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Method for identifying industrial symbiosis opportunities

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ABSTRACT

Industrial Symbiosis (IS) can reduce industrial waste and the need for virgin material extraction by utilizing waste generated by one industry as a raw material for another. Input-output matching is a commonly used approach for identifying potential IS partnerships. Usually, to collect necessary data for input-output matching, companies are asked to participate in workshops or surveys. However, such activities can be costly and time consuming. Additionally, companies may be unwilling to participate due to issues around data confidentiality. This article aims to show how these barriers can be overcome by a new method for identification of IS opportunities, which does not require companies to be surveyed. The developed matching approach uses statistical datasets and IS databases. The underlying principle is to use known IS partnerships and databases developed by the authors containing data on typical waste generation and resource use by industries, to expand and link other potential donors and receivers. This allows the expansion of one IS example into multiple potential relationships. The method promotes Circular Economy development by identifying more opportunities to utilize more secondary resources through connecting previously unrelated industry sectors. The method has been tested in Sweden, where the goal was to identify potential partnerships between industries that generate sawdust as a waste product and companies that could utilize sawdust in their industrial processes. Out of 6,726,534 potential symbiotic links identified by the method, 159,630 were shortlisted using prioritization criteria reflecting an increased likelihood of symbiosis.

1. Introduction

Industrial Symbiosis (IS) involves collaboration between companies, in which they exchange materials, energy, water and/or by-products (Chertow, 2007). Together with eco-industrial parks and supply chains, IS is one of the three main fields supporting sustainable industrialization within the Circular Economy arena (Homrich et al., 2018). In recent decades, IS has gained much attention among policy makers, businesses, and academia, as a means to support the transition to a circular model (Gregson et al., 2015). In the European Union (EU), IS has been recognized as a tool that can be used to promote sustainable growth and resource efficiency in industrial systems. In 2012, IS was defined as one of the top seven priority areas by the European Resource Efficiency Platform (Johnsen et al., 2015).

A number of different methods can be used to identify potential IS partnerships, including New Process Discovery, Relationship Mimicking, Material Budgeting, and Input-Output Matching (Grant et al., 2010; Holgado et al., 2018). Input-Output Matching is perhaps the most commonly used method, and involves finding potential IS matches by analyzing characteristics of output streams (i.e. wastes and by-products) from industries and the material inputs they require, before matching one to the other (Bin et al., 2015; Hein et al., 2016; Low et al., 2018; Yeo et al., 2019). This method can be used to achieve higher efficiency in industrial parks (Holgado et al., 2018), via IT-enabled identification using semantic matching (Trokanas et al., 2014) or expert-facilitated workshops (Maqbool et al., 2019). The most widely known program using Input-Output Matching is the National Industrial Symbiosis Program (NISP), which uses bottom-up approaches to facilitate IS in a given region. Using a cross-sectoral and supply chain approach, NISP is able to identify opportunities among stakeholders participating in workshops (NISP Canada, 2017).

Although bottom-up approaches have been shown to be successful in identifying opportunities for IS partnerships, they have some limitations. In order to obtain the necessary data, companies must take part in certain activities, such as registering resources or wastes on web platforms, or sharing information by participating in workshops or meetings

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(Alvarez and Ruiz-Puente, 2017). However, certain factors can limit the necessary data acquisition, including: 1) data confidentiality, 2) time constraints, and 3) high costs. There are multiple examples of companies being reluctant to share confidential information, e.g. on raw material consumption or waste generation (Bacudio et al., 2016). Additionally, companies hesitate to share information if they do not see clear value gains (Patala et al., 2020) and in many cases companies do not have time to engage in these types of activities (Patricio et al., 2018). Conducting audits and interviews to collect information about inputs and outputs is associated with high costs and may be very time consuming (Hein et al., 2016). Sometimes companies may simply not have been considered for a workshop, forgotten to register their wastes on an online platform, or to fill in a questionnaire.

At the same time, we are facing the Fourth Industrial Revolution (Industry 4.0) which among other things, relies on the availability of large amounts of data. Data-driven analysis can now be used to optimize sustainable solutions, including the efficient use of resources and energy (Reis and Kenett, 2018; Tseng et al., 2018). The results and methods developed as part of Industry 4.0 may help decision-making processes and identify approaches that effectively promote waste circularity (Winans et al., 2017). As a result, it may be possible to employ top-down approaches that utilize available datasets, and to develop tools with the ability to identify IS opportunities. However there are still some challenges relating to data availability that have been identified. Chen and Ma (2015) have pointed out the lack of comprehensive and standardized databases for material streams. This is even more evident for waste generation datasets, which are usually only available with very high aggregation (Reynolds et al., 2016).

It is also known that considering different industries at the same time improves the chances of finding potential applications for waste reuse in a particular geographical area. According to Jensen (2016), diversity within industrial ecosystems promotes resource reuse and, potentially, increased system production. However, there is a lack of tools that allow identification of potential relations between multiple sectors and industries (European Commission, 2018). One explanation for this may be the lack of comprehensive and standardized databases for material flows (Chen and Ma 2015). In particular, waste generation datasets are usually only available with very high aggregation (Reynolds et al., 2016). If this data was available, input-output matching could rely on information about stream characteristics and technological capability, rather than the willingness and ability of individual companies to share data (Yeo et al., 2019).

The aim of this article is to introduce a method for identification of potential IS partnerships that makes use of available detailed datasets. This has been achieved by coupling a top-down approach with input-output matching. The developed method intends to: 1) use available data to avoid direct involvement of companies in the preliminary phase of IS, overcome common issues, including confidentiality problems and the use of time-consuming tools such as surveys or interviews, and to 2) employ comprehensive tools to consider potential relationships between companies from different sectors operating within the same spatial area. To achieve this, the method considers 103 industries, 1,264 material input types, and 816 waste types. The method has been tested in a spatial application on the Västra Götaland region.

2. Method

The method developed in this study identifies potential matches for IS using a top-down approach. A schematic diagram of the method is presented in Figure 1. The method consists of three steps: 1) identification of industrial wastes generated by industries, 2) identification of material inputs needed by industries, and 3) matching industrial wastes to material inputs. It has been developed using Eurostat standard nomenclatures, which correspond to similar nomenclatures used in other regions of the world. The method has been tested in a spatial application that involved analysis of potential IS opportunities considering distances between companies. In this study, the method was applied to wood wastes generated in the Västra Götaland region in Sweden. The methodology is explained in detail in Section 2.2.

2.1. Nomenclatures and Data Collection

In this article, industries, material inputs and wastes have been classified using Eurostat standard nomenclatures, which correspond to similar nomenclatures used in other regions of the world (Ramon, 2020).

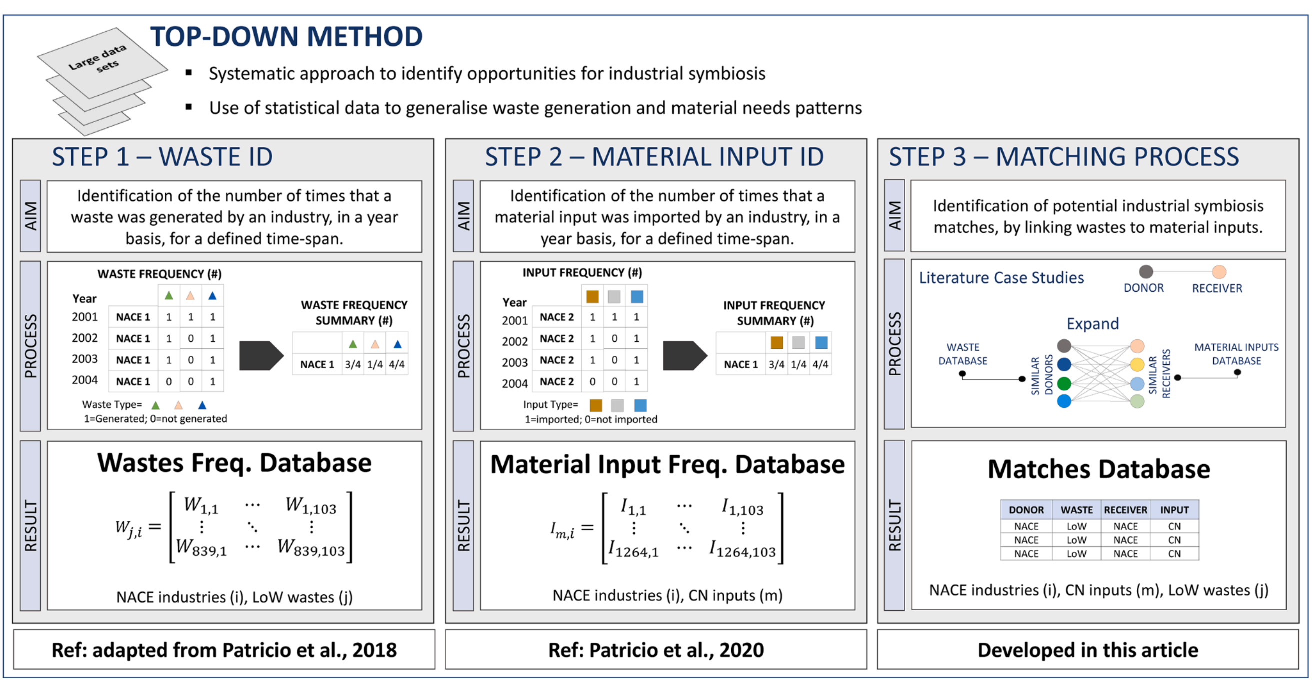

Figure 1. - Top-down Method for Identifying Industrial Symbiosis Opportunities

- Industries are classified using the Statistical classification of economic activities in the European Community nomenclature, abbreviated as NACE. More specifically, the NACE rev. 2 nomenclature at 3 Digits is used. This study includes companies from agriculture, mining and manufacturing sector, corresponding to NACE 011 up to NACE 380, a total of 103 activities, referred henceforth as 'industries'. For example, NACE code 310 stands for "Manufacture of Furniture". The entire list of NACE codes can be found in Table 1 in Supplementary Information. There is a correspondence between NACE and United Nations' International Standard Industrial Classification of all economic activities (ISIC).
- Products or material inputs are used interchangeably in this article and represent all the goods used by industries. This includes structural products, auxiliary products and investment goods (see Patricio et al (2020) for more details). They are classified according to the Combined Nomenclature (CN), the classification used in the European Commission for collecting and processing data on foreign trade. The four-digit disaggregation (CN4) is used (Table 2 in Supplementary Information), which includes 1,264 different products. As an example, CN4 code 4407 stands for "Wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness of $>$ 6 mm" (Eurostat, 2020). The CN codes correspond to the Harmonized System (HS) which is the internationally standardized system of names and numbers to classify traded products.
- Industrial wastes are classified according to the European List of Wastes (LoW) nomenclature, developed by the European Commission. This waste nomenclature encompasses 839 wastes types. As an example, LoW code 30101 stands for "Waste bark and cork (Eurostat, 2010). The LoW codes can also be aggregated into European Waste Classification for Statistics (EWC-stat) waste categories. Following the same example, LoW code 30101 (waste bark and cork) belongs to the EWC-stat 07.5 "Wood wastes".

$$W_{j,k} = \begin{bmatrix} W_{1,1} & \cdots & W_{1,103} \\ \vdots & \ddots & \vdots \\ W_{839,1} & \cdots & W_{839,103} \end{bmatrix} W = \textit{Waste Outputs frequency},\ j = 1,2 \,..\, 839 \textit{ classes of wastes } (\textit{LoW codes}) \textit{ and } k = 1,2..103 \textit{ industries } (\textit{NACE codes}) \tag{1}$$

The method employs three databases that were developed using existing datasets: 1) Material Input Data contains detailed international trade data on products (8-digit CN codes) imported in a specific year, at country level and by industry (NACE codes). The International Trade dataset is a detailed database that measures value and quantity of goods traded both between EU Member States and between EU Member States and non-EU countries on a product basis (Eurostat, 2016). Data for Portugal for the years 2000 through 2012 was used; 2) Industrial Waste contains detailed data on wastes (LoW codes) generated by industries (NACE code). 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. Data for Portugal for the period from 2010 until 2014 was used; 3) Industrial Symbiosis Case Studies, developed using published literature, contains IS case studies with information on waste donor, waste receiver, and type of exchanged waste (See Table 3 in Supplementary Information for more detailed information on the databases). Due to difficulties in acquiring the first two datasets for Sweden, data for Portugal was used. As shown in Patricio et al. (2021), material inputs to industries in Portugal and Sweden are 60-80% similar, which makes use of developed databases suitable for Swedish conditions as well. The use of the datasets is limited to identifying the frequencies of production of waste and the frequency of use in industries since some products with high dependence on domestic input sources will not be captured with the International Trade datasets and therefore skew the quantification of the inputs amounts in weight.

2.2. Top-Down Methodology

2.2.1. Typical Waste Identification (Step 1)

The first step identifies the types of wastes generated by different industries (by NACE codes). This is based on the assumption that companies within the same industry generally generate similar types of waste. Based on the previous work by Patricio et al. (2020), a matrix of typical wastes generated within each industry was developed. The Waste Frequency database has also been created based on the Industrial Waste dataset described in section 2.1 Nomenclatures and Data Collection. The frequency value indicates the number of years in which at least one company within a particular industry (k) generated a specific waste type (j) within a given time span. This means that if only one company within a particular industry generated a specific waste type in a given year, the frequency value is 1, regardless of the amount of waste generated. The time span used in this study was four years (2012 to 2015), and the frequency values therefore vary from 0 to 4. As an example, a frequency value of 2 means that at least one company within a particular industry generated a specified waste in two of the four years. This does not necessarily have to be the same company. Following the same example, a frequency value of 2 can also mean that two companies within the same industry each generated the same waste type once in two different years. A frequency value of 4 represents a waste that is highly likely to be generated by a certain industry, and 0 represents a waste that is unlikely to be generated within a given industry.

2.2.2. Typical Material Inputs Identification (Step 2)

Typical inputs used by industries were identified using the method developed by Patricio et al (2021), which assumes that companies belonging to the same industry (NACE codes) typically use the same types of material inputs. Using international trade statistics, a Material Inputs Frequency database was developed for all industries and all CN codes. This database is the equivalent of the Waste Frequency database, but for material inputs. It contains information on the frequency for each CN product (i) used by each industry (k) during a fourteen year-period (2000 to 2013). The frequency value indicates the number of times a given product was imported by an industry, and the values therefore vary between 0 and 14. The value 0 corresponds to a product that was never imported by an industry, and the value 14 a product that was imported in all the years. Any product with a value of 14 in the Material Input Frequency database is highly likely to be used by companies operating in that industry.

Table 1
- Summary of Potential Matches between Wastes and Material Inputs

	Meat and edible meat offal	Oil seeds and oleaginous fruits;	Lac; gums, resins and other vegetable saps and extracts	Vegetable plaiting materials;	Sugars and sugar confectionery	prepared animal fodder; residues	plastering materials, lime and cement	Ores, slag and ash	Mineral fuels, mineral oils and products of their distillation;	Inorganic chemicals;	Organic chemicals	Fertilisers	Albuminoidal substances; modified starches; glues; enzymes	Miscellaneous chemical products	Plastics and articles thereof	Wood and articles of wood; wood charcoal	Pulp of wood or of other fibrous cellulosic material;	Silk	Wool, fine or coarse animal hair;	Cotton	Man-made staple fibres	Other made-up textile articles;	Articles of stone, plaster, cement, asbestos, mica or similar materials	Other base metals; cermets;	Electrical machinery and equipment and parts thereof;
EWC / CN Groups	**2**	**12**	**13**	**14**	**17**	**23**	**25**	**26**	**27**	**28**	**29**	**31**	**35**	**38**	**39**	**44**	**47**	**50**	**51**	**52**	**55**	**63**	**68**	**81**	**85**
01.1 Spent solvents											5358			595											
01.2 Acid, alkaline or saline wastes							52			8826		34													
02.1 Off-specification chemical wastes							92			168			1005												
02.3 Mixed chemical wastes											1026														
03.1 Chemical deposits and residues												27											2233		
03.2 Industrial effluent sludges						36	87			42		54													
06.1 Ferrous metal waste and scrap										144															
07.2 Paper and cardboard wastes																	555								
07.4 Plastic wastes															7848							5995			
07.5 Wood wastes																7594	1680								
07.6 Textile wastes																		288	288	864	720	790			
08.4 Discarded machines and equipment components																									8800
09.1 Waste of food preparation and products	145	120	48		20	3084	87					2862													
09.2 Green wastes																480									
09.3 Slurry and manure				213																					
10.2 Mixed and undifferentiated materials							418					135													
11.1 Waste water treatment sludges												162													
11.2 Sludges from purification of drinking and process water												378		245											
12.1 Construction and demolition wastes														3740											
12.3 Waste of naturally occurring minerals							459		138																
12.4 Combustion wastes							4782	10	140															23600	
12.5 Various mineral wastes										100				55											

$$\mathrm{I}_{i,k} = \begin{bmatrix} I_{1,1} & \cdots & I_{1,103} \\ \vdots & \ddots & \vdots \\ I_{1264,1} & \cdots & I_{1264,103} \end{bmatrix} I = Material\ Inputs\ frequency,\ \ i = 1, 2\ ..\ 1, 264\ classes\ of\ products\ (CN\ codes)\ and\ k = 1, 2..103\ industries\ (NACE\ codes) \tag{2}$$

2.2.3. *Matching Process (Step 3)*

In this step, potential IS partnerships between NACE industries are identified. IS case studies found in the literature and the frequency databases developed in Section 2.2.1 and Section 2.2.2 were used to identify other industries that generate similar wastes (Donors) and need similar material inputs (Receivers). The core idea is to expand one single IS case study into multiple potential IS matches, defined in this study as the Matching process. The Matching process is divided into 4 stages: 1) Industrial Symbiosis case study details; 2) Expansion; 3) Matching, and; 4) Results printing. The Matching process is explained in detail below and in Figure 2.

In Stage 1 (utilization of IS case studies), the tasks done involved the identification of proven links between wastes and material inputs from IS case studies found in the literature. Existing databases are preferred sources of data, as they include multiple IS partnerships in a summarized format, and some are compiled using standard nomenclatures. The MAESTRI (MAESTRI project, 2020) and IS Data (IS Data, 2020) are examples of such IS databases. For illustration purposes, this article uses the MAESTRI database.

The MAESTRI database is a list of IS examples assembled by an EU-funded research project (MAESTRI Project, 2020). For each IS case study, the MAESTRI database contains information on: the NACE code of both industry Donor (i.e., waste provider) and Receiver (i.e., material inputs user); LoW code for the exchanged waste; and the CPA (Classification of Products by Activity) code of the material input. To use the MAESTRI database, certain data treatment was required. First, some missing nomenclature codes were added to the MAESTRI database, based on descriptions available in the database. Second, nomenclatures were converted into the ones used in this method. The CPA codes for material inputs in the MAESTRI database were converted to CN codes using a correspondence table, available in Eurostat (Ramon, 2020).

In total, the MAESTRI database contains 425 IS case studies. Non-applicable case studies were excluded as part of the data treatment performed in Stage 1. The removed case studies included: symbioses not related to materials, for example, heat, electricity, water, or vapor (72 cases); and lacking fundamental information, such as LoW or CPA codes (155 cases). Additionally, some of the case studies were duplicates. Each of the remaining 158 case studies in the MAESTRI database were used to create a match between a waste (LoW code) and material input (CN code). The relations between wastes and material inputs were then used in Stage 2, Expansion.

Stage 2 (Expansion) tasks, involved identification of potential Donors and Receivers for each relationship identified in Stage 1. Starting with the first relationship, the Waste database (section 2.2.1) was used to identify all industries that may generate the waste in question, by selecting those with frequency values higher than 1. Frequencies with a value of 1 are not considered because they may relate to sporadic events or measurement errors, for which the nomenclature was not correctly assigned. In this article, these industries are defined as potential Donors. The same process was applied for the material inputs, i.e. all industries which may use the relevant material inputs in their industrial processes and had a frequency value above 1 in the Material Input database (Section 2.2.2) were identified. These industries are defined in this article as potential Receivers. The frequency value for each material was extracted from the Waste and Material Input databases.

Stage 3 is defined as the Matching process. In this step, the relationships found in the MAESTRI database were expanded to match more potential Donors and Receivers. All potential Donors were matched to potential Receivers, as identified and selected in Stage 2. These expanded matches of potential IS partnerships are here defined as Potential Matches. They are represented with arrows in Figure 2.

The final stage, Stage 4 (Results printing), consisted of registering all obtained Potential Matches into a final database, defined as the Matches database. All four stages were repeated for all the 158 IS case studies selected from the MAESTRI database, and the resulting pairs were entered into the Matches database.

2.2.4. Cross-Comparison Analysis for Method Validation

To validate the method, the Matches database was crosschecked against the existing MAESTRI database. The cross-comparison process consisted of verifying whether, for each case study, the actual industry Donors and Receivers from the MAESTRI database were captured in Stage 2 (Expansion). If they were captured, they would also be identified in Stage 3 (Matching process). These are represented with blue arrows in Figure 2. For a blue arrow, the Donor industry, represented with a grey circle, is the same as the Donor industry in the case study from Stage 1 – IS Case Study details. The Receiver industry is represented with a black circle and is also the same industry as in Stage 1. This shows that both the Input Frequency and the Waste Frequency database were able to capture the industries identified in the original case study.

Only complete case studies in the MAESTRI database were considered in the validation process, i.e., cases where Donor, Receiver, LoW code, and CN code of the Material Input data were present. For each MAESTRI case study, the validation process included three checks: 1) whether the Donor of the waste in the MAESTRI case study was also found in the Matches database; 2) whether the Receiver of the material input in the MAESTRI case study was also found in the Matches database; and, 3) whether both the Donor and the Receiver from the MAESTRI case study were found in the Matches database. Additionally, an analysis of the obtained Waste frequencies and Material Input frequencies for both Donors and Receivers was performed. The aim of this final analysis was to verify whether the frequency databases returned high values for the wastes and input materials considered.

3. Results and Discussion

3.1. Waste and Material Input Frequency Databases – Step 1 and 2

The Waste Frequency database provides information on the types of wastes generated by different industries. The heat map presented in Figure 3 relates to the Waste database compiled in this study. Waste types (LoW) are presented in rows, while the industries that generate them, along with the corresponding industry sectors, are found in the columns. The heat map shows which industries can be expected to produce a given waste. As an example, Box 1 shows that animal and vegetable wastes are mainly expected to be generated within the food processing and agricultural sectors. It would also be possible to identify the types of wastes expected to be generated by a given industry. Box 2 shows that companies within the Manufacture of musical instruments (NACE 322) sector produce mostly wastes belonging to the metallic waste group.

The Material Inputs typically needed by each industry have been visualized using a heat map (Figure 4). The rows contain the types of input materials, according to CN4 code. The columns show the industry types as well as the sectors they belong to. As an example, Box 1 shows that base metals are widely used within the Manufacture of electrical equipment, with frequency values very close to the maximum of 14. Box 2 shows that food related products are generally not used in industries belonging to the Textile, Wood, or Transport sectors. Finally, Box 3 represents all the material inputs needed by an individual industry within the Agriculture sector.

3.2. Matches Database – Step 3

The matching process developed in this article aims to identify potential IS relationships between two industries, using their NACE classification codes. Using the developed methodology, 158 IS cases from the MAESTRI database were expanded to a total of 211,114 potential IS matches, which were stored in the Matches database. Records with a frequency value of 1 were removed from the Waste and Material Input databases, which reduced the number of matches to 96,622. Additional exclusions are possible, such as removing industries with low values for Waste or Material Input frequency. Table 4 in Supplementary Information shows the number of matches between Wastes and Material Inputs for each frequency value (excluding those with a frequency value of 1). There were 6,707 matches between industries with a frequency value of 2 (out of maximum 4) for generation of a particular Waste and industries with a frequency value of 2 (out of maximum 14) for requiring a particular Material Input. Theoretically, matches become stronger with increasing frequency values, as both supply and demand for the waste become more reliable. The strongest possible matches, with values of 4/4 and 14/14 for Waste and Material Input frequency, respectively, comprised 10% (9,709) of the total number of obtained matches. However, all the frequencies could be considered, as the reliability of individual matches may also depend on other factors in addition to supply and demand.

Table 1 presents a summary of the obtained 96,622 matches. It shows the relations between Waste and Material Inputs, aggregated by waste and material input groups. These represent unique matches between two industries. Note that a cell may contain a repeated Waste – Material Input relation, however the industries will be different. Wastes are presented in rows, the columns contain the Material Inputs they may be able to replace. Both wastes and material inputs have been aggregated into European Waste Classification for Statistics (EWC-stat)[1] and CN 2 categories[2], respectively. In the Matches database, 67 different potential wastes (LoW codes) were matched with 80 material inputs (CN codes). As an example, Spent solvent wastes, in row number one, can be used to replace two material inputs, namely Organic Chemicals and Miscellaneous Chemical products. Cement-related inputs could be replaced by Combustion waste materials. The most representative waste group in numbers is Combustion wastes. These wastes have been identified as potential replacements for material inputs used in the production of Cement and concrete products. A total of 115 unique potential Donor industries were found, and 112 industries were identified as potential Receivers. Although, approximately 100,000 possible IS matches are

[1] The European Waste Classification for Statistics (EWC-stat) covers 12 waste groups and further subcategories. Each LoW code is assigned an EWC category

[2] The Combined nomenclature 2 digits, includes 99 groups of goods.

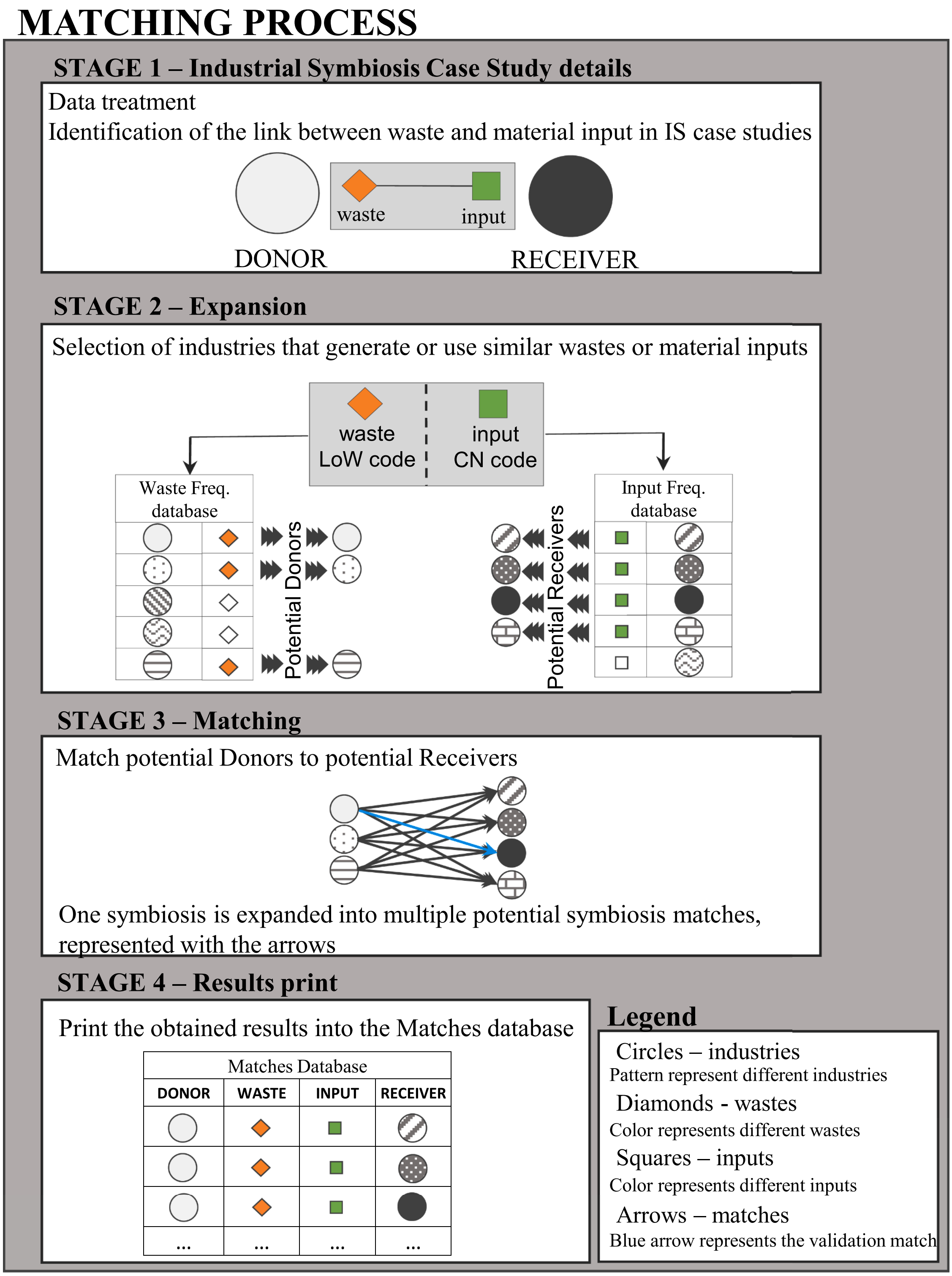

Figure 2. – Schematic diagram of the matching process

identified with the MAESTRI database, the same process could be applied to the IS Data dataset and to other cases found in the literature to enrich the database and update with new possibilities that arise from technological development. Recent developments in data mining could also be employed to further the possible IS matches, such as, applying a big-data approach to discover Industrial Symbiosis using standard nomenclatures (Song et al. 2017).

3.3. *Matching Validation*

The validation process included verification of whether the industries from the MAESTRI database case studies used were also present in the Matches database. For the cross-comparison, all MAESTRI case studies containing complete information on Donor, Receiver, exchanged waste, and material input were used; 146 cases in total. With respect to the Donors, 98 of the 146 industries in the MAESTRI database were also

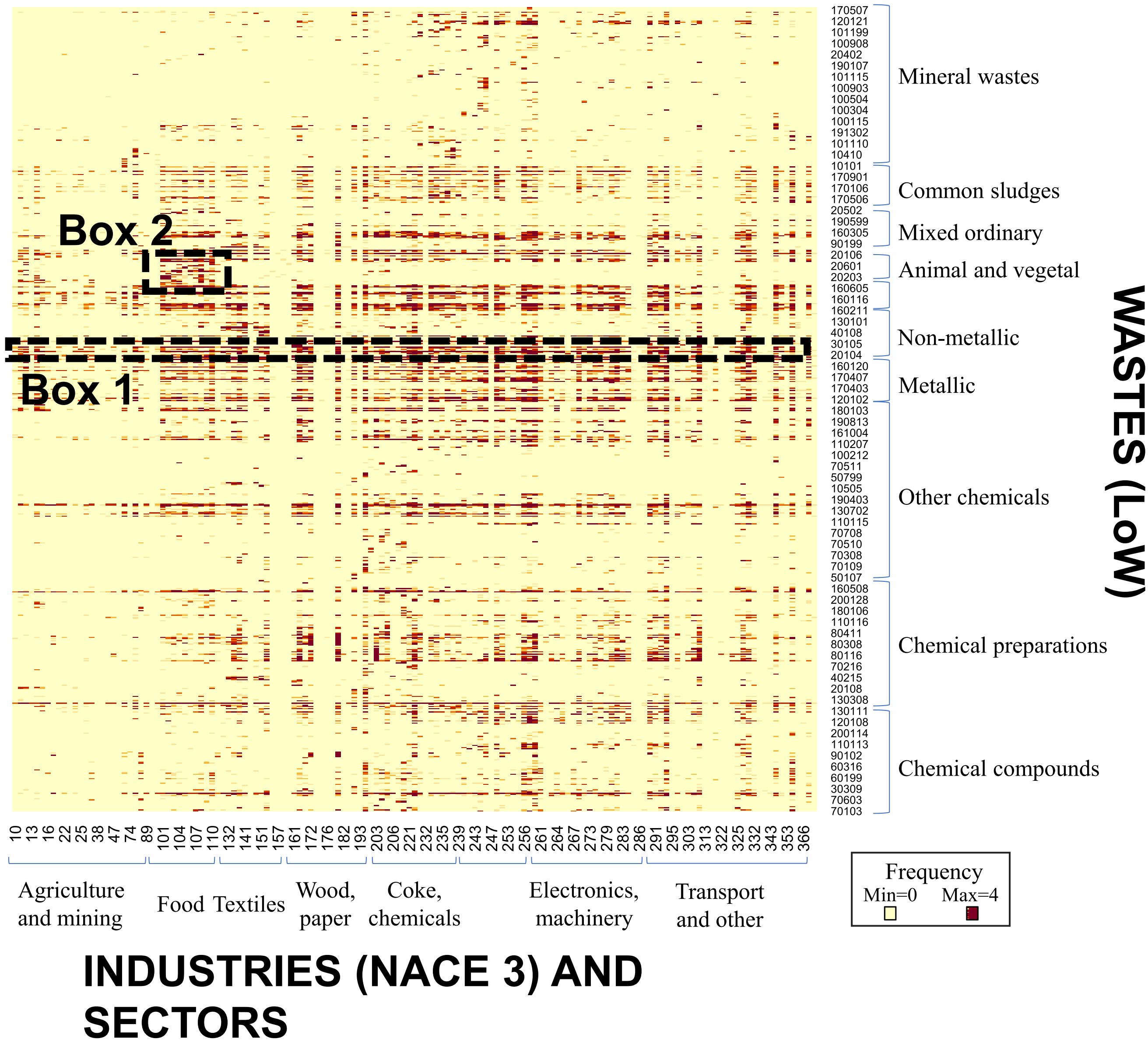

Figure 3. – Heat map for the Waste Frequency database

found in the Matches database. More than 75% of these 98 Donors had the maximum Waste frequency value of 4 out of 4. Therefore, these industries were considered high probability waste generators. In the case of the Receivers, 119 of the 146 industries present in the MAESTRI database were also found in the Matches database. Here, 50% of the industries had a frequency value of at least 10 for Material Inputs, and more than 25% registered a value of 14. In 77 out of the 146 cases, both Donor and Receiver were found in the Matches database. There are a few reasons why more Receivers than Donors were found. In a review of the European list of waste classification, some difficulties were mentioned by the Member States, including: Problems resulting from the lack of suitable waste codes; Ambiguous classification on account of two or more possible codes; Problems resulting from unclear or imprecise definitions (Ökopol GmbH, 2008). Therefore, in some particular cases, the LoW codes may not have the adequate level of detail for IS exploration.

3.4. Application of the Matching Process

In this section, an example from the MAESTRI database is used to illustrate the Matching process. In the MAESTRI case study, the Donor is a plywood manufacturing company (NACE 162) that generates sawdust (LoW 30105), which is then used as fuel wood (CN 4401) by a chemical production company (NACE 205) (Receiver). Applying the developed methodology, the waste type (LoW 30105) and the input type (CN code 4401) are the only fixed variables.

All industries (NACE codes) that may generate waste type LoW 30105 were identified using the Waste database. In total, 44 industries were identified as potential Donors; 11 industries with frequency value 1; 4 with frequency value 2; 5 with frequency value 3, and; 24 with frequency value 4. Some of the industries identified as potential Donors were expected, including Manufacture of products of wood, cork, straw and plaiting materials (NACE 162), Manufacture of furniture (NACE 310) and Manufacture of cutlery, tools and general hardware (NACE 257). One of the industries identified as a producer of waste type LoW 30105 was Plywood manufacturing (NACE 162), which shows that the model also captures the industry that generates the waste in the MAESTRI case study example.

The identification of industries that use similar material inputs to the one identified in the case study (potential Receivers) is performed in

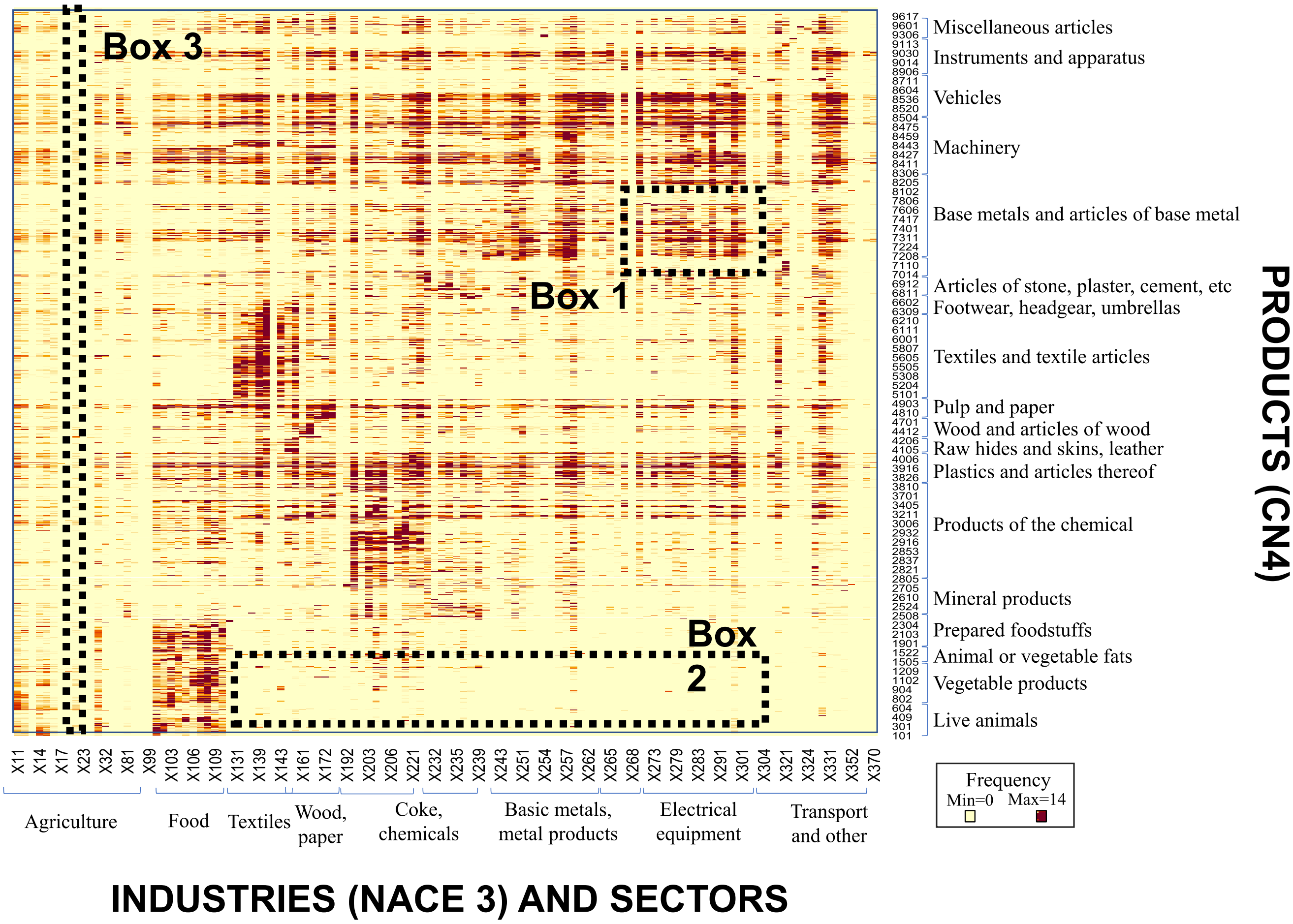

Figure 4. –Heat map of Material Input Frequency database

Stage 2 – Expansion. In the CN nomenclature, fuel wood has the code 4401 (Fuel wood, in logs, billets, twigs, faggots or similar forms; wood in chips or particles; sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar). Table 5 in the Supplementary Information shows the industries identified as currently using this product as a material input, as well as the corresponding Material Inputs Frequency, extracted from the Material Input database.

The identified uses are not limited to the original usage from the MAESTRI database. In the MAESTRI database, sawdust was used as an energy source. However, with the applied method, many other potential uses were identified; a selection of potential uses is available in Table 5 in the Supplementary Information. Each possibility identified through the Material Input Frequency database was cross-checked through a literature review. In the case of this particular waste being used as material input, the cross-check confirmed that the method correctly identified potential users. For example, high frequency values, of 12 and 14 respectively, were found for sawdust being used for animal bedding in NACE 14 (Animal production), or to produce wood boards such as fiberboards or oriented strand board in NACE162 (Manufacture of products of wood, cork, straw and plaiting materials).

The final step included matching all companies that may generate sawdust with all potential sawdust users. In this process, a single IS case study from the MAESTRI database was expanded into 910 different matches.

3.5. Spatial Application

In this section, the matching method presented above is applied to industries working with wood resources in the Västra Götaland region, Sweden. This example analyzes residual sawdust, shavings, cuttings, wood, particle board, and veneer (LoW 30105). Based on the geographical location of the companies, the linear distances between potential Donors and Receivers were calculated. This section demonstrates how spatial proximity can be used to identify realistic IS opportunities by applying different filters to the Matches database.

A total of 2,520 companies located in the region, and potential Donors or Receivers of LoW 30105, were analyzed. Each company was classified by NACE code in the dataset used. In total, 6,726,534 potential IS links were identified. These links did not take into account in-house reuse, i.e. companies that reuse their own waste. First, a set of three restrictions was applied to select the most promising links: 1) Waste generation frequency; 3) Material Input frequency; and 3) distance between companies, where distances above 48km were excluded. This distance was selected based on results obtained by (Jensen et al.,2011), where typical resource movement distances for different waste types were calculated based on actual IS partnerships in the UK. The summary of results of this analysis is provided in Table 6 in the Supplementary Information. With the unrestricted dataset (R0) as a starting point, the distance restriction of 48km was introduced, along with frequencies for Waste and Material Input (R1). The latter restriction led to a significant reduction in the number of potential Donors and Receivers.

Application of the most restrictive filters (R2) reduced the number of potential IS relationships to 159,630 links, which is only 2.3% of the initial number. By applying restrictions relating to distance and possibility that a given waste will be produced (Waste Frequency), and used (Input Frequency), the number of potential opportunities can be reduced to more feasible cases, which can then be used to stimulate policies, business opportunities, and ultimately reduce the requirement for

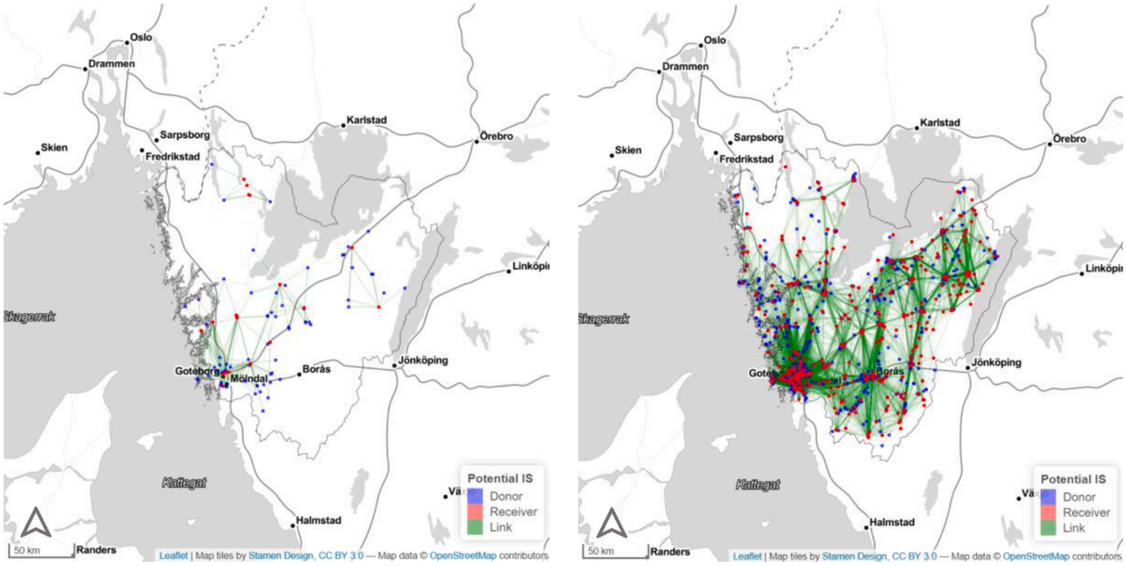

Figure 5. – Map of obtained potential IS links for LoW 30105. Left map (A) using the MAESTRI case study; Right map (B) using the matchmaking process presented in this article

natural resource usage. Among the Potential Donors, NACE 256 and NACE 331 (Machining manufacture and Repair of fabricated metal products, machinery and equipment, respectively) were among the most representative Donors in terms of number of companies (17% and 11%, respectively). Of the potential Receivers, companies with NACE code 162 (Manufacture of products of wood, cork, straw and plaiting materials) accounted for 29% of the database, followed by those with NACE codes 259 (Manufacture of plastics products), 310 (Manufacture of other fabricated metal products), and 293 (14%, 11%, and 10% respectively).

Two maps were produced to spatially locate the Donors and Receivers, and the corresponding links (Figure 5). Map A shows potential IS relationships by mimicking the original case study from the MAESTRI database. In this example, LoW 30105 generated by a plywood manufacturing company (NACE 162) is burned to produce energy by a chemical production company (NACE 205). Once the 48km restriction had been applied, 19 similar opportunities were identified in the region. Following the methodology developed in this article, Donors and Receivers of the same waste type were mapped and linked. MAP B shows the obtained results, with 159,630 potential symbiotic links mapped.

3.6. Discussion

The method presented in this article identifies potential IS partnerships in a given spatial area. The results show that the databases developed by the authors can be used to identify potential partnerships without the need to survey companies. This overcomes some of the challenges of the bottom-up approaches, such as the dependence on the willingness of companies to share input and output data, confidentiality issues, and time constraints. However, the reliability of the obtained results would be greater if more datasets were available. For example, there is a very limited number of detailed datasets on industrial waste generation. Still, the available datasets can be used to give an indication of potential IS partnerships.

A comprehensive approach is applied that considers all businesses, wastes, and material inputs, and uses data to identify companies from different sectors with the potential to engage in IS. This has been demonstrated in the spatial application, according to which it would be possible to share sawdust between companies from a multiple number of different sectors operating in the studied region (see Table 5 in the Supplementary Information for different application examples). This shows that the ability to evaluate several sectors simultaneously opens opportunities for innovative resource management.

The spatial analysis shows that the method can be easily applied to any given situation, and that the number of identified potential IS links can be very high. On one hand, having many links increases the probability of finding a promising IS relationship. On the other hand, having many links can also be overwhelming and make it difficult to prioritize potential IS partnerships. In fact, this is one of the drawbacks of using a top-down approach (Jiang et al., 2014). Nevertheless, techniques can be applied to aid the selection of the most promising IS partnerships. In this context, frequency values and distances between potential Donors and Receivers have been shown to be easily available criteria for filtering of potential IS partnerships. Additional criteria can be applied, depending on the aim of the analysis and the type of stakeholder that is analysing the possibilities. For example, available quantities and Technology Readiness Level information for the IS could be used to identify the most likely options for companies interested in sharing their waste or substituting their raw materials, or specific benefits such as CO2 mitigation potential (Patricio et al. 2017) or Biogas production potential of each different process (Patricio et al. 2020) could be relevant for regional planners to understand the impact of their choices.

The developed top-down method provides a starting point for identification of potential IS relationships. However, there are some limitations in the obtained results. One is the level of uncertainty. Unlike bottom up approaches, this method is based on statistical data and the usage of standard nomenclatures, which in some cases may be too broad. For example, within the Waste nomenclature, LoW code 30105 includes a wide range of wastes, including sawdust, shavings, cuttings, wood, and particle boards. In another example, facilities with the same NACE code are assumed to use similar technologies in their industrial processes but some NACE codes are broad and include more than one type of manufacturing process or final product. NACE code 241, relates to all industries that manufacture basic chemicals, including the production of plastics in primary forms and manufacture of industrial gasses. Therefore, potential IS partnerships should be selected for more detailed studies.

The analysis performed in this study was based on datasets collected for one country. It may be worth performing the Material Inputs and Waste frequency analysis for more countries, to evaluate if there are major differences in the types of materials needed and wastes generated. Additionally, the Waste frequency analysis was performed for a time span of 4 years. The analysis could be optimized if the database covered more years, however, detailed information on the wastes generated by companies is very limited and difficult to obtain (Salhofer, 2000).

This method does not provide any information about the expected mass. Accounting for mass may be a way to make the matching process significantly more accurate. Additionally, the Material Inputs database has been populated with international trade data. Although some of the domestic material inputs are also expected to be captured in this database (see Patricio et al., 2021 for further explanations), some products may be missed.

Technologies in the initial development phase, or emerging technologies, may have a very low frequency value or may not be captured by the Material Input database. Therefore, low frequency material inputs should not be ignored, as they may contain valuable information. In some cases, it may be useful to cross-check the potential uses of different types of input materials, using for instance literature review.

4. Conclusions

This study is a contribution towards promoting IS development. A top-down method that identifies potential IS partnerships without any need to survey companies has been developed and presented. Instead of contacting companies, the method uses available statistical datasets. The method consists of three main steps: 1) Identification of Waste generated by companies; 2) Identification of Material Inputs used by companies, and; 3) Matching of Waste to Material Inputs, in a so-called Matching process. The final result is a Matches database, containing potential relationships between industries. The database is comprehensive, considering 123 industries, 839 waste types and 1,264 material input types. The method can be applied at different scales, from single facilities to industrial parks, regions, and entire countries.

The Matching process identified 96,622 potential matches between Waste generators and potential Material Input receivers, after applying filters reflecting the probability of waste generation or material input needs, based on frequency values relating to production and use in the datasets. This process was performed using 158 IS case studies from the MAESTRI database. Of the 96,622 matches, 10% corresponded to relationships with the maximum values for Waste or Material Inputs Frequency.

In this article, the Matches database was further expanded in a spatial example, used to identify potential IS partnerships for wood wastes generated in the Västra Götaland region. Based on known IS partnerships, available in the MAESTRI database, multiple similar Donors and potential Waste Receivers were mapped using the matching process developed in this study. The spatial application identified 159,630 potential symbiotic links between companies that generate sawdust and companies with the potential to use this waste as raw material.

In the future, this top-down method can be applied to additional waste and material input datasets. Regarding the Västra Götaland example, future work includes adding more features in order to prioritize and select links with higher implementation potential, considering different types of stakeholders and their specific needs. Additionally, there is room for methodological improvements. First, the number of matches identified in the Matches database can be expanded. In this article, only one database of IS case studies was used, namely the MAESTRI database. To systematically increase the number of links in the Matches database, other IS databases should be used.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106437.

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