Journal of Cleaner Production 297 (2021) 126673

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Development of an interactive industrial symbiosis query system with structured industrial waste database in Taiwan

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ARTICLE INFO

Article history:
Received 13 July 2020
Received in revised form
3 March 2021
Accepted 7 March 2021
Available online 11 March 2021

Handling editor: Bin Chen

Keywords:
Industrial symbiosis
By-product synergy
Information system
Interactive visualization
Web applications
Automatic data processing

ABSTRACT

Industrial symbiosis (IS) has contributed significant environmental and economic benefits in many industrial parks or regions, with inter-firm trade of wastes or by-products for reuse. To facilitate IS in more regions, information systems and tools could help identify the opportunities for more companies to mimic the successful cases of by-product synergies. A review of existing IS information systems showed that most lack sufficient quality data, are not operational, or are not publicly accessible. In addition, studies on the development of IS information systems have only limited descriptions of the programming approaches used to create the tools for matching companies and illustrating complicated network by-product synergies based on IS data. Based on Taiwan's waste data, this work presents a well-established IS information system with three applications designed for target users, including the companies involved in IS, the facilitators seeking to grow IS in industrial parks or regions, and waste management authorities. This web-based system was based on massive amounts of detailed industrial by-product input and output datasets. In the by-products' records of more than one metric ton per year, there are 1833 patterns of different by-products reused by various industries. A comparison with other IS information systems and data repositories shows the advantage of using a government-owned industrial waste database with detailed waste classification in identifying massive by-product synergies. Novel data visualization technologies are employed to interactively generate diagrams or networks in response to the user selection of by-products or industries of interest. A demonstration of the query on the sugar manufacturers using sugar cane presents ten by-products and potentially 222 reuses by different industries.

1. Introduction

In an economic system with various industrial processes, industrial symbiosis (IS) is an attractive approach for reducing industrial waste and demands for virgin resources in business. Waste or by-product outputs from one factory could be valuable resources for other factories. The IS in Kalundborg first demonstrated significant economic and environmental benefits (Jacobsen, 2006). Many IS studies also show IS benefits resulting from various economic activities in different countries or cities (van Berkel et al., 2019). Therefore, developing strategies to facilitate IS growth has become an important goal, especially in the research community focused on industrial ecology and cleaner production (Gibbs and Deutz, 2005). Facilitators of IS, which could be government or private organizations, require a system engineering approach based on sufficient information to identify potential opportunities in an area to develop new by-product synergies between the firms producing the by-products and the companies that can use those by-products (Haskins, 2007). Lack of information has been recognized as a barrier to IS (Kosmol and Leyh, 2020). Several studies have recognized the role of IS information systems in discovering IS opportunities and facilitating the planning or networking with businesses. With modeling for scenarios, Fraccascia and Yazan (2018) further show that online information platforms can increase the economic and environmental performance of IS networks. Also, IS networks can be designed based on the exploration for new networks like the Eco-industrial Parks of Ulsan (Behera et al., 2012), Queensland (Roberts, 2004), and Netherlands (Van Leeuwen et al., 2003). Data is essential for IS exploration.

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https://doi.org/10.1016/j.jclepro.2021.126673

Many IS information system projects were developed for similar purposes. The reasons include finding opportunities by mimicking the interfirm relationships from existing synergistic cases, optimizing material and energy flows in the systems, assessing economic viability or environmental benefits, and serving as a platform for engaging business communications and transactions (Yeo et al., 2019). Different technologies were used or suggested to empower IS information systems for these purposes (Van Capelleveen et al., 2018). However, most projects have failed to maintain and update their systems or engage massive industrial partners (Maqbool et al., 2019). A recent review on IS tools indicates that few of the tools are tested on actual sites. Most of the tools are theoretical (Lawal et al., 2020). The most successful case is the SYNERGie 4.0 system developed by International Synergies (Lombardi and Laybourn, 2012). This information system was supported by the National Industrial Symbiosis Program of the United Kingdom (Mirata, 2004). Although there are massive material and industrial matching records in the SYNERGie system, the data is not available to the public due to the confidentiality issue. Most publicly accessible IS data repositories, like the ISDATA (ISDATA, 2019), have a limited amount of data or lack consistent classification systems to develop data structure for analysis. Facing the need for promoting IS in many potential areas, an IS information system with abundant cases and public availability is crucial.

In recent years, several studies proposed frameworks to develop information systems for specific purposes and users (Low et al., 2018). For example, Benedetti et al. (2017) proposed a framework for creating a novel IS knowledge repository. Bin et al. (2015) developed a solution framework that enabled big data analytics for IS in large cities. Song et al. (2017) proposed another big data approach. To facilitate collaboration between firms, Low et al. (2018) presented an architecture for an information platform to enable IS. However, few studies have built a working information system due to insufficient quality data for match-making and opportunity identification. Looplocal is a visualized IS tool that demonstrated an information system supporting the identification of areas of high IS potential in Sweden (Aid et al., 2015). However, the Eurostat waste generation data and life cycle inventory data used by the Looplocal were too aggregated in IS identification. So, the aggregated industry and symbiosis data affected the preciseness of matching by-product synergies. In this system, an allocation approach was used to estimate facilities' material flows in a region. This article also presented visualized spatial data on a heat map with Google API and stated that a function for network mapping of actors is not yet programmed (Aid et al., 2015). The SHAREBOX project worked with International Synergies, the team that created the SYNERGie platform, to develop a web-based IS platform for resource sharing and identification of new symbiotic synergies (Gatzioura et al., 2019). However, the progress of the SHAREBOX at the end of the project on the CORDIS website does not include the expected next-generation IS platform (CORDIS, 2019). From the review of emerging studies and projects for the IS information system, information systems with rich IS data and public accessibility remain unavailable for businesses and IS facilitators. Besides, several web-based information systems with well-designed visual output have demonstrated how they facilitate energy and resource management (Yeo et al., 2019). However, the approach used to develop interactive data visualization tools, analyze, and present the potential IS network is not well described for target user applications (Vivanco et al., 2019). The proposed frameworks of information tools for IS also need real and sufficient data with visible information outputs to validate the usability of these frameworks (Grant et al., 2010). Facing the limitations of existing IS tools, this research recognized opportunities to have some breakthroughs in building IS information systems with structured industrial waste input and output datasets.

Data is a vital issue for developing IS systems. Many projects can generate a limited suggestion for by-product synergies because the cases of by-product exchanges in their datasets is insufficient. Another challenge is integrating datasets from a variety of sources that might present different formats, inconsistent material classification, and economic activities classification. We may expect a structured database that has accumulated large amounts of waste stream data might produce fruitful results of potential synergies. This study aims to examine how such data can gain insights for IS players to mimic the synergies in the past years. Very few IS information systems can accumulate large data through numerous match-making workshops like the SYNERGie system, EPOS system, and the SHAREBOX project (Artacho-Ramírez et al., 2020; Cervo et al., 2019; SHAREBOX, 2019). If the government of a country or city can build an information system to collect waste generation and by-product input from the industries, there would be an alternative data source for creating an ICT system of rich IS information.

Taiwan's industrial waste database has accumulated a large number of monthly material input and waste output records from most of the firms in Taiwan. This data was used to explore a variety of by-product exchanges between industries and assess the potential to improve national-level IS (Chen and Ma, 2015). Firm input and output data confidentiality issues can be resolved by aggregating the firms belonging to a single industry to a detailed classification level so that most of the firms in one industry might have similar kinds of materials in their input and output streams. To effectively deliver complex IS information via interactive visualizations on the web-based user interface (UI), the programming with R language can utilize modern packages like Shiny and networkD3 to generate interactive tables, graphs, and diagrams according to the request of users (Allaire et al., 2017; Chang et al., 2019).

This work examined the variety of by-product synergies in a government-owned industrial waste database. Based on the organized data, this research aims to develop the methodologies to build a web-based IS information system with interactive data visualization applications for potential users. The applications for query by-product synergies are tailor-made for three kinds of target users: (1) businesses seeking other companies that could use their by-products by learning from existing by-product synergies, (2) the government agencies responsible for diverting industrial waste streams toward more reuse pathways, and (3) IS facilitators seeking coordination between industries in an industrial park or region to maximize the benefits of by-product exchange. The methods sections describe data sources and programming methods for extracting relevant data and building this interactive system. A website to access this developed information system is publicly available. The results section presents the UI with the designed control widgets visualized IS diagrams and table outputs. Further applications of the methodologies introduced here and further advancement of this system are then discussed.

2. Methods

The industrial by-product synergies query system was developed through a series of data preparation and modeling procedures. Fig. 1 illustrates the process of building the three apps for by-product synergies in Taiwan. To use rich information from a state-level industrial waste database, the procedure in this study was adapted from the frameworks developed by Aid et al. (2015) and the collaboration platform architecture proposed by Low et al. (2018).

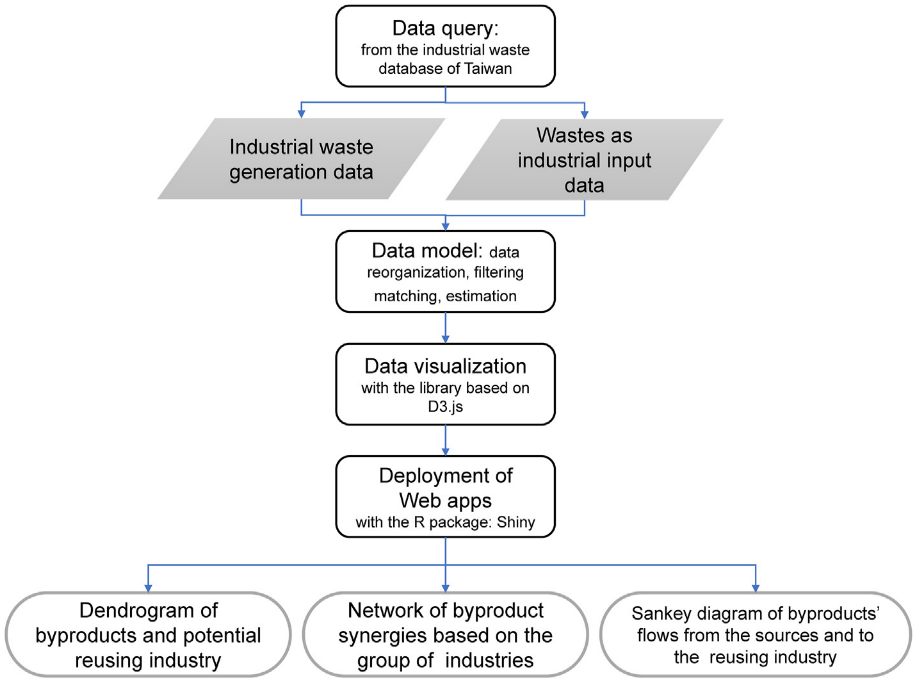

Fig. 1. Flowchart to establish an IS query system based on Taiwan's industrial waste database.

2.1. Data source

Taiwan's EPA has been accumulating waste generation data reported by firms in Taiwan since 2005. The Waste Disposal Act requires firms exceeding certain production levels (including more than 20,000 firms and 80% of industrial waste) to report the types and quantities of wastes or by-products generated each month. In addition, these firms should report their material inputs and product outputs to verify the mass balances of waste reporting. This research used the data of industries' generation of wastes and the data of industries' inputs for materials classified as wastes in the database from 2010 to 2017 (Taiwan EPA, 2019a; Taiwan EPA, 2019b). In 2018, the classification system in Taiwan EPA's industrial waste database indicated the generation of more than 415 kinds of waste products. Taiwan's industrial classification was adapted from the International Standard Industrial Classification in 2018 and now encompasses 519 industries.

2.2. Data processing model

This system used the datasets from the Taiwan EPA. The raw data for all firms' reported quantities were summed for each industry. The aggregated data maintained the confidentiality of each firm's waste generation and material inputs without losing the details for identifying by-product synergies. The waste generation and material input datasets had the fields shown in Fig. 2. The detailed industrial waste generation data contained 28,769 records, and the industry material input data contained 52,223 records.

A data processing algorithm based on the high-level programming R language was coded to extract by-product synergies from the datasets. The algorithm was designed to match the producing industries with reusing industries of a by-product by searching for the rows containing the given waste name in the data of industries' waste generation and the rows in the data of industries' material inputs. As the example shown in Fig. 2, one record of waste generation shows industry M was producing waste B, and another record of material input shows industry N was using waste B. Therefore, a by-product synergy of waste B can be identified with a matching of industry M to industry N. Similarly, a by-product synergy for waste D from industry P to industry Q can be identified. Before this input-output matching of by-products, the raw datasets needed data cleaning.

In the data preparation for matching, the system filtered the datasets to exclude irrelevant data records and shorten the running time.

For the waste generation dataset, the records in which the quantities of waste generation were zero are excluded. The records of wastewater names were removed before the matching of by-product synergies. We considered the majority of the firms with wastewater inputs reuse their wastewater directly. In addition, wastewater outputs from different sources vary in their content of substances and affect reusability in other facilities.

For the material input dataset, the data model filtered out materials that were not waste according to the code of materials. The records of waste treatment sectors and waste management sectors were removed because they do not reuse wastes as materials for production.

To compile the script for the data model, the coding imports the tidyverse package, enabling the data manipulation methods in the dplyr packages. The data model uses the filter () function for filtering data. The filter () function is also used for matching the generating industries with the reusing industries of a selected by-product. A function with the list () function in a for-loop can transform our data into a nested data structure, which is required for data visualizing the networks in the synergies finder application. To generate the data table that dynamically counts the number of potential synergies in a cluster of industries, the function of group_by () and summarize () are employed.

2.3. Data visualization

Data visualizations of IS analysis were developed to enhance the target user experience for exploring opportunities or potentials for industrial symbiosis that are derived from the datasets with

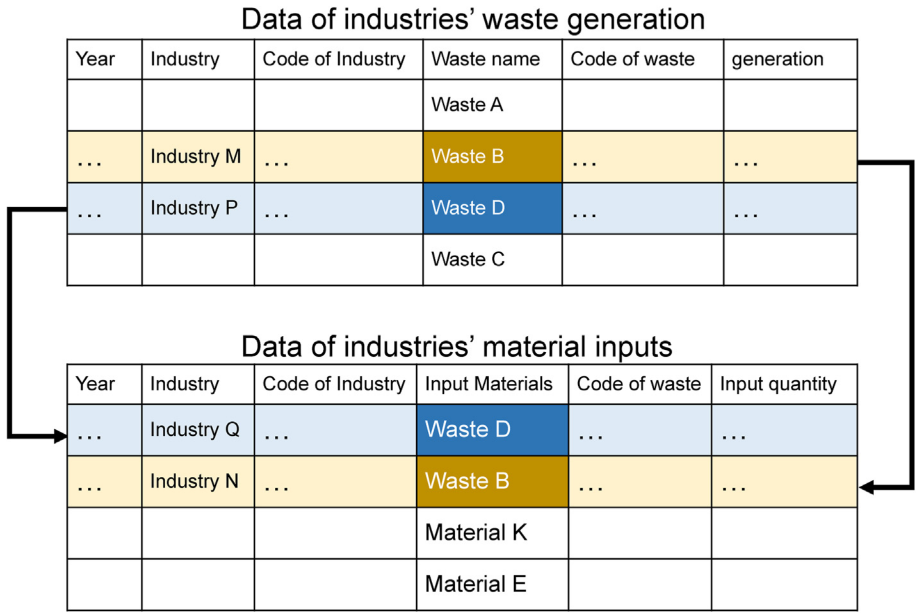

Fig. 2. Matching by-product synergies between waste generation data and material input data.

detailed industries and waste categories. This study selected three kinds of visual presentations and designed the program to plot the diagrams for the three target users, interactively. The first kind of target user is the companies generating wastes and seeking the opportunities to turn the waste into by-products and find potential buyers for these by-products. They might want to know related synergy cases in which some industries can use these by-products. The second kind of target user is the facilitators of IS for an industrial park or region. To identify all the opportunities in the area of IS potential, they need to make an inventory of the by-product inputs and outputs and spend significant effort in matching the producer and reuser companies. A vision of a possible complex eco-industrial network might be essential for IS planning. The third kind of target user is the government agencies managing the waste or promoting resource circulation. They need to monitor the generation of wastes/by-products and the volume that industries can reuse. The gap between the amount generated and that being reused could represent the criticality of managing the waste or the need to develop the by-product's circular economy.

For a firm looking for partner companies that can use its by-products, the diagonal network (tree-shaped diagram) is rendered to show the industries potentially reusing each waste or by-product, as the chart output of the developed application shown in Fig. 4a. For facilitators of industrial symbiosis in a region, the force-directed network style is rendered to illustrate the network-shaped graph of by-product flows existing or possibly emerging in the area, as the graph shown in Fig. 5a. For the Waste Management Department of Taiwan EPA, a Sankey diagram is rendered to visualize the generation flows of by-products from the source industries to the reusing industries with the quantities represented by the widths of the arrows, as the diagram shown in Fig. 6.

The d3. js JavaScript library was used to build interactive diagrams automatically based on the user's selection of industries or wastes/by-products for exploration (Bostock et al., 2011). In the R programming environment, the developed program imports the package networkD3 for drawing the three kinds of data visualization based on the D3. During data manipulation for IS visualization, the imported data is transformed into data frame objects and could be filtered based on the user's selection. Then, a data transformation is followed to generate a data structure that can be used for the data visualization of the three kinds of diagrams. The diagonal network required a three-level hierarchical (tree-like) data structure. A data manipulation code was designed to put industries into the first level of the hierarchical data and put the subordinate industrial wastes into the second level. In the next step, the data frame of all industries' waste lists is expanded with the associated records in the data frame of waste's corresponding list of potential reusing industries by a data filtration for matching based on the wastes that were reused by the industries in the third level.

The force-directed network for the second application needs a list of nodes and a data frame of three fields, including the sources, targets, and values of material flow quantities. The program can generate a list of nodes by combining the selected industries and the wastes either generated or reused by the chosen industries. Then, a data frame of material flow arrows is generated by concatenating the data frame of the industries' waste generation, which has been filtered by the selected industries into the data frame of the waste as by-products reused by industries that have been filtered by the generated by-products. The records in the data frame represented the number of wastes generated or reused in Taiwan in a selected year.

The Sankey diagram for the third application also used the same frame structure as that of the force-directed network. The code also concatenates two processed data frames. The first data frame is extracted from the waste generation data by selecting a waste to get all the industries to generate this waste and the flow quantities. The second data frame is extracted from the data of industries' material input by selecting the same waste to get the flows to the reusing industries.

2.4. Deployment of three web applications

This study used the R package, Shiny, to build web applications. In the Shiny web application framework, the UI of web-apps is created by putting the UI objects and layout of the webpages in a UI function. The code for data processing and diagram plotting was written in a server function. In the interface, the control widgets to select waste, industries, and year were added to the side panel of each application page when necessary. The server function receives inputs when the user changes the selection in the widgets and uses the inputs to filter the part of data for transformation, calculation, plotting diagrams, and generating tables to count synergies. The diagram generated by the code in the server function appears in the main panel of the page. When users make a change in the widgets, the system redraws the diagram. Three applications were created for the target users, including the companies finding synergistic partners, the facilitators/planners of eco-industrial parks, and the Department of Waste Management at the Taiwan EPA. The web-apps above have been deployed with the Shiny Server on an Ubuntu Linux platform. First, deployment needs the installation of R and the packages that will be used in the R script. Second, the Shiny Server should be downloaded and installed. Third, the Shiny Server needs to be configured and started. Finally, the R scripts of UI and server should be placed in the directory to host applications. The waste generation and material input data files should be stored together with the R scripts. The IS information system platform is accessible at https://pure.shinyapps.io/IS_Tool_Taiwan/

3. Results and analysis

3.1. Synergies in the waste data

The exploration of the material inputs dataset in the waste database found a large number of synergies in Taiwan. In 2018, 183 industries were reusing by-products as process input. The number of types of by-products being reused in 2018 is 237. Filtering the data for each industry's waste inputs generates 2118 records of different by-products used by various reusing industries. Among these records, 1833 are more than one metric ton per year. The actual number of synergies is much higher because each industry has many companies, and each by-product might have more than one source company. Table 1 shows only the industries that used more than five kinds of by-products in 2018 and the mass of all by-products being used. The variety in by-product reuses by industries provides the basis for building a IS information query system able to show many reuse opportunities. In 2018, the sum of each industry's inputs of wastes or by-products is up to 1760 kinds of industrial by-product reuse patterns. Fig. 3 shows the number of industrial reuse patterns of products that appeared in Taiwan from 2010 to 2018.

3.2. Synergies finder for business

The first IS query application was developed for business users. Users could search for the industries with the potential to take the industrial wastes from the user's company as valuable inputs. As shown in Fig. 4a, once an industry of interest is selected, a diagonal network is generated to show the possible by-products of the target industry in the branches from the left end as the source industry. Each by-product node has a number of industries that could take the by-products as inputs. A large illustration of the network of Fig. 4a can be browsed on the web-app via the link provided before the results and analysis section.

For example, the sugar industry in Taiwan generates seven kinds of wastes or by-products, including bagasse, molasses, bagasse ash, sugar mill mud, and organic sludge. The bagasse could be used by cattle and pig farms or by manufacturers of fertilizer and animal feed. There are 222 industries that could use the by-products generated by the sugar industry in Taiwan or by-products from

Table 1
The industries using more than five kinds of by-products in Taiwan in 2018.

Industries using by-products	Types of by-product inputs	By-product consumed (t/y)
Manufacture of Other Basic Metals Not Elsewhere Classified	53	418,972
Manufacture of Other Non-metallic Mineral Products Not Elsewhere Classified	45	2,443,289
Materials Recovery	37	471,534
Manufacture of Basic Chemical Material	33	4,978,087
Manufacture of Other Chemical Products	31	227,095
Wholesale of Recyclable Materials	25	636,988
Manufacture of Other Fabricated Metal Products Not Elsewhere Classified	25	41,334
Manufacture of Fertilizers	23	257,337
Smelting and Refining of Iron and Steel	20	8,118,235
Manufacture of Ready-mix Concrete	20	3,904,020
Manufacture of Cement	17	621,966
Manufacture of Synthetic Resin and Plastic Materials	16	102,119
Other Manufacturing Not Elsewhere Classified	13	120,651
Manufacture of Petroleum and Coal Products	13	88,214
Manufacture of Cement Products	13	160,504
Manufacture of Clay Building Materials	12	140,861
Raising of Swine/Pigs	11	133,354
Manufacture of Paperboard	11	1,418,298
Manufacture of Other Plastic Products	11	94,712
Manufacture of Other Paper Products Not Elsewhere Classified	11	1,019,484
Cutting, Shaping and Finishing of Stone	10	60,590
Treatment of Metal Surface	9	104,633
Manufacture of Bare Printed Circuit Boards	8	216,932
Manufacture of Prepared Animal Feeds	7	197,411
Manufacture of Other Glass and Glass Products	7	55,673
Other Metalworking Activities	6	8,779
Manufacture of Other Electronic Parts and Components Not Elsewhere Classified	6	112,855
Finishing of Textiles	6	21,329
Manufacture of Paper	5	1,400,988
Manufacture of Other Products of Wood and Bamboo	5	76,970
Manufacture of Other Porcelain and Ceramic Products	5	46,120
Manufacture of Other Metal Containers	5	8,319
Casting of Other Basic Metals	5	37,008
Casting of Aluminum	5	62,180

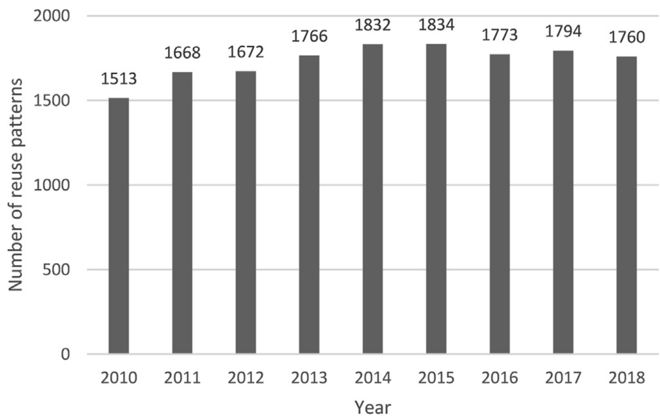

Fig. 3. Kinds of waste/by-product reused by industries in Taiwan EPA database from 2010 to 2018.

other industries with the same waste names as those produced by the sugar industry. This application has a supporting page to show a chart focusing on three selected wastes for a zoomed-in view of the industries that may be able to reuse one of these wastes, as shown in Fig. 4b.

The actual number of synergies that could be developed might be smaller than the synergies shown in the application because the composition of all industrial wastes classified as a defined waste type could vary depending on the source industries. The first application can display IS opportunities, and business users could use this application to identify possible partner companies classified as reusing industries, as suggested by this application. Further confirmation of the by-product composition, amount, transportation cost, and other issues of concern would be required for the generating company to make a deal with a reusing partner company.

3.3. Network simulator for eco-industrial park planning

The design of the second IS query application is for planning eco-industrial parks. Potential users could be the industrial development authorities of central or city governments or the administrative offices of industrial parks. This application would allow the experiment on what agglomeration of industries and their by-product types in an industrial region or park might generate the most potential synergies.

The UI of this application renders data visualization of IS network in response to users' inputs. The side panel contains a checkbox list of industries for users to select several industries in the study area. Based on the selected industries, the right panel shows a force-directed network diagram to illustrate the possible by-product synergies in this experimental industrial cluster, as shown in Fig. 5a. Each blue node represents one industry, and each orange node represents one waste or by-product. The outward arrows from an industry node are the generation of by-products or wastes produced by the industry. The arrows pointing toward an industry node indicate the by-products that could be used by the industry. Potential by-product synergies in the study area are indicated by by-product nodes with both inward arrows from industries and outward arrows, which point to one or more industries that could use it as a resource. The arrow width reflected the mass of material flows. To improve the readability of graphs with many overlapping characters, the programming colors the nodes' labels with transparency on the website. When users move the mouse cursor over one node, the node's label becomes highlighted by switching its color to pure blue or orange.

On the main network panel, a table shows the statistics for the by-product synergies in the experimental industrial cluster. Fig. 5b shows an example of a combination of beverage and pulp-making industry groups, in which 21 kinds of by-products have the potential to be used by other industries in this cluster. The number of industries generating wastepaper, organic sludge, and waste wood was 11, 11, and 10, respectively; the number of industries with the capability to reuse these three by-products was 5, 4, and 4, respectively. This composition of industries featured 55, 44, and 40 generating industry pairings with industries reusing organic sludge, pulp-making sludge, and waste food, respectively.

The network analysis tool is a realization of the concept tool Looplocal developed by Aid et al. (2015) for Sweden. Looplocal was limited by its input data showing the national production of over 60 wastes from 22 (sector-organized) producer groups. The detailed waste and industrial classifications of the EPA database and the mandatory reporting of waste outputs and raw material inputs by industries allow the interactive experimentations on the network of potential synergies for the planning of IS facilitation in an area with IS potential.

3.4. Inventory of synergies for waste management

The target users for the third IS query application are the government agencies for environmental protection and waste management in Taiwan. When the user selects a waste from the list, then this application shows a Sankey diagram of the balance of waste generation and reuse flows according to the waste stream data for the selected year.

Using waste wood as an example, as shown in Fig. 6, the straight bar in the middle is the selected waste. The nodes on the left-hand side are the industries that generated waste wood. The widths of the arrows from source industries on the left are proportional to the amount of waste wood produced by each sector. The widths of the arrows on the right are proportional to the amount of waste wood consumed by each industry with reuse capabilities.

The waste wood balance results showed that the industries in Taiwan demand for waste wood greater than the amount generated by domestic industries. Therefore, Taiwan imports waste wood to meet the demand. The implications of these results could suggest ways to collect more waste wood from industry or households. However, for most waste categories, generated wastes were more than the amount domestic industries could consume. Waste management authorities could seek ways to encourage more companies capable of reusing waste products (industries on the right side of the diagram) to implement reuse practices realistic for their industries.

This application has an extensive page for users to select a group of wastes and explore all the flows from the sources to reuse industries. In the current model, there are three waste group options, namely, sludges, agricultural wastes, and basic metal scraps. Each waste group includes several waste types of similar material properties. The thematic view of the waste balance diagrams could be used to examine material substitution opportunities and capacities of existing reusing industries. The industries using a by-product might be able to accept alternative inputs of by-products in the same waste group due to similar physical or chemical properties of by-products. To allow users to focus on major flows, the UI has a filter setting for users to hide the flows much less than a certain percentage of the largest flow in the Sankey diagram.

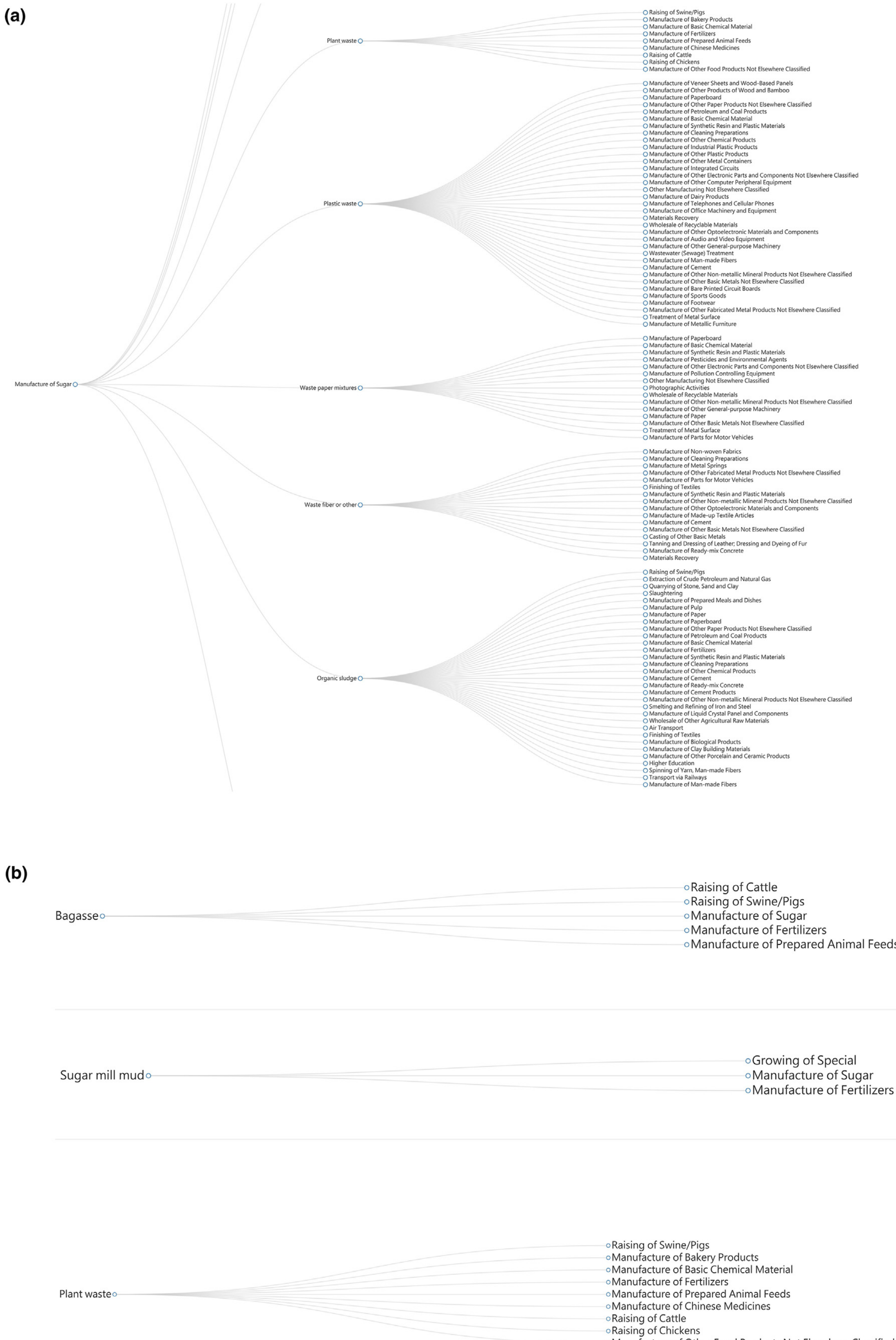

Fig. 4. Overview of the webpage and part of the sugar industry by-products and potential reusing industries in Taiwan.

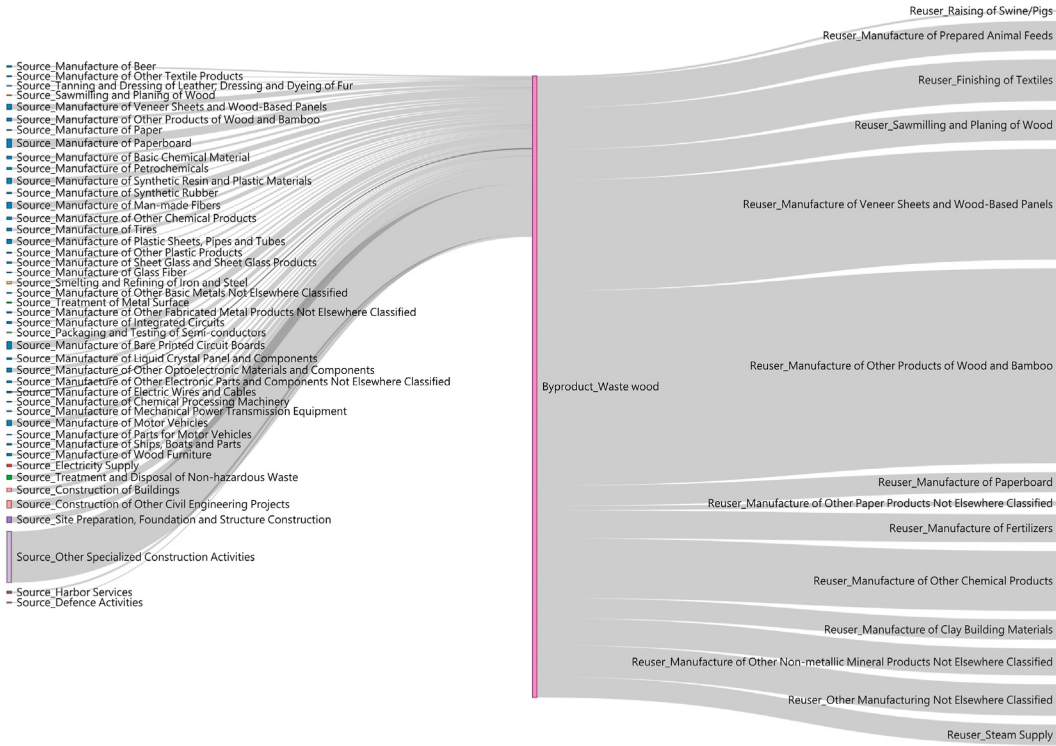

Fig. 5. The force-directed network of the by-product output, input, and linkages between industries.

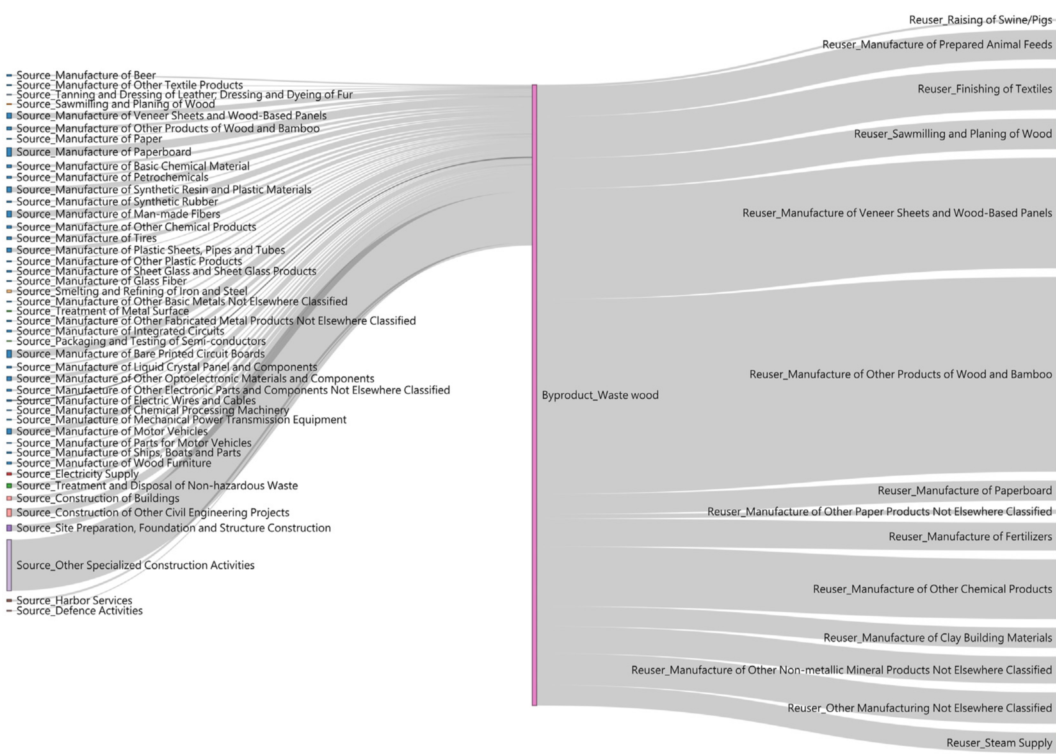

Fig. 6. The Sankey diagram for the waste generation and reuse flows for waste wood.

Table 2
Comparison of IS data between IS information systems or projects.

Systems of IS data	No. of Synergies	Area includes	Main Data Sources	References
ISDATA	74 case studies in the database spreadsheet	UK, South Korea, New Zeeland, and Romania	NISP, EIP Excellence Case Book, and other sources	ISDATA (2019)
SYNERGie 4.0	5720 interfirm cases	The UK and other 22 economies	Matching workshops	Humphreys (2019)
Looplocal	191 potential exchanges	Sweden	LCI data and Waste data	Aid et al. (2015)
SHAREBOX	Initiate 26 synergies being alive by August 2019	Three or more countries in Europe	Database of SYNERGie and Matching workshops	CORDIS (2019)
This study	Records from 2010 to 2018 show 2118 combinations of by-products and receiver industries	Taiwan	Mandatory reporting from industries	

4. Discussion

4.1. Comparison with previous main works

Searching for the reuse patterns of wastes by industries in our database, we found that 152 industries in Taiwan used their specific sets of wastes and can recognize up to 1760 kind industrial reuse patterns in 2018. The actual number of by-product synergy cases might be much more than 1760 cases because each industry might have many firms. In addition, a kind of waste/by-product might be generated from several industries of similar processes. Table 2 compares the previous main works on IS information systems or data repository projects that own a certain amount of by-product synergy data. SYNERGie 4.0 could be the only one having the cases more than the government-owned structured database in Taiwan. If further research can access the detailed data of individual firm's waste inputs and outputs, a lot more synergy cases and reuse patterns can be identified.

The detailedness of by-product classification and the number of data records should be why this IS information system and the SYNERGie system can generate many synergies. The industrial waste database of Taiwan uses a classification made up of 695 waste codes. Among these codes, 302 categories of waste (43%) found from the 34,920 records (the years 2011–2019) were reused as inputs by the industries. The SYNERGie system might also benefit from a very detailed European Waste Catalogue, which is made up of roughly 650 codes divided across 20 chapters. The number of waste categories in the ISDATA and Looplocal study is much less than that used in this study and the SYNERGie system.

4.2. Potential application in Taiwan and broader use in other areas

Since 2020, the authors have been applying this IS query information system in a project of Taiwan's Ministry of Economic Affairs to help the industries reduce their wastes by matching by-product generating firms with potential reusing firms. The project used the third query application to identify the waste categories of higher urgency to promote reuse in industries or as civil engineering materials based on the current gap between the total generation and total reuse. The first query application is used to discover the firms that can reuse the waste categories of higher urgency. This project has a plan to apply the second query application in organizing business opportunity networking workshops to group the representatives from specific sets of industries for making more matches, based on the network analysis. This open information system might be accessed by more businesses than the information systems not publicly available, as those identified in Grant et al. (2015) study. The companies in other countries might also find their partners for building by-product synergies by exploring the massive cases in Taiwan because they might have similar waste output and by-product inputs with the same industries in Taiwan. It is interesting to know why the interactive visualization of a large number of synergistic cases can help companies identify their potential partners. The question might be answered after the developers have collected sufficient feedbacks from the users. The developers can use the feedback to continue improving the information system, like adding a function to focus on the reuse patterns of higher potential or value by extracting them from a complex network of synergies.

We expect that the structured database can appear in more countries, and the methodologies to build an interactive industrial symbiosis query system can be applied in more projects. The opportunity will arise in the countries with a comprehensive and detailed waste classification system and a system to collect the data of industrial waste inputs and outputs. A few states have adopted a detailed waste classification system like Taiwan. Although their database might use a different waste classification scheme, these countries might be able to develop their IS data applications like this study. EU has developed a List of Waste for the classification of waste. The annex of the EU's technical guidance on the classification of waste shows a very detailed list with 842 entries of waste types (EUR-Lex, 2020). The coding system includes the sources of waste and allows the IS analysis for tracking sources industries based on the code. The UK's waste management policy regulates the activities to move or dispose of waste to report the operation with the description of wastes with the European Waste Catalogue (EWC) and the producer of waste. The SYNERGie 4.0 App also uses the EWC for the classification of resources in the IS information system. To develop a novel knowledge repository supporting IS, Benedetti et al. (2017) suggest using the EWC code for the identification of the exchanged materials.

Another issue is the need for the data of industries' consumption of by-products. Some of the IS information system projects collect data from industries. For instance, the International Synergies have collected data from IS facilitating workshops. Taiwan's database benefits from the mandatory reporting of both waste generation and material inputs from companies under the Waste Disposal Act. The countries with the regulation for industrial waste reporting might consider the inclusion of material inputs for two benefits, including the verification of the correctness of the reported waste generation in terms of mass balance and the data for developing IS information systems. The U.S. EPA encourages businesses to participate in the WasteWise program and report their baseline data and annual data to a sustainable material management system (US EPA, 2016). This kind of volunteer reporting program for collecting waste generation and management data is of potential to gather enough information for developing IS information systems.

4.3. Limitations and the outlook for improvement

Although the data used in this study have very detailed industrial and waste classifications, there could be differences between the inputs and outputs of the industrial processes in each industry or between the compositions of wastes in each waste category. These differences could impact the applicability of the by-product synergies suggested by the information system to other potential companies. Having authorities from industrial waste management review and update the waste classification system might result in better identification of IS opportunities. In addition, the current matching method doesn't capture the possibility that a waste stream could substitute a waste stream with a different name. Future development may address by adding information on waste properties.

New functions are being developed to empower this system further. First, similar to the functions and interfaces demonstrated in the SHAREBOX project system (SHAREBOX, 2019) and the collaboration platform in Singapore (Raabe et al., 2017), a web map application of company locations and business data (including the type of industries) will be developed to examine the existing and potential by-product synergies in a selected area. Second, an optimization tool for regional IS will be developed to search for suitable industry newcomers who may gain the most from by-product reuse in the industrial area. Third, as suggested by Grant et al. (2010), other implicit data, including economic and price data, may be incorporated into the database to assess the feasibility and barriers to building new synergies.

5. Conclusions

The development of strategies to facilitate IS growth need sound and clear information to identify IS opportunities. However, many IS information tools are facing the issue of a lack of data. A well-structured industrial waste database that accumulates rich mandatory reporting data in Taiwan has shown rich by-product reuse patterns in this study. These patterns of by-products reused by different industries serve as a basis for exploring the potential to build more by-product synergies. We see many economies, including some EU member states, are developing their waste statistics and considering industrial symbiosis as a venue toward higher resource efficiency and less waste. The data structure with a detailed classification of wastes introduced in this study can be an example for these economies to develop their own IS information systems. This web-app of massive by-product synergies might provide IS insights to the facilitators of other areas having the economic activities that can be found with resue data in Taiwan.

The advancement in ICT tools is an essential issue in the research community focused on industrial ecology and cleaner production. This paper delivers the methodology of rendering interactive data visualizations based on selected and refined information in different network formats to three kinds of target users, including the facilitators who need to identify the IS opportunities in a region of a specific cluster of industries. The information system presented here features three kinds of visualized data applications with interactive interfaces for different users. The facilitators and companies looking for IS opportunities could use our web applications to explore various types of by-product synergies in Taiwan. The data processing and programming method introduced may be applied to other projects developing or upgrading IS information systems. The data in this system may present the largest number of by-product synergies compared to existing open IS repositories, information systems, and software.

CRediT authorship contribution statement

Pi-Cheng Chen: Conceptualization, Methodology, Investigation, Software, Visualization, Validation, Writing – original draft. **Kun-Hsing Liu:** Resources, Data curation, Writing – review & editing.

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.

Acknowledgments

We thank the Taiwan EPA for providing the detailed input and output data of industrial wastes.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126673.

Funding information

Funding: This work was supported by the Environmental Protection Administration, Taiwan [grant numbers EPA044108009]; and the Ministry of Science and Technology, Taiwan [grant number MOST-107-2923-I-006-001-MY3 and MOST-109-2628-E–006-007-MY3].

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