A Literature Survey of Information Systems Facilitating the Identification of Industrial Symbiosis

Guido van Capelleveen, Chintan Amrit and Devrim Murat Yazan

Abstract Industrial Symbiosis (IS) is an emerging business tool that is used by practitioners to engage cooperation among industries to reuse waste streams. The key to reveal IS opportunities for organizations is both connecting the supply and demand of various industries and providing technical knowledge on the IS implementation. This process is increasingly supported by information systems which act as a facilitator of communication and distributor of knowledge. However, we lack understanding of a describing role of each type of information system within the process of IS identification. IS literature could benefit from a clear overview of (i) the characteristics of these different information systems, (ii) the role of support these systems provide, and (iii) the technologies used to enable such identification. This paper analyzes the current state of literature that addresses information systems that facilitate IS identification and studies these systems using these three pillars. Our study contributes by providing a classification framework of information systems that facilitate industrial symbiosis identification and reveals three research directions to progress IS identification tools, namely (i) software product and service development (ii) data integration, and (iii) adoption of intelligent learning.

1 Introduction

The reduction of waste emissions, primary resource and energy use in resource-intensive industries contributes to the development of a sustainable environment (European Environmental Agency 2016). One of the attempts to reduce waste, emissions and resource use is industrial symbiosis. Industrial symbiosis (IS) is a cooperation among industries wherein waste streams as a secondary output of an industry, are utilized as (part of) resources for the production processes

G. van Capelleveen (✉) · C. Amrit · D.M. Yazan
Department of Industrial Engineering and Business Information Systems,
University of Twente, PO box 217, 7500 AE Enschede, The Netherlands
e-mail: g.c.vancapelleveen@utwente.nl

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of other industries (Chertow 2000). The IS methodology is gaining popularity as a means to improve sustainable production because of its ability to provide economic benefits while simultaneously providing ecological benefits as well as social benefits (Chertow 2007). While most studies focus on evolutionary models (Boons et al. 2016), less attention is devoted towards the use of information systems.

IS literature still lacks a clear overview of the different type of systems and the functional support these systems can provide. In particular, there is a gap of knowledge in the understanding of the role of information systems as a tool to support industrial symbiosis development. This study provides an overview with a focus on the systems facilitating the identification of IS. We contribute by providing a conceptual framework to practitioners and policy makers that outlines the course of actions for information systems that facilitate IS identification. Moreover, this review reveals research directions for the IS community to consider by suggesting advancements to be made in order to strengthen community engagement and enrich data use for computerized exploration.

2 Research Design

We analyze the Industrial Symbiosis (IS) literature from 2000 to 2016. We have selected the time-frame based on the publication date of the well cited paper (Chertow 2000), which can be seen as one of the early foundations on the concepts of industrial symbiosis. To capture the scarcely published research on IS tools we take an inter-disciplinary approach in retrieving articles from a variety of journals and conferences, as information system literature is scattered over a multi-fold of disciplinary fields ranging from ecological ecosystems to computer sciences.

We initially conducted a Scopus (Elsevier 2017) search for bibliographic scientific material. Our queries search for a set of keywords in the title, abstract and keywords of articles. The keywords reflected the concepts of "industrial symbiosis" and "information systems" and were applied in various combinations between the concepts. The keywords were "industrial symbiosis, industrial ecology, eco-industrial park, synergy, by-product exchange, recycling network, waste exchange", and "information system, ICT, tool, decision support, intelligence, expert system, identification, assessment, mapping". To prevent missing articles due to the use of inconstant terminology practiced over different disciplines, we performed a first degree backward and forward analysis based on the citations of the relevant publications (snowballing technique). We use the following selection criteria to filter relevant IS articles that we included in our review:

- The article mentions, or presents an IS identification tool that is primarily focused to reveal options, industries or individual organizations in support of waste exchange or industrial symbiosis network development.
- The tool is considered an information system, and thus utilizes various ICT techniques.

- The article provides extensive information on the implementation of the tool or elaborates on the techniques that are essential and specific to this type of information systems.

Then, we use the selected literature to conceptualize the IS systems into a matrix using the methodology of Webster and Watson (2002) to further develop an understanding of the key concepts of the information systems that stimulate IS facilitation.

3 Industrial Symbiosis Tools

This section describes our typology consisting of six concepts (see Table 1), created from the identified literature, and summarizes advancements of each of the areas.

Table 1 Literature classification framework of information systems that facilitate industrial symbiosis identification (Note that Grant et al. 2010; Veiga and Magrini 2009; Massard and Erkman 2007, 2009 discuss more than one concept)

Type	Information system	Type of support	Characteristics	Common technology and techniques	References
A	Open online waste markets	Passive facilitation of waste transactions	A web-based information system that provides an open business-to-business sales platform service for waste materials. The platforms do not or -to a minimal extend- interfere or coordinate transactions. Most systems form an open market and information is visible to the outside world. Typically, this type of market is mostly driven by governmental agencies or individuals from an idealistic view without a sustainable profitable business model	Web-based e-commerce platforms, rule-based matchmaking algorithms, ontology engineering	(Cecelja et al. 2015; Chen et al. 2006; Dhanorkar et al. 2015; Dietrich et al. 2014; Grant et al. 2010; Große et al. 2016; Hein et al. 2015; Hickey et al. 2014; Raafat et al. 2013; Trokanas et al. 2015)

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Table 1 (continued)

Type	Information system	Type of support	Characteristics	Common technology and techniques	References
B	Facilitated synergy identification systems	Active facilitation of waste transactions	An information system used to support private community-based business-to-business sales of waste materials which in many cases are facilitated through an intermediary. These type of systems are used during or after identifications workshops and tend to be more structured and coordinated by the intermediary. Typically, these markets are initiated by consortia, industrial parks or third party facilitator and are more driven upon profitable results	Rule-based matchmaking algorithms, national input-output tables, and life-cycle assessment databases	(Alvarez and Ruiz-Puente 2016; Baas and Hjelm 2015; Clayton et al. 2002; Cutaia et al. 2014, 2015; Grant et al. 2010; Massard and Erkman 2007;, 2009; Mirata 2004; Raabe et al. 2017; Song et al. 2017; Sterr and Ott 2004; Veiga and Magrini 2009; Zhang et al. 2017)
C	Industry sector synergy identification	Profiling of waste production and use per industry	A system approach that examines synergies between industry sectors rather than between factories. Using national waste statistics per industry sector it is possible to detect the abundant waste inputs and outputs. Using this information and the help of manufacturing process information it is possible to determine waste flows that can potentially be converted into synergies	National waste input-output tables	(Chen 2015; Horvath 2016)

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Table 1 (continued)

Type	Information system	Type of support	Characteristics	Common technology and techniques	References
D	Social network platforms and social network communities	Mixed: (a) Building social relations (b) Knowledge exchange	The role of Social Networks (SN) in sharing knowledge and information on IS experiences and opportunities among industries. The tools unfold either as independent SN platforms or as a formation of groups on existing SN platforms	Social networks, and social network integration	(Ghali et al. 2016)
E	Industrial symbiosis knowledge repositories	Knowledge exchange	Knowledge systems that contain a collection of historical industrial symbiosis examples or theoretical literature references to potential IS cases. The systems enable collaborative knowledge creation by providing a platform to share and discuss synergy implementation experiences	Content Management systems (e.g. Wikis), and collaborative web-based spreadsheets	(Davis et al. 2010; ISDATA 2015; Veiga and Magrini 2009; Yu et al. 2014)
F	Region identification system for industrial symbiosis	Urban planning and policy making	Geographical information systems (GIS) that estimate the potential of areas for the application of industrial symbiosis development	GIS visualizations, Geographical-data based scoring algorithms, fuzzy rule based expert systems, and simulation software	(Aid et al. 2015; Dou et al. 2016; Massard and Erkman 2007, 2009; Ruiz et al. 2012; Togawa et al. 2016)

3.1 Open Online Waste Markets

Open online waste markets or waste e-marketplaces are web-based platforms for business to trade industrial residues. Three key characteristics are observed in this category of information systems. Firstly, the markets provide an electronic service to connect organizations' supply and demand, such as in other traditional e-marketplaces. Secondly, the marketplaces are open to any industry and items that are publicly listed. Finally, the marketplaces act as an independent service without active involvement of IS facilitators. The diversification of systems generally result from the type of commodities that are transferred, the geographical areas covered and the type of actors who initiate these systems. The U.S. Environmental Protection Agency (EPA) defined these online material and waste 'exchanges' as *"markets for buying and selling reusable and recyclable commodities. Some are physical warehouses that advertise available commodities through printed catalogs, while others are simply web sites that connect buyers and sellers"* (Environment, Health and Safety 2017). The labeling of these symbiosis as exchanges is contested by the IS definition provided by (Lombardi and Laybourn 2012), who argue these could be better referred to as business transactions. These online waste markets also predominantly select a business model considering waste as transactional items rather than for forming collaborative relations in order to continuously reuse multiple wastes among industries.

Most electronic waste markets originate as a result of promoting the concept of waste transfers between industries in Europe in the beginning of 1970 (U.S. EPA 1994). During this period, clearinghouses acted as intermediaries to list the wastes of industries. However, the success of the Internet in the 90 s increased the ease of communication linking regional markets together and resulted in the online material and waste markets as we know them today. The success of e-marketplaces is mainly attributed to the involvement of industrial actors in establishing a critical mass of users and creating sufficient supply and demand (Evans and Schmalensee 2010). Only a few of these IS markets attract this critical mass, whereas the majority fail to become largely populated and as a consequence do not take off (see e.g. (Environment, Health and Safety 2017)). Moreover, the established markets struggle to sustain their business. This is, among other reasons, because the market existence is based on a continuous flow of supply and demand, which requires the participating organizations to repeatedly invest in the identification of new potential waste transactions or frequently attract new organizations to join. Although many of these systems struggle to become economically viable and find it difficult to engage industries, there is potential that is recognized to gain both economic and ecologic benefits (e.g. in a case of construction and demolition waste (Chen et al. 2006)). The challenge often is to bootstrap such systems, such as in The Resource eXchange Platform (TRXP) (Dietrich et al. 2014; Hickey et al. 2014), a resource 'exchange' web-platform facilitating industrial symbiosis by building a network of organizations in Europe that could reuse or disassemble industrial streams of ICT equipment. The researchers (Dietrich et al. 2014) show that the open platform is technically feasible and could extend reuse streams by means of industrial symbiosis. However, the promoters also demonstrate with scaling their concept of re-usability that economic validity remains difficult, and that regulatory constraints affect the success of such networks.

Research that investigates a viable example of an online waste platform operating in Minnesota, United States (Dhanorkar et al. 2015), identify patterns in the successful transactions and relate positive effects back to the presence of rich re-purposing information and product information. Providing sellers access to re-purposing alternatives positively affected their network commitment.

Furthermore, the rich product information and transaction process explanation used to inform buyers is also found to positively affect successful transactions by reducing the buyers' uncertainty. Interestingly, the analysis reveals that items that require longer term contracting are underrepresented in the successful transactions and are suggested to benefit from more intensive facilitation that supports the contracting, reduces the uncertainty and builds trust (Dhanorkar et al. 2015).

From a technical perspective, ontological engineering techniques studied by (Raafat et al. 2013) demonstrate the ability to enhance and structure waste item information in e-marketplaces, such as in the e-symbiosis system (Cecelja et al. 2015). These ontologies enable the use of systematic matching in online systems that support waste transactions (Trokanas et al. 2015). The design of techniques that should match process waste to primary inputs raises some challenges. For example, an input-output matching approach, which basically matches supply and demand items based on a classification code, would identify only the resources that could directly be matched, while (Hein et al. 2015) points out also to consider the process of substitution. This suggests to provide relationships between wastes and the potential resulting materials from processing, in matching wastes to inputs. Connecting industries through web-based interfaces gains popularity while slowly also becomes an object for investigation to energy based symbiosis (Große et al. 2016).

3.2 Facilitated Synergy Identification Systems

Our second information systems concept is classified as facilitated synergy identification systems. Although technically these type of systems share to a large extent similar technologies with open online waste markets, from organizational perspective these systems are quite distinct. The major difference is found in how the systems are being used by clusters and facilitators to explore IS; aligning this group of systems with the facilitated industrial symbiosis approach (Paquin and Howard-Grenville 2012), or in few cases to planned conditions in eco-industrial parks or IS networks (Boons et al. 2016; Chertow 2007). Furthermore, these systems typically adopt more coordinated forms of waste identifications, few are publicly accessible and tend to have a larger impact in creating sustainable long term oriented symbiosis from waste streams than most open online waste markets (e.g. (Sterr and Ott 2004)).

The initial waste transactions often created using these type of IS tools are generally the result of organized IS identification workshops, within eco-industrial clusters or among regional participants from different industrial sectors (Mirata 2004; Paquin and Howard-Grenville 2012; van Beers et al. 2007). During the workshops synergy identification tools can assist providing in identification support and exploration of IS opportunities. This type of support varies from input-output matching to the review of substitutes, affective regulations or the assessment of financial and environmental impacts (Grant et al. 2010). In addition, after the initiation of such networks, the systems can potentially serve as a communication hub for an internal waste market. It also has been suggested that academic and business conferences can play such a role by disseminating ideas and helping with the identification of sustainable transactions (Baas and Hjelm 2015).

Remarkably, many studies acknowledge the support given by synergy identification systems. However, few reach the desired long-term impact, and remain operative over a period of time (Grant et al. 2010). This is observed in the WasteX system in Jamaica which demonstrates the feasibility of a web-based waste 'exchange' system developed for developing economies. The project struggled for a while with industrial adoption due to a lack of critical mass of users (Clayton et al. 2002), and later became inoperative (Grant et al. 2010). The study of (Grant et al. 2010) reveals that the majority of systems have not been designed with a commercial prospective in mind. On the contrary, the system development concentrates on the functionality; which is provided as one of the main reasons why many systems have failed to sustain. This can be related back to the fact that tools often do not consider the need to enhance social participation; focusing more on determining technical opportunities rather than building human relationships. Furthermore, positive effectors considered to succeed sustainable markets are the industry adoption of standardized waste taxonomy and the presence of a key number of organizations in order to bootstrap the newly created market.

Examples of IS tools resulting in fruitful and sustainable collaborations include the Institute of Eco-Industrial Analysis (IUWA) Waste manager implemented applied in the Rhine-Necklar region in Germany (Chen et al. 2006), and the information management tools used in the National Industrial Symbiosis Program (NISP) in the United Kingdom (Mirata 2004). The study of (Sterr and Ott 2004) shows that such identification tools can promote the potential for symbiotic cooperation at a wider regional level in order to establish more connected industrial waste reuse networks. Nonetheless, enlarging regional size presents new challenges including higher organizational costs, building trust and coordination and requires more practical ways of information exchange to detect appropriate partners (Mirata 2004; Sterr and Ott 2004) shows a similar tool deployed in the National Industrial Symbiosis Program (NISP) in the United Kingdom. A material flow database in combination with a decision support tool is used to reveal feasible industrial synergies and to evaluate the environmental effect of IS actions. Here, the important role of coordinating bodies is to provide support for a whole range of activities, including processing, logistics, capacity management of regional parties, technology alternatives, environmentally preferable practices, market dynamics and regulatory issues (Mirata 2004). These ideas emerged into the SynerGIE system practiced by the facilitators in the NISP program, and is now applied in many other countries (Ghali et al. 2016; Lombardi and Laybourn 2015).

Recent studies (Cutaia et al. 2015; van Beers et al. 2007; Veiga and Magrini 2009) continue to experiment with tool support in facilitated form to create IS relations. They investigate not only the effectiveness of exploring new synergies, but also address numerous forms of synergy assessment support that may be given with these systems, for example, in a project in the Kwinana and Gladstone mineral industry in Australia (van Beers et al. 2007). The project aims at developing practical assistance to the industries with tools that could identify and develop new synergies with sustainable outcomes. Furthermore, we observe attempts at creating and adopting packaged software solutions (commercial of-the-shelf) in facilitated IS research. An example of this is the Facility Synergy Tool (FaST) developed by the U.S. Environmental Protection Agency (EPA) that was used to identify IS opportunities in the eco-industrial-cluster in Rio de Janeiro (Veiga and Magrini 2009). The integration of identification and assessment components was part of these tools. These elements are combined into an overall platform in order to provide a toolbox that can be used by practitioners. Similarly, the IS platform developed in Catania, Italy, reports one platform combined by geographical information, environmental regulations, best IS practices and to a certain extent life cycle assessment technology (Cutaia et al. 2015, 2014). Showing the economic viability to organizations as a component of a platform aimed at IS identification is also argued as one of major facilitators (Raabe et al. 2017). A data oriented approach would both help to reveal new industrial symbiosis opportunities as well to assess the economic benefits that could demonstrate the IS viability (Song et al. 2017).

3.3 Industry Sector Synergy Identification

Another interesting concept applied in information systems is to examine synergies among industries rather than between firms which is demonstrated in a case study in Taiwan (Chen 2015). With the help of input-output tables, opportunities to use by-products were identified for each industry type, and used as suggestions for organizations that share common features and production processes. Following this holistic view to link industry sectors, a hypothetical decision support system is suggested that could review the duties and responsibilities of authorities in IS creation and then support them through the analysis of production industries to detect open and fixed material loops (Horvath 2016). This type of information system would not only support direct identification, but also help in developing new environmental policies that stimulate industries to adopt industrial symbiosis.

3.4 Social Network Synergy Identification

A fairly new development considers the potential of social network platforms to identify and develop groups for actors who share IS interests. Social media can be a helpful tool to distribute information, build relationships, share experiences and coordinate communities. The suggested web-based platform, that is based on social network content, could serve an IS community to forge new relationships and share experiences (Ghali et al. 2016). Although organizations may be hesitant to share information extensively using these networks, they might be effective in introducing people who work on similar topics, as observed in industry related LinkedIn groups (2017).

3.5 Industrial Symbiosis Knowledge Repositories

IS knowledge repositories can be helpful tools for organizations to reveal new potential synergies. Not only do they enable organizations with repositories to share their IS experiences, but also provide them with a gateway to a variety of structured and unstructured information on industrial symbiosis. Nowadays, a few of the IS knowledge repositories started to develop web interfaces that authorize access to databases, e.g. life cycle inventories, resource substitution data, IS technologies, regulations, and services that support taxonomy translation.

A good example of an IS platform is the Industrial Symbiosis DATA repository (ISDATA 2015). The platform collects IS case studies, cross analyzes material properties and maps open data sets related to the identification of IS. Many other data collections, both developed by businesses and governmental agencies, also act as reference guides in IS identification, such as Nordregio IS cases (Nordregio 2016), the Industrie et Synergies Inter-Sectorielles database, and the collection of NISP case studies (Enipedia 2015). Another type of repositories are IS Wiki's, which are community platforms that enable collaborative data collection and moderation, in which knowledge of implemented IS case examples are shared, e.g. Enipedia (Davis et al. 2010; Yu et al. 2014). What we observe in many tool implementations is that due to the lack of economic incentives, it is difficult to continuously develop and maintain such information sources. This phenomena is also more widely observed in the field of knowledge systems where this lack of active contribution is explained clearly by the social dilemmas of knowledge sharing (Cabrera and Cabrera 2002; Wang and Noe 2010). The dilemma refers to the situation that sharing insights come at a cost of an individual while there usually is less to gain from the sharing act itself. On the other hand, commercial organizations collect and sell such information, but consider a business model to access and use such data. Moreover, data are affected by legal constrains and often require confidentiality; hence, challenges to the design of information use in such platforms.

However, many researchers have pointed out using environmental data sets can add value to IS identification systems (Cutaia et al. 2015; Davis et al. 2009; Mattila et al. 2012; Sterr and Ott 2004). Incorporation of these external information sources into facilitation tools can enhance the exploration and assessment model. Analyzing the IS case data would enable the creation of expert systems that could recommend based on historical cases. However, the ability to link all such information generally requires common, unambiguous terminology or a service for taxonomy translation (ISDATA 2015; Sander et al. 2008). Common resource and waste classification standards, such as the widely used European Waste Catalogue (EWC) (European Commission 2000), are not ideal for this purpose, as there is overlap of classifications, ambiguity in classifications and, in some cases, an inadequate level of detail not sufficient to IS exploration (Sander et al. 2008).

3.6 Industrial Symbiosis Region Identification

Our final category considers systems that aim to support the strategic location of industrial symbiosis investments. We conceptualize these tools as IS region identification systems. The main function of such systems is to identify regions conducive for industrial symbiotic development, mostly with geographical interface elements, such that industrial park planners and facilitators of IS can optimize their investment of time and resources. For example, in the IS project situated in Geneva where a geographical analysis tool is being developed that visualizes the economic activity of the Swiss canton (Massard and Erkman 2007, 2009). The key of the system is its function to locate the regions that have a high economic viability for IS implementations. The approach of region identification is in line with IS facilitators who suggest that current industrial sites with existing cooperation provide the best prospects for identifying new industrial symbiosis opportunities. The design of a symbiosis suitability index demonstrates this ability to identify IS regions at the South Humber Bank (Jensen et al. 2012).

Visualizing the economic activity as an assessment of IS viability of a region requires one to connect to a variety of data sources. In general, aggregated data reflecting regional economic, infrastructural or industrial characteristics are most useful in determining the applicability of IS. Characteristic examples include land destination, the projection of waste production, network-density of infrastructures, urban development, diversity of industry, availability of nearby facilities such as power plants, boreholes and waste facilities (Aid et al. 2015; Jensen et al. 2012; Ruiz et al. 2012). Typically, with such a variety of inputs, the decision process involves a multi-criteria evaluation. Hence scoring algorithms or fuzzy rule based expert systems are common approaches that provide such spatial decision support. One method of conducting multi-criteria evaluation is to create weighted normalized evaluations using Analytic Hierarchy Process (AHP), as the one performed in the Cantabria region in northern Spain (Ruiz et al. 2012). The study of (Aid et al. 2015) from Sweden, shows a heuristic tool named Looplocal. The tool assesses IS potential through analyzing resource flow data of regions having the IS knowledge on inputs and outputs derived from a LCA database and a collection of IS case studies. Though there is some interest from the industry for such systems, additional evaluation of relevance is still emphasized (Aid et al. 2015).

Region identification could also be deployed to determine the best location for specific IS cases. For example, this is seen in the spatial planning of district heating systems (Togawa et al. 2016). District heating focuses on the recovery of waste heat from municipal solid waste incinerators and low temperature industrial waste heat utilized for district heating in urban areas. The urban sustainable energy planners in Japan experiment with geographical information systems that analyze the waste heat potential of their regions (Dou et al. 2016). These systems evaluate the usability, feasibility and efficiency of a district heat system quantitatively by calculating CO_2 reductions and through conducting cost benefit analyses of multiple scenarios. Note that most of these regional identification system examples from literature are fairly conceptual and not yet widely adopted by industry or governmental planners, presumably for reasons of economic viability.

4 IT Challenges for Industrial Symbiosis Tools

From an information systems perspective we can derive three key observations that provide directions for the further development of identification tools for industrial symbiosis. The first direction is to move from custom made software (observed in (Grant et al. 2010)), towards mass product software. We believe that the application context (e.g. the parks/regions, industrial sectors, and active regulations) is not that different and hardly affects the type of functions required. This suggests reusing software and moving towards an IS tool package that can be deployed in many situations. Often such a transition of software is associated with the terminology of product software (Xu and Brinkkemper 2007). Secondly, we consider the integration of documented IS cases, linked data and IS tools into a platform. Furthermore, a combination of services in a central environment can streamline work processes, and a utilization of various data sources may help reveal new insights that lead to new type of services. The key requirement for this is the adoption of service oriented architectures into the design of the decision support systems (Demirkan and Delen 2013). A key software requirement to data providers, such as LCA databases, is to provide open accessible interfaces to enable adoption of data services within the tool package that can enhance or enable the use of IS explorations. The advantage of such an approach is that it can lead to the development of services for different devices and multiple platforms (digital mesh). A third research direction for tools is the tailoring of intelligent learning algorithms to the market of industrial symbiosis. Because of the increase in expertise and growing availability of data intelligent learning is slowly becoming more relevant. A particular set of machine learning techniques that in our view apply to IS markets are recommender algorithms (Ekstrand et al. 2011). Popular recommendation techniques that could be interesting to evaluate in the context of IS identification are association rule mining, case-based reasoning, collaborative filtering, knowledge-based recommendation, and rule-based recommendation.

5 Conclusions

Overall, this article reviewed 16 years of literature (2000–2016) on information systems used to facilitate the identification of industrial symbiosis. We provided a framework with six identified concepts to better understand IS identification tools, namely; open online waste markets, facilitated synergy identification systems, industry sector synergy identification, social network platforms, IS knowledge repositories and regional identification systems. In general, many of the identification tools presented in literature report difficulties with wide industry adoption, but also recognize the benefits that potentially can be derived. The key challenge for IS tools is demonstrating those economic, social and ecological benefits of potential IS opportunities to industries, while simultaneously preserving data confidentiality, conforming to regulations and assuring the stakeholders against risks resulting from the IS implementation. Along with the growth in IS experience reports and IS data sources, future research may focus on the development of product and service oriented IS software, the integration of data and tools into a tool package and the adoption of intelligent learning techniques.

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