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A Social Semantic Web Framework for Industrial Synergies Initiation

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Abstract. Industrial synergies join two or more organizations who initially functioned as independent economic actors - who may originate from different sectors - together in order to share resources and exchange by-products for mutual environmental, financial, and social benefits for its participants. Industrial symbiosis are networks of industrial synergies that can be initiated and created over time in various manners (Boons et *al*., 2016). In practice, the initiation of an industrial synergy, and particularly the identification of by-product compatibilities, rely on direct or facilitated knowledge and information sharing, which is essential for discovering industrial synergy opportunities. Beyond its potential contribution to facilitate knowledge and information sharing among organizations, the social semantic web also has the potential to facilitate the initiation of industrial synergy by systematically and automatically identifying and recommending by-products exchange compatibilities to potential partners. This framework exploits the ability of the sematic web to enable the search for analogies between potential partners within a region or district and existing industrial synergies around the world. This paper proposes the SSWISI framework for the initiation of industrial synergies, which is based on the social semantic web. The framework proposed in this paper adopts the concept of Linked Open Data (LOD), which enables the sharing and exchanging of information with external systems. This feature distinguishes the proposed framework from the existing approaches in its initiation of industrial synergies.

Keywords. Industrial symbiosis, industrial synergies, social networks, semantic web, ontologies, social semantic web, linked open data

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1. Introduction

Industrial ecology (IE) aims to study, develop and implement strategies that decrease the environmental impacts of by-products and waste usually associated with industrial systems. It explores various interactions that can occur between industrial systems and the environment. IE adopts a natural paradigm and proposes that industrial ecosystems can behave like a natural ecosystem wherein everything is used and recycled (Davis, et al., 2010). To do so, industrial ecosystems need to maximize resource efficiency by sharing their resources and creating opportunities to use or recycle industrial waste and by-products (Kuczenski, et.al. 2016), (Zhang, et.al. 2015).

Industrial symbiosis (IS) join organizations from different geographical areas and different industrial sectors together in order to share and exchange resources such as energy, materials, and water. Such exchanges can also include information and ideas about business practices that help in sustainable innovation and thus are not limited to material and energy flows (Grant, et al., 2010), (Li & Shi, 2015), (Cecelja, et al., 2015), (Walls & Paquin, 2015). The exchange of information is also helpful for companies to identify appropriate business partners for sharing resources within a business community. IS improves resource utilization and provides mutual environmental, financial, and social benefits to participants (Nooij, 2014), (Raafat, et al., 2013). IS promote collaboration between organizations. Empirical studies reveal that IS replicate the behaviors of natural ecosystems where waste from one organism become a resource for another (Grant, et al., 2010), (Li & Shi, 2015).

However, unlike natural ecosystems wherein waste reuse and recycling is driven by biodiversity and the natural cycles that emerge from the sharing of a collective environment, IS are artificial industrial ecosystems that cannot relies on nature to develop industrial synergies. Each waste or by-product reuse must be identified and initiated through direct or facilitated information sharing between potential stakeholders. This requires (1) stakeholder to acknowledge their need to manage or acquire by-products, (2) data collection about waste and by-products flows and existing synergies, (3) potential synergy identification, and (4) some form of sharing data or contact between potential stakeholders (Ghali, et al., 2016).

In other words, potential partners in such collaborative arrangements do not always have sufficient information about each other, or even about the benefits of exchanging waste and by-products, in order to initiate an industrial synergy development (Ghali, et al., 2016). Potential collaborators need to acknowledge their need to environmentally manage their waste and by-products and the benefits of using them as feedstock, but also their role and contribution in the potential partnership. Then, they need to develop a relationship of trust over time in order to implement the synergy. Therefore, throughout their development IS networks require some form of sharing of knowledge, personal and corporate experience, and information, particularly concerning industrial flows (Walls & Paquin, 2015).

The World Wide Web (WWW) has proven itself capable of enabling collaboration among potential partners in collective actions (Davis, et al., 2010). The web efficiently supports the building of a collective body of knowledge and the creation of feedback loops so that information, once gathered, can be reused for enabling collaboration among organizations. Recently, multiple approaches (Cecelja, et al., 2015), (Ghali, et al., 2016), (Nooij, 2014) based on web technologies have emerged as a site for the development of industrial symbiosis. However, the existing approaches do not exploit the full potential of current web technologies.

The social semantic web (Breslin, et al., 2011), (Passant, et al., 2010) involves the integration of leading web technologies: social networks (Musial & Kazienko, 2013) and the semantic web (Berners-Lee, et al., 2001), (Ding, et al., 2007), (Horrocks, 2008). It can enable industrial engagement, participation, exchange, and interaction, and also contribute to the creation of explicit and semantically rich knowledge representations that can prove helpful for the initiation of industrial synergies.

This paper proposes a framework that exploits the potential of the social semantic web that fosters collaboration and knowledge and information sharing among members of online industrial communities, by enabling the identification of potential synergy partners and the initiation of their relationship. This framework, called SSWISI, extends the features of currently existing approaches (Cecelja, et al., 2015), (Ghali, et al., 2016), (Nooij, 2014) and integrates them into a hybrid approach for industrial symbiosis development. It is a web-based approach that can be openly accessed by anyone only through the simple act of registration. The distinguishing feature of this framework is information sharing with other external systems through the Linked Open Data (LOD) concept (Bizer, et al., 2009), (Davies & Edwards, 2012), (Heath & Bizer, 2011).

Section 2 describes the background technologies essential to understand the SSWISI framework and its organization. Section 3 explores and analyzes the existing approaches dedicated to industrial symbiosis development. Section 4 introduces the SSWISI framework. Section 5 concludes the paper and presents future research opportunities.

2. Concepts and definition

This section outlines the technological concepts our approach as based on: (a) Semantic Web; (b) Semantic Web Languages; (c) Ontologies; (d) Semantic Web Query Language; (e) Linked Open Data - Dbpedia; (f) FOAF Ontology and (g) Social Semantic Web. These technologies have made possible the development of the SSWISI framework for industrial synergy initiation.

2.1.Semantic Web

The Semantic Web (Web3.0) offers a common framework where data can be shared and reused among multiple applications (Berners-Lee, et al., 2001), (Butt & Khan, 2014). It extends the current web through standards defined by the World Wide Web Consortium (W3C) and presents information with well-defined parameters. Its design goal is to empower computers to work or think like humans that can effectively process data on the web. Semantic Web is the web of things rather than the web of documents. It describes the relationship among things and their properties, so that computers can clearly recognize the nature and relationships of things through their properties. Consequently, it helps to retrieve knowledge by applying reasoning, rather than data, from the web (Butt & Khan, 2014), (Horrocks, 2008).

2.1.1. Semantic Web Language

Semantic Web transforms data into information by incorporating a sufficient structure around it. Multiple universal information formats exist that incorporate structure from data as well as metadata on Semantic Web. These formats are recognized as Semantic Web languages/standards. These standards facilitate data integration and interoperability on the Semantic Web (Ding, et al., 2007). They are abstract models that can be represented with multiple serialization formats (i.e., file format), such as XML and turtle. Resource Description Framework (RDF) is a language that provides basic syntax to represent information and to share data in the Web. It is recommended by W3C as a standard for semantic web (Anon., 2014). There are three fundamental concepts: (i) resources, (ii) properties, and (iii) statements. Resources are 'things' that are illustrated by the RDF expressions. A unique identifier is allotted to each resource that is called Universal Resource Identifier (URI). The relationship between two resources is established through such Properties. A resource, along with its associated property and value for that property, originates a statement. An RDF statement is also called "Triple" if it comprises three different parts that are categorized as subject, predicate, and object respectively. Subjects and predicates are resources in an RDF statement and an object could be a resource or a literal. A RDF model, comprising a set of RDF triples, represents a directed graph of information for illustrating personal information as well as social networks. Moreover, it facilitates integrating information over disparate sources of information. Different concepts and their semantic relationships can be effectively represented by an unlimited large graph of information (Butt & Khan, 2014). Resource Description Framework Schema (RDFS) and Web Ontology Language (OWL) have been designed to be used by applications for information processing purpose rather than just for information representation (Anon., 2000). These languages describe vocabularies/ontologies in terms of *Class*, *Property*, *Domain*, and *Range*. They assist in carrying out interoperability and reasoning on the Semantic Web (Anon., 2012), (Anon., 2004).

2.1.2. Ontologies

The core of the Semantic Web is ontologies (Ding, et al., 2007). Ontologies are defined as an explicit and formal specification of a shared conceptualization (Gruber, 1995). They were initially developed by the Artificial Intelligence (AI) community in order to facilitate knowledge sharing and the effective reuse of existing information. Ontologies represent knowledge domains in terms of concepts and relations between them. They describe real-world terms in a formal language such as RDFS or OWL. They can create an integrated view of multidisciplinary information. They represent a data source at a higher level of abstraction and manifest the semantics of a source. Data in ontologies is self-describing because it is described through RDF tags, which makes it readable by machines and able be used in reasoning to categorize and find associations in it (Butt & Khan, 2014), (Farid, et al., 2016).

2.1.3. Semantic Web Query Language - SPARQL

RDF is a flexible and extensible way to represent information about WWW resources. The data, stored in RDF format, can be retrieved and manipulated by the semantic web query language

(SPARQL). SPARQL (Anon., 2013), (Karim, et al., 2015), (Butt & Khan, 2014) is a graph-matching query language. Each SPARQL query consists of a set of triple patterns that is inherently a graph pattern. Triple patterns are identical to RDF triples apart from the subject, predicate, and object, which may be a variable. In processing a SPARQL query, the query graph pattern is matched with a subgraph of RDF data and its variables are replaced with RDF terms from the subgraph. The query result is basically a RDF graph that is identical to the subgraph. A SPARQL query can retrieve data from different sources if the data is stored in RDF format or represented as RDF through middleware (Butt & Khan, 2014), (Karim, et al., 2015).

2.1.4. Linked Open Data – Dbpedia

Linked Data is a method where structured data is interlinked using RDF on the web and becomes more useful through semantic queries (Auer, et al., 2011), (Bizer, 2009), (Bizer, et al., 2009), (Heath & Bizer, 2011), (Lehmann, et al., 2015). Tim Berners-Lee defined fundamentals that can effectively publish and connect structured data on the web if it follows the linked data principles. These principles guide how to use standardized web technologies to set data-level links between data that belong to diverse sources. Linked data identifies web documents and arbitrary real-world entities in the documents using HTTP URIs. The data-level links, which are RDF triples, connect data from diverse sources into a single global data space. These links between data items of diverse sources facilitate navigation from one data source to other sources using a Semantic Web browser.

The software applications, designed based on Web 2.0, work with predetermined data sources. However, linked data applications that utilize data-level links can find new data sources at runtime. Linked data applications can produce comparatively complete and updated answers because they consult with new data sources that appear on the web (Lehmann, et al., 2015). Linked Open Data (LOD) is linked data released under an open license and allows the reuse of data free of cost.

The LOD project goal is to make different open data sources available on the Web and set RDF links between their data items for building huge datasets (Bizer, 2009). LOD formats are crucial in integrating multiple datasets and are jointly exploited by SPARQL.

Wikipedia, a social networking site, provides only full-text searching capabilities for accessing its contents, which is a very limited access model for such a useful knowledge base. However, there are many complex issues in the collaboratively edited data of Wikipedia (e.g., contradictory data, inconsistent taxonomical conventions, errors, and even spam) (Simov & Kiryakov, 2015), (Bizer, et al., 2009), (Heath & Bizer, 2011). The DBpedia project converts Wikipedia content into structured knowledge (i.e. Linked Data). DBpedia, a community project, extracts structured information from Wikipedia and makes it available on the web as LOD. Complex queries can be posed against DBpedia datasets for retrieving useful information. Other datasets on the web can be linked with Wikipedia data through DBpedia.

2.1.5. Linked Open Data - FOAF

Friend-Of-A-Friend (FOAF) is a linked information system that is an application of semantic web. It describes people, their activities, and their relations to one another and objects by integrating the data across a variety of applications, web sites and software systems (Brickley & Miller, 2010). OWL and/or RDFS have been used to define the FOAF ontology. FOAF allows groups of people to establish social networks among themselves without the need of their own computational resources. Users' profiles comprise links to their friends' profiles and produce a homogenous social network (HSN) (Ding, et al., 2007), (Sapkota, et al., 2015), (Golbeck & Rothstein, 2008). Every internet user can use FOAF for free to create his personal profile and to define his or her relationships. Every user has a unique identity in FOAF. These identities empower computers to recognize people who are identical or who maintain identical relationships or have identical interests. Recently, the FOAF format has been adopted by many social networking sites (SNS) in order to exchange user profile information (Musial & Kazienko, 2013). Different FOAF documents can be combined amongst themselves to generate a unified database of information. FOAF adopts the concept of linked data and links together a web based on decentralized descriptions.

2.2. Social semantic web

The social web links people through the World Wide Web. It is a set of social applications and has launched a novel form of users' interaction with and via the web. The Web has been turned from a read only medium to a widely available, collaborative read-write Web (Golbeck & Rothstein, 2008), (Passant, et al., 2010). Huge amounts of user contributions exist within each individual social application. However, those contributions are often available only within the walls of that very application. Thus, it prevents the seamless integration of the available and contributed data and knowledge. The disadvantage of most of these applications is isolation from the rest of the web (Passant, et al., 2010).

Semantic web presents data with well-defined semantics and thus makes data available for automated discovery and integration across distributed applications (Berners-Lee, et al., 2001). In order to develop collective knowledge systems, the social web requires data interoperability across applications. Semantic web technologies can assist the social web for data interoperability by explicitly defining the structure and meaning of data and knowledge. The integration of social and semantic webs can facilitate the creation of collective knowledge across different social applications (Gruber, 2008), (Breslin, et al., 2011). This integration has resulted in a new paradigm known as Social Semantic Web (SSW). SSW facilitates the creation, management, and sharing of information by combining the technologies and approaches from both webs (Breslin, et al., 2011).

SSW creates explicit and semantically rich knowledge representations of the social interactions that take place within each system. It can represent the collective knowledge systems as a large graph. SSW systems can provide similarly useful information, as many users contribute to the collective knowledge stored in them.

3. Online-Existing Approaches to IS

Industrial symbiosis (IS) are industrial networks that cooperatively optimize their use of resources among different industries for economic, environmental, and social benefits in their local communities. Individual IS links are called industrial synergies. They are often – but not necessarily – built between companies of different sectors that do not have traditional supply chain relationships. Grant *et al*. (2010) recognized both explicit and tacit knowledge as pre-requisites for developing and spreading IS culture and principles in common practices. Explicit knowledge can be easily expressed or represented and communicated with various tools. However, tacit knowledge is the accumulated know-how or experience of an individual or the staff of a company. It is difficult to express in written forms. Therefore, developing the IS culture and related principles and, eventually, fully developing industrial synergies requires collecting, processing, organizing, and sharing large amounts of data and knowledge. Online/Computer-supported systems can play a significant role to foster such collaboration, and enable reuse, re-organization, and the subsequent expansion of datasets and knowledge within the industrial ecology community of researchers and practitioners (Davis, et al., 2010), (Grant, et al., 2010).

Several computer-supported approaches to develop IS culture and principles have been developed to, among other things, identify industrial synergies in industrial clusters or parks. These systems support various functions for saving, storing, transforming, processing, and publishing data from one or several sources, and then transmitting this data to one or several destinations. However, they also demand a high level of user involvement and systems knowledge to operate. In other words, their main goal is to assist users in searching for industrial synergy opportunities. However, their access is usually restricted to individual users operating through an online portal or license (Cecelja, et al., 2015), (Ghali, et al., 2016), (Grant, et al., 2010). Moreover, they are not intended to participate actively and communicate among users, which is the main means of sharing tacit knowledge. In the next sections, we will analyze the features of recent web technology-based approaches to IS development.

3.1.Enipedia

The first tool analyzed here is referred to as Enipedia. It is a semantic wiki which aims to develop IS practice. The idea behind this approach is that IS can be developed by means of studying existing real world examples and IS case studies. Enipedia is a hybrid technology of wiki and ontology, where wiki enables the collection and sharing of knowledge and information contributions, and where ontology specifies how the concepts in these contributions relate to each other (Nooij, 2014). In this approach, there are two important elements (also referred to as categories) contributing to establishing industrial synergies: *facilities* and *synergy links* that connect facilities. Facilities can be by-products, companies, or any the provider or user behind a by-product. Facilities also have their properties, such as industry type, industry location and composition of a by-product. They are illustrated in a wiki page through the synergy link. Therefore, such a repository of information and knowledge could potentially be very useful for finding by-product exchange opportunities. In other words, with Enipedia, a firm with a specific by-product could easily find information related to potential uses of its by-products, as well as the types and sectors of a related firm that might have use for it. However, these data sets do not contain any information about potential specific users of by-products nor do they highlight social connections in order to share experience. Therefore, another IS-event element was introduced in Enipedia in order to store social interaction information. For example, an IS-event can be a match-making workshop organized by a third-party.

This tool was designed and tested with data from two case studies. However, the proposed approach lacks in providing the complete services as desired by conceptual scope of IS. It should ideally take advantage of a larger base of potential contributors. Furthermore, the proposed ontology of Enipedia cannot link with Linked Open Data (LOD) for exchanging information and sharing knowledge because it does not fully adopt the principles of open linked data.

3.2. eSymbiosis

This approach uses ontology to model and formalize the knowledge in the domain of IS (Cecelja, et al., 2015), (Raafat, et al., 2013), (Trokanas, et al., 2014). Their proposed ontology comprises three high level modules: (i) IS matching process ontology, (ii) IS domain ontology, and (iii) IS service description ontology. The three modules form the IS meta-ontology. The IS domain ontology is used for describing material (or energy) processing technologies and input-output requirements. It was designed with four different levels of abstraction for conceptualization including a meta-level, an upper-level, a domain level, and an instantiation level ontology. The approach was implemented as an automated web service, thus reducing costs and easing its integration with other systems.

In brief, the eSymbiosis approach (Cecelja, et al., 2015) focuses on developing ontology dedicated to modeling and analyzing knowledge. It ignores the social network, where users and companies can actively participate, exchange, and interact among themselves for sharing tacit knowledge. Moreover, the proposed ontology of eSymbiosis cannot link with Linked Open Data for exchanging information and sharing knowledge because, like Enipedia, it does not fully adopt linked Open Data (LOD) concepts. In other words, the knowledge-base of this system is restricted to data that is fed into it and is not dynamic.

3.3. Green Social Networking

Ghali *et al*. (2016) introduced the concept of Green Social Networking (GSN). In this paper, they systematically analyzed social networking in a way that could lead to the development of online social networks that support the formation of industrial synergies. They also showed that online social networks could be used in order to support their members/users discovering solutions to the problems that have already been solved by other members. This approach helps non-contributing members to benefit from exchanged knowledge by receiving emails or notifications for each new discussion. Moreover, social networks build relationships and develop trust among partners in a way that plays a crucial role in the formation of IS.

The GSN approach (Ghali, et al., 2016) adopts social networks and their functionalities for sharing knowledge among companies and other users to initiate industrial synergies. However, social networking sites are knowledge islands and are not linked with other knowledge bases. On their own, social networking sites are difficult to integrate with each other because their data is not rich semantically (Mikroyannidis, 2007), (Passant, et al., 2010).

3.4. Critical Analysis of Existing Systems

These web-based technologies of IS development (Nooij, 2014), (Cecelja, et al., 2015), (Ghali, et al., 2016) contribute to the industrial synergies initiation phase at a certain level. However, they do not exploit the full potential of current web technologies (i.e., social semantic web) where participation, exchange, and interaction among companies and with other users both within and across each system can take place. In addition, SSW facilitates the creation of explicit and semantically rich knowledge that can contribute to the initiation of industrial synergies. Hereafter, we compare these web-based approaches with respect to the social semantic web features as shown in Table 1.

Table 1: Comparative analysis of web-based approaches to IS development

	Rich Knowledge Representation	**Creativity & Innovation**	**Globalization**	**Active User Participation**
Enipedia	**Yes**	**Yes**	**No**	**Yes**
eSymbiosis	**Yes**	**Yes**	**No**	**No**
GSN	**No**	**No**	**No**	**Yes**

On the one hand, Table 1 shows that Enipedia and eSymbiosis use rich knowledge representation because they deploy an ontology for storing information, which, in turn, fosters creativity and innovation by letting users explore the logical associations among the various concepts of the ontologies in play. On the other hand, active user participation takes place in Enipedia and GSN because both approaches use social networks to support user interaction and collaboration in order to initiate industrial synergies. Moreover, industrial symbiosis involves organizations from different economic actors within different sectors in order to share resources and exchange by-products. It is also a dynamic domain of knowledge in which new industrial synergies enabling new technologies are constantly developed. Therefore, a single master ontology or repository (i.e., a site of social network) cannot possibly describe all information. Indeed, different sources of information are being developed in this domain at all times (Davis et al., 2010). Consequently, the notion of linked open data, which supports information exchange among autonomous information sources, can be instrumental for integrating this information into a coherent and organized data web. However, these approaches are unable to fully adopt these concepts, as they are restricted to data that is fed to them and do not exchange information with external Linked Open Data resources for globalization.

4. Proposed Framework - SSWISI

Industrial Networks that emerge from networks of personal contacts (i.e., people who work for different companies) initiated by necessity (e.g., supplier selection), can also develop by taking advantage of a business opportunity (e.g., partnership) or a pre-existing personal relationship (e.g., personal acquaintance). Industrial Networks are forged by people who eventually exchange information and work together to achieve their goals. In particular, sharing experiences, both at the individual and corporate levels, about by-products and industrial waste reuse opportunities, or even the sharing of personal knowledge or experience of industrial ecology practice, can eventually lead to the discovery of by-product exchange compatibilities and other synergistic opportunities (Ghali, et al., 2016), which can in turn lead to the creation of industrial synergies. There are many examples of known (i.e., collectively acknowledged) industrial practices that involve by-products utilization, although there are not necessarily acknowledged as industrial ecology practice by the industry (Jayathilakan et al., 2012; Siddique, 2014). This implies that the generalization of less known by-product utilizations developed around the world in specific contexts must somehow be shared in order for industrial ecology to become an industrial norm. Such sharing can take several and complementary forms. The framework proposed in this paper aims at developing a form of sharing that takes advantage of a wide spread technology (i.e., social networks), and the modelling of both explicit and tacit knowledge to accelerate specific knowledge discovery.

Web technologies have been recognized as a potential solution for sharing both explicit and tacit knowledge (Davis, et al., 2010), (Ghali, et al., 2016), (Nooij, 2014). In this work, we propose a framework based on Social Semantic Web (SSW) (Breslin, et al., 2011), (Mikroyannidis, 2007), (Golbeck & Rothstein, 2008) to support the early phase of industrial synergies initiation. Particularly, this paper focuses on the knowledge discovery phase, during which by-products compatibilities and potential industrial synergies are identified using a process of finding analogies between potential partnerships within an industrial region or district, and existing synergies around the world. In this framework, referred to as Social Semantic Web for Industrial Synergies Initiation (SSWISI), we adopt and integrate some features of Enipedia, eSymboisis, and Green Social Networking. SSWISI is an interactive web-based platform enhanced by social functions. It is based on ontologies that contribute to the sharing of knowledge and experience.

The main components of the framework are: semantic web (Berners-Lee, et al., 2001), (Horrocks, 2008) and social networks (Musial & Kazienko, 2013). Ontology, the semantic web core plays a back end role by structuring knowledge and information, while social networks play a front end role enabling both direct interactions between users and the sharing of their individual experience.

Social networks facilitate (i) learning from each other, (ii) information sharing, (iii) relationship building, and (4) community coordination (Ghali, et al., 2016). These features can contribute to stimulating social connections, and they can ultimately lead to the identification of material flow compatibilities (Davis, et al., 2010), (Ghali, et al., 2016). On the other hand, semantic web (i.e., through the adoption of ontologies) provides the means to organize, connect, and retrieve data, information, and knowledge in a way that efficiently enables the extraction of relevant information and knowledge about by-products exchanges.

4.1. SSWISI Ontology – OntoEco

An ontology can be used to model the tacit knowledge of a company's staff or any other research or technology transfer center related to waste and by-product streams (Cecelja, et al., 2015), (Trokanas, et al., 2014) (i.e., material, energy, water), their treatment, their processing, their handling, as well as the difficulties and solutions related to the development of their exchange potential with other companies. Similarly, an ontology can also be used to model the explicit knowledge of industrial symbiosis, synergy members, or any other potential partners, in the form of relevant information about their processing capabilities, supply needs, or inventory constraints, that can be used to identify potentially interested by-product exchange partners (Cecelja, et al., 2015), (Trokanas, et al., 2014). Our framework has been built on the conceptual model of the eSymbiosis's ontology and extended it.

OntoEco is an IS related ontology that is structured into four layers of abstraction, such as the eSymbiosis ontology. However, the concepts and properties in OntoEco have not been imported from eSymbiosis. Because by-products exchanges are often considered a form of innovation developed all over the world, and because industrial ecology is not yet a mature domain of knowledge, knowledge is often implicit and distributed solely across the staff and in-house experts of the engaged companies. Therefore, in order to accelerate the adoption of the principles of industrial ecology and foster the development of industrial symbiosis, we need to adopt a technology to access this ill-structured and broadly distributed knowledge. In other words, the early phase of industrial synergies initiation needs to explore new data sources and updated knowledge bases about by-product properties, their processing requirements, and their classification and composition.

In order to do that, ontologies must be linked to one another in order to automate extended search for information across multiple sources. Using interlinked ontologies, a user can navigate from a data item within one data source to related data items within other sources. In the SSWISI framework, we exploit this linked data concept (Bizer, et al., 2009), (Davies & Edwards, 2012), (Heath & Bizer, 2011), (Simov & Kiryakov, 2015). In other words, any linked data applications based on the SSWISI framework can discover new data sources and updated knowledge at runtime by following data-level links (i.e., URIs aligned with classes/properties), and we can thereby deliver more complete answers as new data sources appear on the Web.

Ontology models are structured with respect to concepts, properties, and associations (Horrocks, 2008), (Farid, et al., 2016). In this framework, the concepts, properties, and associations of OntoEco are imported from external ontologies thanks to Linked Open Data (LOD) (e.g., DBpedia (Anon., n.d.); FOAF (Brickley & Miller, 2010); and schema.org (Anon., n.d.), E-PRTR (http://prtr.ec.europa.eu/#/home), Toxic Release Inventory (https://www.epa.gov/toxics-release-inventory-tri-program), WikiData (https://www.wikidata.org/wiki/Wikidata:Main_Page)). However, the external ontologies are not limited to these mentioned sources. These imports featured in OntoEco enable OntoEco to be linked with external resources for discovering updated knowledge and new data sources in clouds of open data on the web. Moreover, it distinguishes between OntoEco and both eSymbiosis and Enipedia ontologies, which are close.

The core structure of OntoEco is illustrated in Figure 1. The ontological structure of OntoEco is divided into three segments located in three distinct ontological files: OntoEco-Schema, OntoEco-Data, OntoEco-rq. First, OntoEco-Schema supports the conceptual structure of the ontology. Next, OntoEco-Data preserves data (i.e., instances of OntoEco), while the third ontology contains SPARQL queries. In the remaining subsection, we describe these segments in details.

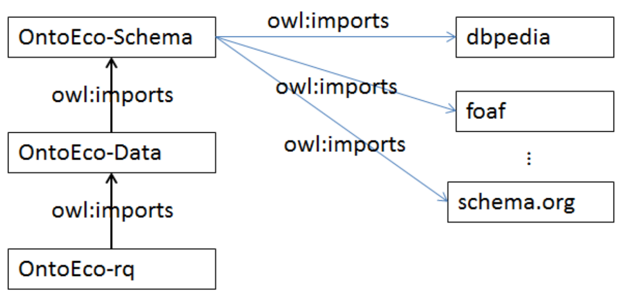

Figure 1: OntoEco Core Structure of the SSWISI Ontology

4.1.1. OntoEco-Schema

OntoEco-Schema is the domain ontology that models both tacit and explicit knowledge collected by IS practitioners and experts. The ontology is structured into four layers of abstraction: meta, top, domain, and instantiation levels as shown in Figure 2. The meta-level describes general concepts independent of the domain and facilitates sharing and reusing. The concept *Thing* is the base class of all ontology classes. The concept *Agent* is a subclass of *Thing*; similarly, *Organization* is a subclass of *Agent*. These are DBpedia classes. *Agent* represents things that perform some activities and *Organization* represents social institutions such as companies, societies. These classes have been mapped with FOAF and schema.org with the sameAs property.

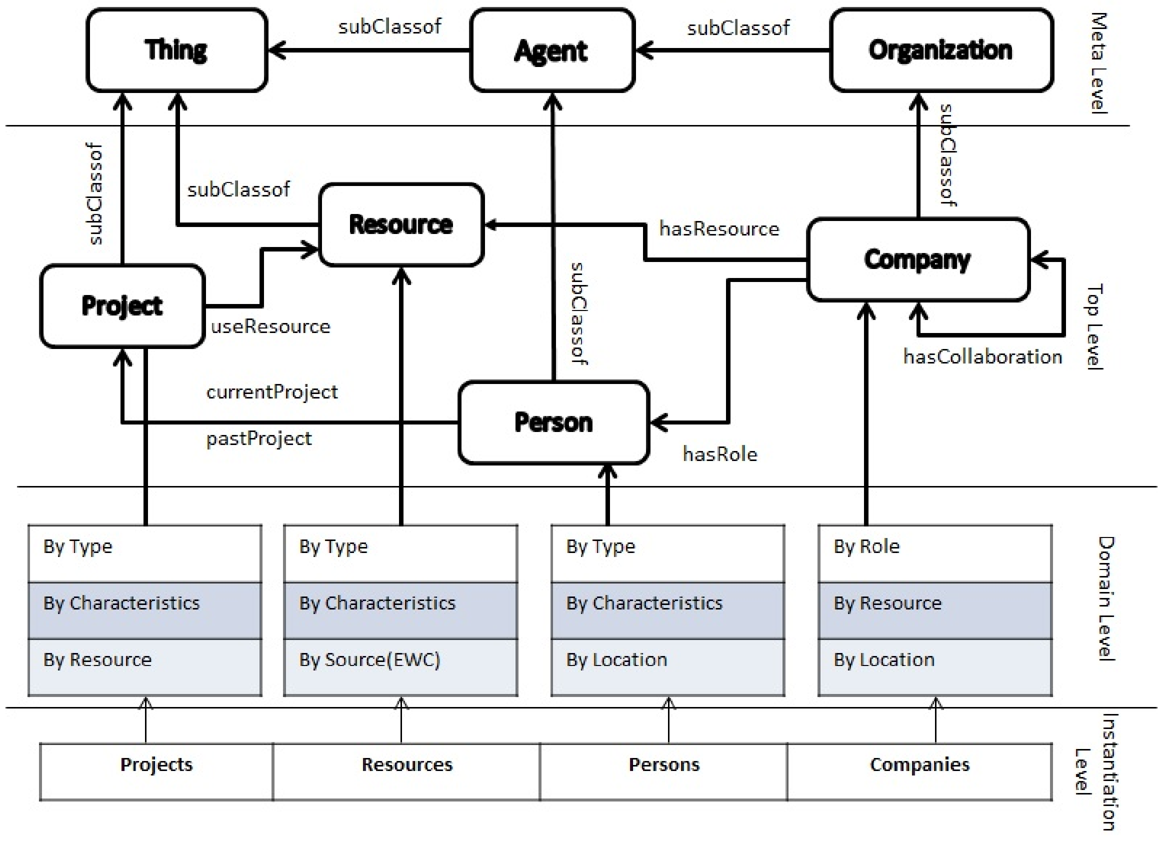

Figure 2: Design of OntoEco Ontology of Proposed SSWISI Framework

As stated earlier, ontology conceptualizes a knowledge domain in terms of concepts and relations between them. In this research, the knowledge domain is the industrial symbiosis, which is an association between two or more industrial facilities or companies where the wastes or byproducts of one become the raw materials for another. The main actors in the association are industrial companies; and wastes or byproducts. It is established through human beings for some projects. In order to conceptualize industrial symbiosis, we consider these four characters: resource, company, person, and project as abstract concepts for the domain that are linked in the association to achieve the desired objectives. The top-level of OntoEco describes the abstract concepts that construct the basic structure of the ontology. They are described as follows. ***Company***. This is a subclass of Organization in Dbpedia, and it represents a kind of *Agent* corresponding to companies or industries. The *Company* class and its properties represent industries involved in the initiation of synergies. It has been further classified through properties on the basis of By-Role (e.g., Owner, Key Person), By-Product (e.g., Fuel, Energy, water), By-Location (e.g. City, Country).

Person. This is a subclass of the *Agent* class and represents people, since all people are considered 'agents' in FOAF. This class is mapped to *Person* class of DBpedia and schema.org through sameAs property. Every user of SSWISI framework is an instance of the *Person* class. This *Person* is associated with hasRole property with *Company*. It has been further classified By-Type (e.g., ceo, manager), By-Characteristics (e.g., Education, Experience) and By-Location (e.g., City, Country).

Project. This is also a subclass of *Thing* that represents a collective endeavor of some kind in FOAF. It represents a particular case study of an industrial synergy or a new synergy that a user would like to initiate. A *Project* is categorized based on By-Type (e.g., thermochemical, mechanical, biochemical), By-Characteristics (e.g. Volume, Funds, Impact) and By-Resource (i.e. a broad category of Resource e.g., Energy, Water, Chemical).

Resource. This is a subclass of *Thing* and is mapped to *Product* class of schema.org through the sameAs property. It represents any by-product or service. It refers to any material, waste, or energy component or stream that a user may offer or require. It expresses knowledge accumulated from various sources (i.e., general knowledge on process industry, existing classification of resources and experiential knowledge of resources from past cases). In OntoEco, resources are classified on the basis of By-Type (e.g. water, energy, material), By-Characteristics (i.e. key attributes e.g., hazardousness, processing, phase (solid, liquid, or gas) and By- Source (i.e. classification by European Waste Catalogue (EWC, EWC STAT).

The top level of ontology defines its top-level RDF object-properties, which provide relationships between the concepts and RDF data-properties characterizing the concepts. The RDF object and data properties and their domain and ranges are listed in Table 2. The property list is not exhaustive but denotes all significant properties.

Table 2: Significant RDF Properties of OntoEco

Property	***Domain***	***Range***	***Comment***
Surname	Person	rdfs:Literal	Person surname
Lastname	Person	rdfs:Literal	Person last name
currentProject	Person	Project	Current Project of a Person
pastProject	Person	Project	Past Project of a Person
hasCollaboration	Organization	Organization	Collaboration of Organization to another one
hasRole	Organization	Person	Person role in Organization
hasResource	Organization	Resource	Resource of Organization
projectObjective	Project	xsd:string	Defined objective of a project
projectStartDate	Project	xsd:date	The start date of the project
projectEndDate	Project	xsd:date	The end date of the project
Category	Resource	rdfs:Literal/Thing	A category for the item
Description	Resource	xsd:string	A description of the item
isConsumableFor	Resource	Resource	A pointer to another resource

The domain level ontology further details concepts from the top-level by embedding their classifications and knowledge on IS obtained from IS experts and practitioners. With passage of time as the number of the particular instances increases, the domain ontology can contain several thousand concepts in addition to the subsumption of the top levels of such concepts, which can be imported from external ontologies. The concepts can be classified into hierarchical levels according to the knowledge on industrial symbiosis. Table S-1 in the supporting information document represents the examples of domain level concepts and their possible hierarchical levels.

4.1.2. OntoEco-Data

The instantiation level of the ontology contains all the instances of ontology classes, including registered users, companies and their properties, which are generally used to characterize all the concepts. OntoEco-data is used to store instantiation level data (as illustrated in Figure 3 in a graphical form). In this illustration example, four companies are included in the database of facts: Novo_Nordisk, Asneas, Statoil and Gyroc_Saint_Godain. Next, industrial synergies between them are revealed through the resource (i.e., by-product) they share. More specifically, Asneas has the following resources: Steam, Gypsum, Cooling_Water and Waste_Water. It is illustrated as instances of the "hasResource" property.

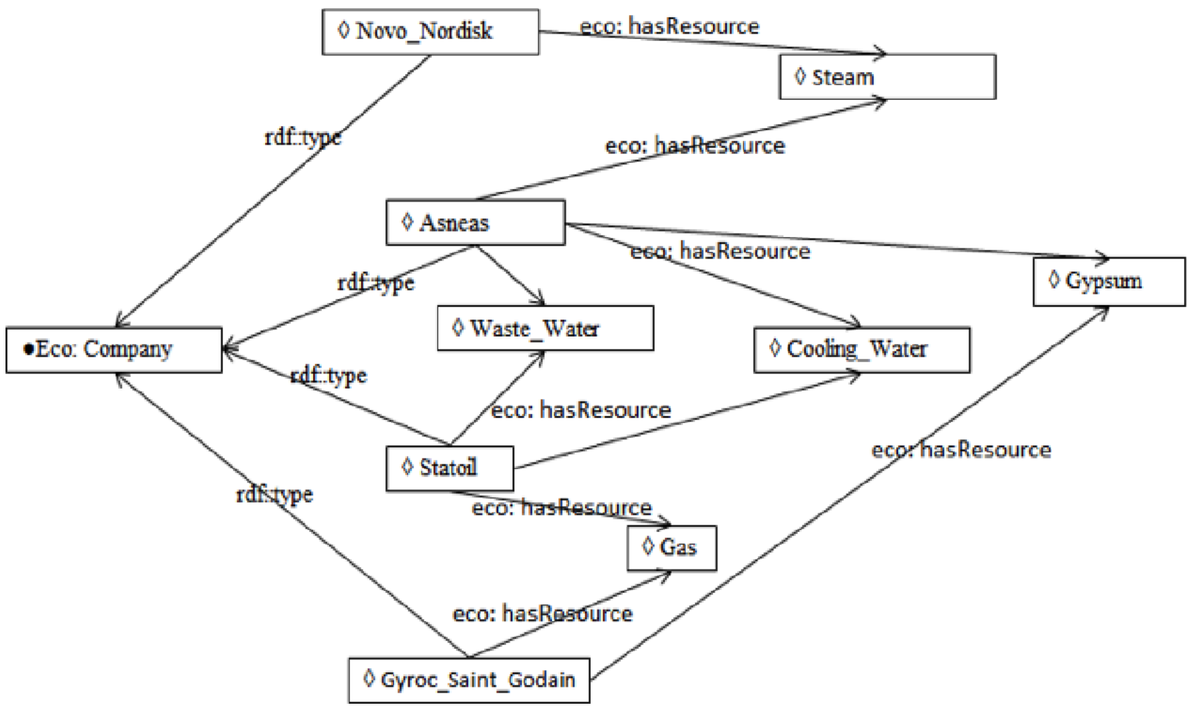

Figure 3: Graphical Representation of OntoEco_data

4.1.3. OntoEco-RQ

The third segment of the OntoEco's structure contains queries in any semantic web query language, such as, SPARQL, whose aim is to explore OntoEco-schema and its OntoEco-data along with Linked Open Data (LODs) for potential industrial synergies. As an example, a SPARQL query structure of OntoEco-RQ, shown in Figure 4, represents use-cases, which aims to identify the potential industrial synergies between any two companies. They are developed based on the assumption that if a substitute industrial synergy (e.g., sharing of a by-product) exists between two companies with specific profiles (e.g., a power plant and a petroleum refinery), then any pair of companies with similar specific profiles could potentially have a by-product compatibility.

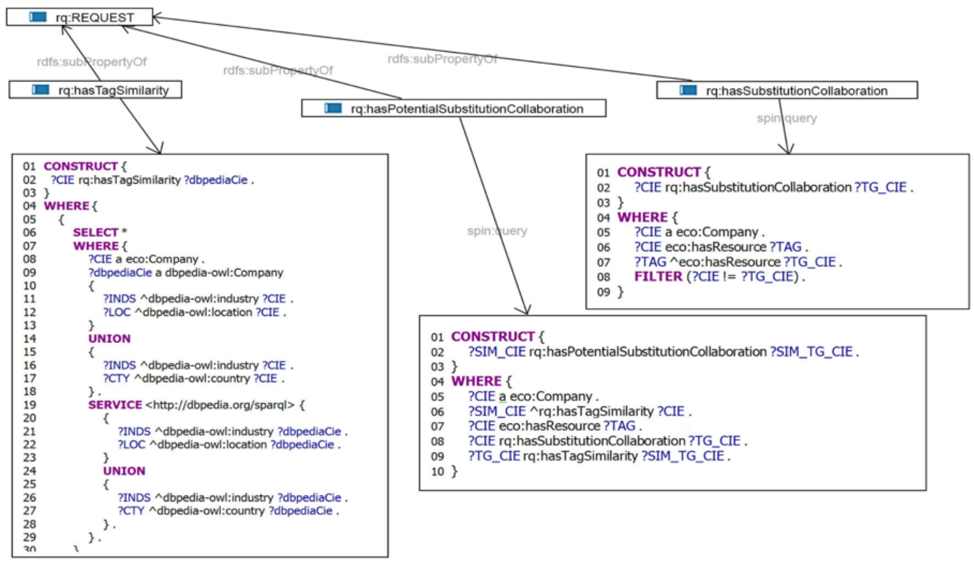

Figure 4: Sample SPARQL queries structure of the OntoEco-RQ

First, the query construct rq:hasSubstitutionCollaboration represents a use-case which aims to filter data from OntoEco_data in order to identify existing synergies (i.e., sharing of a resource: *?TAG*) between two companies (i.e., *?CIE and ?TG_CIE)*. In this query construct, the notion of similarity is limited to the sharing of a single or specific resource. However, other filters can be developed in order to identify more specific and detailed similarities, such as by-product exchanged quantity, the type of logistic involved, or the by-product sorting or treatment processes involved.

In order to validate the feasibility of this query construct, we implemented and tested it on a sample dataset in which two companies (i.e., *CIE* and *TG_CIE)* are linked with a resource (*TAG*). The result of the query in the form of RDF triples as shown in Figure 5 that represents a company (Subject) has a substitution collaboration with another company (Object).

[Subject]	Predicate	Object
OntoEco-Data:Asneas	rq:hasSubstitutionCollaboration	OntoEco-Data:Novo_Nordisk
OntoEco-Data:Asneas	rq:hasSubstitutionCollaboration	OntoEco-Data:Gyproc_Saint_Gobain
OntoEco-Data:Asneas	rq:hasSubstitutionCollaboration	OntoEco-Data:Statoil
OntoEco-Data:Gyproc_Saint_Gobain	rq:hasSubstitutionCollaboration	OntoEco-Data:Statoil
OntoEco-Data:Gyproc_Saint_Gobain	rq:hasSubstitutionCollaboration	OntoEco-Data:Asneas
OntoEco-Data:Novo_Nordisk	rq:hasSubstitutionCollaboration	OntoEco-Data:Asneas
OntoEco-Data:Statoil	rq:hasSubstitutionCollaboration	OntoEco-Data:Asneas
OntoEco-Data:Statoil	rq:hasSubstitutionCollaboration	OntoEco-Data:Gyproc_Saint_Gobain

Figure 5: Result of Query :hasSubstitutionCollaboration

Next, query construct rq:hasTagSimilarity aims to identify a *Company* (*?CIE*) from the given local ontology (i.e., Ont_Eco), which is deemed similar (i.e., the *Company* has the same instance of specific *Resource*, such as cooling water) to a *Company* in an external knowledgebase i.e., DBpedia (?dbpediaCie) applying search criteria (*?INDS* and *?LOC*) or (*?INDS* and *?CTY*).

Finally, the third query construct rq: hasPotentialSubstitutionCollaboration as presented in the previous section aims to identify two potential companies (i.e., ?SIM_CIE and ?SIM_TG_CIE) in an external knowledgebase, e.g., DBpedia that can establish an industrial synergy collaboration (i.e., connected through property hasResource) based on their similarities (i.e., using the predicate hasTagSimilarity) with companies (i.e., ?CIE and ?TAG_CIE) that have already-existing or known synergies amongst themselves in the given local ontology. Both the second and third query constructs have also been executed on the sample dataset for validation and they produced the desired results.

Used together, these constructs can find pairs of companies that are similar to existing pair of companies known to have an industrial synergy. The notion of similarity deployed here can be adjusted to match any particular needs. Furthermore, other SPARQL query structures using other concepts of OntoEco-schema can be designed in a similar manner: for instance, to identify potential mutualisation synergies between more than two companies. The following section details how the generic test scenario model is implemented in the case of the OntoEco ontology..

4.2.SSWISI - Social Network

Social networks are employed for sharing information and initiating industrial synergies in SSWISI framework. Functions are required in social networks to allow for information sharing. These functions support the exchange of quality information and help in the building of trust between organizations (Ghali, et al., 2016). Moreover, the functions of social networking enable the discovery of similar, complementary and shared interests between different users/groups and professional communities. They are useful for initiating industrial synergy and developing knowledge. Ghali et al., 2016 classified these functions into two categories: primary and secondary. Primary functions support initial information exchange and discussion, while secondary functions complement and support the primary functions. For example, “Sharing” on Facebook and “Retweeting” on Twitter are primary functions and event creation and opening an account are secondary functions. Secondary functions are not directly related to the basic principles of social networking, which are the existence of contacts and the formation of connections between contacts. The data of the functions are preserved in the SSWISI ontology: OntoEco for record and searching.

We summarize the desired functions of social networking, as described with details in Ghali, et al., 2016, and mapped them to relevant classes and/or properties of OntoEco in Table 3. These functions are manipulated in the initiation of industrial synergies. The SSWISI synergies initiation process has been adopted from Ghali, et al., 2016 and customized accordingly. There can be four steps in an initiation process.

1. **Need acknowledgement**. Synergy initiation requires a declaration for the production of waste material or industrial by-products and their consumption. A need is declared by a member (i.e. Person class) of an Organization through posting the details of a Product in both cases i.e., either consumption or production. The details of the Product help in finding information related to its context and related opportunities.
2. **Data collection and repository**. Waste flow information (i.e. both Product and Project classes) is the essence of industrial synergies. Data of Product and Project classes must be collected in the case of both production and consumption as instances in OntoEco-Data file and linked with instances of the Person and Organization classes. The data could then be used for analysis and matching process.

Table 3: Summary of desired social networking functions

Cat	Function	Purpose	Class/Properties
Primary	Information	Aggregate users' professional experiences, create and maintain profile	Manipulate *Person* class and its properties, e.g. education, experience, achievement, activity, project, employer
	Exchange/ Sharing	Communicate information content that is to be shared	Manipulate *Project* and *Product* classes and their properties, e.g. *projectEndDate, ProjectStartDate, projectObjective, releaseDate, purchaseDate, review*, *weight*
	Discussion	Communicate publically with other social media members in real time	Manipulate mainly *Person* & *Document* classes and their property: *weblog*

	Contact	Get in touch with other people	Manipulate classes e.g., *OnlineAccount*, *PersonalProfileDocument* and their properties e.g., *accountName*, *account*, *familyName*
Secondary	Search	Retrieve relevant information	Manipulate sparql queris of OntoEco-rq.
	Membership	Manage users' registration process	Manipulate *Person* class and its properties e.g. *surname*, *lastname*, *birthDate*, *email*
	Link	Provide a mean to establish	Manipulate *Person* class and its properties e.g. *follows*, *knows*, *memberof*

3. **Potential synergies identification and preliminary analysis**. SSWISI platforms use the data of classes stored in OntoEco-Data for finding potential matches. SSWISI uses semantic similarity through SPARQL queries to analyze the compatibility levels between persons, organizations, projects and products. Two types of queries are manipulated in SSWISI framework: batch and ad-hoc. Batch queries are utilized from commonly used search functions of social networks and ad-hoc queries are used for complex analysis. Moreover, data mining and web mining techniques could also help in finding these compatibilities.

4. **Contact**. If feasible opportunities are found, there can be various ways to connect the concerned person and/or organization. The detailed profiles of persons and organizations are available in SSWISI framework. SSWISI functions can automatically initiate the contact process as a middleman between organizations. A third party facilitator can register in SSWISI and participate in information exchange processes as well. He/she can play a more proactive role in carrying out compatibility analysis to identify synergies using his or her experience and expertise. SSWISI platforms can then be augmented by including further optimization features which serve to find optimal or near optimal synergy initiations among networked organizations.

Conclusion

With the development of web technologies, affordable approaches have been enabled to support the early stage of industrial synergies and their initiation. This paper has proposed an approach for initiating industrial synergies that extends existing approaches. These approaches have been analyzed in detail alongside the essence of web technologies and their role in initiating industrial synergies. The proposed approach is thus a hybrid that integrates the aforementioned approaches with social semantic web. This refers to a web-based framework that is designed to be openly accessed by anyone only (and simply) through registration. The social networking feature of the framework assists in relationship building and community coordination for the sharing of information. Semantic web technology in the framework provides sufficient data structure to transform it into usable information, which is required for data sharing and reuse across applications, enterprises and communities. It also enables advanced search functions that can be used in order to identify potential industrial synergy compatibility. Ontology-based queries and their constructs were developed, programmed and tested in order to demonstrate the feasibility of such advanced search functions. Another distinguishing feature of the proposed framework concerns the sharing of information with other external systems through the import and export of information via the Linked Open Data (LOD) concept. The proposed framework paves the road towards the further development of SSWISI platforms which provide the foundation for the early phases of industrial synergy initiation. The proposed framework does not focus on the credibility and privacy of knowledge. This is an interesting initiative for our future research work.

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