secondary resources of an area, the developed method provides public sector agencies with a systematic approach to a community and regional development using IS and CE frameworks. Using regional scale for IS projects brings several advantages including economies of scale, proximity between companies and diversity of industries that leads to greater resource pathways opportunities. The developed method can then be combined with IS facilitation methods, such as the one developed by Rosado and Kalmykova (2019) to ensure that IS is put into practice. Application of IS and CE practices could create conditions for economically, environmentally and socially sustainable communities, cities and regions by providing green jobs, eliminating waste, preserving virgin resources, and promoting city-countryside connections (Rosado and Kalmykova, 2019).

In general, as well as in relation to this study, the main drawback of a top-down approach is the higher level of uncertainty, compared to bottom-up approaches. We therefore highlight that the results of the developed method should be seen as a starting point that gives valuable indications on which industries or sectors should be analyzed more comprehensively. The Sector Waste Ratios can be considered to be reliable as they were calculated using data from 28 countries. Statistical analysis could not be applied to Industry Waste Ratios (IWRs) due to insufficient sample points. The IWRs therefore have more uncertainty, even though they provide a high level of detail. The quality of the IWRs could be improved by employing the method with data from additional countries. The developed databases for sectors and industries can be used independently. Within the developed method, the estimation of waste quantities generated is prone to uncertainty as it uses number of employees as a proxy and is performed with sector level data. Conversely, this is the best method currently available as number of employees is the only readily available data when scaling geographic boundaries down from country level. Otherwise, information on industrial waste generation is only available at national level and for each NACE sector. Another source of uncertainty is the assumption that companies within the same NACE sector generate similar types of waste.

Additional layers of information on NACE activities could be added to the industries waste generation profiles in order to reduce the uncertainty of the results, using detailed industrial processes descriptions available in the literature or within LCA databases. There are also web portals with information about manufacturing processes and the waste streams of individual processes (Song et al., 2017). More detailed nomenclature for waste types can be used, if necessary. The EWC42 can be further disaggregated into the List of Waste, which includes approximately 840 waste types.

4. Conclusions

High hopes are attached to the implementation of circular economy in society, as this approach could potentially solve multiple challenges, including security of resource supply, environmental impacts and economic growth. One of the powerful strategies of a circular economy (CE) is industrial symbiosis (IS), where the waste from one industry is utilized as a resource for another. Currently, implementation of the CE, and of industrial symbiosis in particular, is hampered because of a lack of sufficiently detailed data on the available industrial wastes. Obtaining facility level industrial waste data is time-consuming and often even impossible for confidentiality reasons. The presented method addresses this gap and enables planning of the CE and IS by providing an approach to industrial waste generation estimation. Development of this method has been inspired by multiple requests from public sector agencies and trade organisations to assist in CE and IS planning and implementation.

This study is a contribution towards enabling IS design by providing characterisation of industrial waste at facility level and for 42 waste types. This is done by developing two waste generation profiles database, one for industries and one for sectors. This new level of detail is sufficient to identify materials that can be reused by another industry and to produce an industrial waste generation profile for a given region. A circular economy action plan for a region can then be devised based on the available secondary materials. The method and the resulting waste generation profiles databases can be adapted to multiple scenarios: focus on different geographic boundaries, including municipal, regional or country level; focus on industries or sectors, including which types of wastes are expected to be generated and in which quantities; and focus on types of wastes, as for instance investigating by which industries a type of waste is expected to be generated and in which quantities.

The profiles databases set up according to the described method can be filtered by waste nomenclature (EWC), to focus on a certain target waste and look for industries or sectors that generate it, the geographic locations where the waste is generated, and the potential quantities available. The latter application is illustrated in a framework included in this article, where industrial wastes with a high potential for use in biogas production are quantified and mapped for the Västra Götaland region in Sweden. The results of the developed example show that 11 out of 49 municipalities generate sizable quantities of waste that could be used in the production of biogas. The potential for biogas production from industrial wastes was calculated as 0.590 TWh. These results have been used as a starting point for the initiation of a collaborative project with a potential IS facilitator for the region – Hållbar Utveckling Väst, which is the regional energy agency for the Västra Götaland region. The agency works to promote sustainable development in general, and sustainable energy sources in particular. As illustrated by this example, the developed profiles databases can help local authorities, regional developers, NGOs and industrial associations, among others, to obtain the data needed to implement a circular economy in a given region. There is a need to further investigate the best data content and format for different stakeholders, which is a work in progress.

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