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e-Symbiosis: technology-enabled support for industrial symbiosis targeting SMEs and innovation

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Abstract

The paper introduces a new paradigm for Industrial Symbiosis by pioneering the use of ontology engineering in the field. Semantics are used to model Industrial Symbiosis flows, to model enabling technologies and to systematise the development of a matching service. Combined with a systems engineering approach, semantics further combine tacit knowledge from Industrial Symbiosis experts with explicit knowledge from Industrial Symbiosis participants. The new approach promises systematic venues to discoveries, innovative solutions, and a holistic methodology in the development of Industrial Symbiosis networks. The paradigm has been implemented as a multilingual web service to support Industrial Symbiosis communities and to embrace small and medium enterprises that are currently side-lined from developments. The approach has been tested and validated using real-life data and its functions are demonstrated with illustrative examples.

Keywords: industrial symbiosis, ontology, web service

1 Introduction

Industrial symbiosis (IS) is one of the most successful and convincing applications of Industrial Ecology, a science advancing sustainable industrial ecosystems through paradigms that support interactions and exchanges between industrial flows and their surrounding environment. The purpose of an IS network is to build collective flows among actors leveraging the exchange of materials to benefit the environment by reducing carbon footprints, minimising landfill waste, and saving virgin resources. IS networks exchange resources, i.e. by-products, assets and services, through closed and sustainable lifecycles. To this purpose, IS networks are excellent candidates to illustrate the concept and the potential of the Triple Helix. In line with a general definition of the Triple Helix framework as a core concept in the discourse of university-industry-government relations and beyond (Meyer et al. 2013), here we refer to it as the link between industry, society and knowledge institutes and as a driver for rethinking a green economy with clean technology, renewable resources and energy, low carbon emissions and bio-fuels.

The notorious case of Kalundborg (Chertow 2000; www.symbiosis.dk 2012) introduced IS in the form of a *closed model* which succeeded in connecting pre-selected industries and included, among others, fish farms, power plants, refineries, pharmaceuticals plants, and construction companies. Kalundborg not only created benefits for the individual industries but further provided significant and measurable environmental and social gains bringing the region closer to Industrial Ecology standards. Motivated by the

example, IS networks are being set up to trade material, energy, and water and reporting similar economic, environmental and social gains (Lehtoranta et al. 2011). Such examples constitute shorter-term consumer-supplier relationships to trade materials, energy and water between neighbouring industries (Chertow 2004). Off-market prices generate economic gains and cost savings for the participating partners. The reuse, or the alternative use of waste, energy and water inherently leads to environmental credits, diversion from landfills, the reduction in greenhouse gases (GHG), and improved efficiencies in the use of virgin resources (Mirata and Emtairah 2005; Chertow 2007).

Instead of closed models, the development of *open models* stands consistent with the dynamic nature of IS networks. Open models enable unrestricted and wider participation of partners as well as competitive terms in exchanging materials and energy. In open models there is an increasing interest to measure and monitor IS flows so that to monitor and measure sustainability indicators which relate to the amount and the type of material exchanged, the environmental benefits created from the exchange, social gains, costs savings and profits. Measured gains could be interpreted by planners, real estate developers and agencies (Chertow 2004; Alberta and Kevin 2008) to monitor the progress and the success that is accomplished by the municipalities to meet Triple Helix targets (Desrochers 2004; Jacobsen 2006; Chertow 2007; Lehtoranta et al. 2011; Chertow and Ehrenfeld 2012). Provision of government support in the development of open model networks has proved vital (Lehtoranta et al. 2011). As reported, open models have been set up in the UK in the form of National Industrial Symbiosis Programme (NISP) (Boons et al. 2011; Jensen et al. 2011), in Brazil (Veiga and Magrini 2009) and several other places around the world (Desrochers 2004; Mirata and Emtairah 2005; Jacobsen 2006; Chertow 2007).

In practice the process of IS involves the formation of symbiotic links, the matching stage, at which the partners are screened, and the monitoring stage at which the performance is assessed. Systems available to support the process of IS are reviewed by Grant et al. (Grant et al. 2010). Used to support manual intermediation by trained practitioners, existing support systems are primarily helpful at the second stage of IS operation, namely where a selected match is monitored towards completion. The matching stage, however, remains entirely empirical either because the suppliers are fixed (closed systems) or because the practitioners are biased towards their own expertise (tacit knowledge) or particular industries they wish to serve. As confirmed by Grant et al (Grant et al. 2010), the only known system to address the challenge of tacit knowledge is the DIET system introduced by the U.S. Environmental Protection Agency. DIET models tacit knowledge with the use of production rules that constitute an expert system. Although the operational efficiencies of DIET are not known, the limitations in the use of production rules are well elaborated. Limitations are pronounced in the use of higher level tacit knowledge and the reuse and share of knowledge (Gruber 1995; Turban and Aronson 2001). For clarification, here we refer to tacit knowledge as knowledge which resides within individuals or a company and which is difficult to express in written forms, i.e. expertise (Lam 2000).

Despite their increased popularity, the IS networks have to make a long progress before they match Industrial Ecology expectations. Networks should build capabilities to progress dynamically and to integrate surrounding flows, especially flows related to SMEs and municipal activities. SMEs are characterised by small flows and have difficulties to regularly exchange information and data or to handle overheads and costs associated with participating practitioners. The participation of SMEs in symbiotic networks is accordingly limited and practically excluded. In addition and unlike the description of virgin resources, waste material and waste energy both lack specifications as products. More pronounced in the case of municipal flows, the emphasis in waste characterisation is to distinguish them from other waste, much less to define them as useful products or resources.

Modeling and the use of tacit knowledge offers tremendous opportunities to enable IS networks (Chertow 2004). Modeling of waste streams is a daunting task because concomitant material and energy streams are dominantly characterised by tacit knowledge based on associations, know-how expertise and engineering intuition. Although rarely measured explicitly, environmental and social benefits of IS are inherently presumed, which inevitably increases the number of options to consider, especially at the early stage of symbiosis. Substandard and non-market transactions add further to complexity. The use of knowledge is currently restricted to manual interpretation of best practice and extensive reference to case studies worked in the past.

Symbiotic links admittedly constitute a complex task that involves background knowledge from a variety of disciplines, i.e. chemical engineering, mechanical engineering, electrical engineering, chemistry. Information and Communication Technologies (ICT) are particularly useful to integrate disciplines and shape up IS into a powerful service with capabilities i) to organise symbiotic data (resources, actors, flows) in taxonomies and catalogs (Hepp 2006), and ii) to store data into repositories for querying and retrieval (Phillips et al. 2005). Unless equipped with semantically enabled features to trace and match resources, as already proven by recent research (Phillips et al. 2005; Kraines et al. 2006), basic database models, e.g. Crisp model used by NISP, will remain unable to include SMEs, consolidate tacit knowledge, and/or invite innovation and the inclusion of new processing technologies.

Ontology engineering features capabilities to unlock the potential of IS by offering semantics with powerful modelling capabilities that could enable the effective monitoring and exploitation of resource flows at various use levels, also to build sharing communities. Building upon early demonstration of usefulness of semantic to systemise complex data used in the area of Life Cycle Analysis (LCA) and generally environmental assessment (Phillips et al. 2005; Kraines et al. 2006), this paper introduces a new paradigm pioneering the use of ontology engineering in the development of IS networks. Ontologies, as explained in detail in Section 3.1, are introduced as technologies to model flows and to capture various forms of tacit and explicit knowledge (Gruber 1995). The approach is able to simplify the inclusion of SMEs offering technology to advance existing IS networks towards systems aligned with Industrial Ecology standards. Moreover, the systematisation of the approach builds capabilities to support and scope for innovative solutions. The work is an EU collaborative project, the eSymbiosis, that combines expertise by IS practitioners, developers and academics familiar with Industrial Ecology in general and IS and ontology engineering in particular. The paradigm is demonstrated as a Web service using real-life data from a prefecture in Greece.

2 eSymbiosis: Application Domain and Challenges

2.1 Regional Industrial System Level

To demonstrate its functions, eSymbiosis has selected an application domain that features most of the adverse factors responsible for the difficulties outlined in the implementation of IS on Triple Helix standards. Located in the Northern border of Attica (Figure 1), the region of Viotia in Greece is one of the fifty-one prefectures of the country. The prefecture is hosting the majority of industrial activity in the country supplying the capital with a wide range of commercial products. Quite recently the region expanded as the Prefecture of Central Greece, now covering over 3.211 square kilometres and hosting a population in excess of 135,000 residents. Industrial production is the primal economic activity. Its extensive flat area is particularly rich in agricultural production and secondary activities, i.e. ginning houses, craft industrial units and services, and around several small cities including Livadia, Sximatari and Oinofita.

Even though Viotia hosts over 3,000 SMEs and large industries, no symbiotic activity has been reported or established so far.

Figure 1 The geographical location of the Viotia region

The industrial sectors of Viotia include 25 different divisions that combine 11 general sub-sectors in food and beverage, leather and textiles, wood, pulp and paper, chemicals, manufacture of non-metallic mineral products, basic metal production, retail, livestock farming, and unclassified industries. eSymbiosis has produced a pilot to study the largest portion of existing industries including over 1,000 SMEs that represent all the industrial sectors in the region. Industrial activities are classified and maintained in conventional databases that provide some data used by the models described in the following sections. The database is a typical example of the type of information faced in practice: a subset of data, *the primary data*, is directly useful to IS. They relate to the company identity, the location, the area of industrial activity (industrial code), the material streams produced as waste and the capacities of plants. The majority of information remains marginal to the concept of IS. Such *secondary data* relate to industrial technology and patents used in production, details of the processing stages involved and their capabilities, as well as details of environmental records and reports to governing bodies including data referring to material composition and flows of waste as analysed for environmental control.

In the light of current activities in Viotia, primal emphasis has been set on solid waste as it accounts for the majority of the waste produced. Volumes of solid waste are predominant in basic metal production, food and beverage, chemicals, plastic and rubber products, and manufacturing of non-metallic minerals. These industrial clusters comprise approximately 62% of the installed industries and include 97 industries in metallurgical products (28%), 41 in food and beverage (11%), 77 in chemicals (22%), and the largest portion of remaining industries in plastic and rubber products.

2.2 Industrial Symbiosis in Practice

IS practice currently relies on manual interpretation of data in the course of face-to-face communication and case-by-case analysis by IS practitioners assigned to assist in projects. In the course of their service, practitioners access and interpret data collected from industry combining them with other data stored in

- proprietary databases built to monitor the activity of industry, e.g. Viotia databases, including industrial sectors, industrial volumes, planning and marketing datasets, and occasional project management technologies, e.g. environmental records, quality management practices, or
- custom-made databases that offer access to case studies, e.g. Crisp system (Grant et al. 2010).

Whenever available, databases of the former class contain a combination of primary and secondary information to mine and extract for relevant features. Custom-made databases contain explicit knowledge with information gathered by participants, case studies and best practice. Such information adds value to most stages of IS, including those for monitoring and managing the symbiotic matches. However, datasets are backward-oriented and unable to assist innovation (Grant et al. 2010).

In both cases, data have to be exploited in the context of specific knowledge domains, the description of which can be rather complex and daunting. Figure 2 demonstrates aspects of complexity in a small domain of plastics. Such complexity increases as the network and the number of material streams increase. Quite apparently, the systematic and thorough analysis is impossible with a manual manipulation of data (Desrochers 2004; Mirata and Emtairah 2005; Jacobsen 2006; Veiga and Magrini 2009; Boons et al. 2011; Jensen et al. 2011; Chertow and Ehrenfeld 2012) because of the complexity involving;

- the size of the problem as compounded by the different industrial streams, e.g. plastics, metals, technologies, and objectives, e.g. environmental effects, economies and social benefits;
- the representation of the trading region (supply and demand as available at different locations);
- the complexity added in considering innovation, i.e. complex networks, inclusion of new technologies, inclusion of additional stages for waste pre-processing, pre-treatment, transportation and storage;
- the complexity added in building up scale, e.g. partial matching by merging smaller flows of SMEs into single input/output streams;
- the analysis of dynamics as they are related to material, energy and information flows.

Figure 2 Technology related options in processing plastic waste

2.3 Methodological challenges

The formation of IS networks is characterised by a cyclic process (Grant et al. 2010) comprised of five main phases: i) opportunity identification, ii) opportunity assessment, iii) removal of barrier for realisation, iv) commercialisation, and v) documentation and publication. Each of these phases remains information intensive, heavily relying on tacit knowledge and judgement. Methodological challenges associated with the IS accordingly include:

- i) Modelling and capturing of a broad range of information in relation to the supplying and receiving industries. Waste exchange requires a minimum set of data to support the exchange and the formation of a synergy. More often than not, such data bear origins in users of diverse and different vocation and background;
- ii) Modelling and capturing a broad range of regional data that contain patterns of industrial activity within a region, different behavioural patterns, and background industrial activities the co-location of

which may be crucial for IS. Such data are particularly important for strategic decisions and the sustainable development of the region;

- iii) Modelling and capturing of best practice and IS experience (tacit knowledge) that reflects on technological, economical and environmental benefits from tested cases.

The acquisition and the classification of data is critical to the development of IS synergies. Basic information relates to the company identity and profile, the nature of industrial activity, and the existence of occasional synergies. Even structured data, such as data presented for Viotia, require separate and significant effort to process as useful information. In practice, however, the collection of data remains manual and is usually available from industrial workshops organised by practitioners. The effort to compile raw data, to reconcile interpretations (synonyms for waste content and industrial activity) and to review and scope for synergies (interpretation of semantics for sources and sinks) is also a manual task.

In systematising and automating the application of models in i) and ii), one is challenged to offer a flexible description of the domain with alternative ways to read and translate inputs. Unlike marketable commodities, waste description is nonstandard with variable composition and availability. It is characterised by a significant degree of tacit knowledge and features dynamic data that are subject to frequent changes. Similarly, the description of the domain, as presented in Figure 2, is amenable for alternative interpretations. The knowledge domain is rich on semantics that consist of concepts, properties and associations between the different elements of the representation. Semantics of users have to match the semantics of different application domains and further connect with primary data and data generated by the analysis (Mirata and Emtairah 2005; Chertow 2007; Boons et al. 2011).

The modelling challenge outlined in iii) addresses a fundamental problem to model and represent knowledge of IS from the best practice, expertise of IS practitioners, as well as technological, economic and environmental relevance. Once established, such models are used to assist the matching between sources and sinks and also to predict and measure the performance of the network against economics, environmental, social indicators.

3 An Ontology Engineering Approach to Industrial Symbiosis

3.1 Ontologies for Industrial Symbiosis

Ontology models are used to represent i) tacit knowledge in the form of description of waste streams (material, energy, water), description of enabling technologies and description of the IS process, and ii) explicit knowledge about participating companies in the form of IS relevant data (Raafat et al. 2013). Models are structured with respect to concepts, properties and associations and with the view to drive the whole IS process including:

- Acquisition of explicit data and tacit knowledge of participating companies, their resources and/or enabling technologies;
- Integration of resources with references to technological, economic and environmental relevance;
- Integration of expertise as available by IS practitioners and experts who have practiced ways to enable input/output matching and to propose solutions;
- Provision of including numerical models to produce meta-data for analysis;
- Integration of information and data from proprietary and public datasets that contain useful information to draw conclusions, i.e. datasets on geographical locations, pattern of availability, material quality, technology properties and regional priorities including environmental, economic, and social targets.

The IS knowledge is modelled using ontologies, which are widely accepted tools for knowledge representation and processing. Ontologies are formalised as interlinked and otherwise characterised group of terms and concepts describing a specific domain, the IS domain in this work (Gruber 1995). Ontology terms are represented by classes that group term-relevant individuals (instances) organised in class-subclass structures per their belongings and associations (subsumption). Classes are characterised by properties, the data properties, and further enhanced by associations with classes other than class-subclass participation, the object properties. Classes are labelled with additional information to supplement respective semantics, i.e. industry relevant and multilingual synonyms or links to relevant datasets. Restrictions on properties are logic-based constructs that allow a higher level of knowledge representation, i.e. conditional or procedural logic, and for inferring new knowledge (Trokanas et al. 2014). The ontology is instantiated and represents specific entities of the domain. More rigorously, an ontology is defined as a six-tuple (Ehriq and Staab 2004) which consist of the following six elements:

- a set of classes sharing common properties organised in a hierarchical subsumption per belongings of entities or instances. The unique names of classes relate to the domain concepts;
- a set of data properties which characterise classes and a set of object properties providing additional links between classes in the form of purpose-defined relationships;
- the subsumption of properties organised in property-sub property manner, hence enabling further granularity of respective semantics;
- sets of instances: every class can contain instances and classes without instances, empty classes, can still contain properties used to enhance the semantic aspects of ontology;
- sets of values which fill in properties of a class that an instance is the member of;
- sets of axioms, the restrictions on properties, acting to restrict the ranges of object properties, to define the cardinality over object or data properties, and to define exact values of instances for object properties and data values for data properties.

Ontologies are used to share and expand knowledge in participating communities and over the Internet. Their semantic aspects provide means to integrate with other ontologies, the means for updating without a need for redesign, still capturing new elements in the course of their life. In the case of eSymbiosis, the proposed paradigm includes classes, object and data properties and axioms, all structured to model knowledge in the domain of IS as acquired by IS practitioners and experts. In particular, ontologies are designed to include

- associations between waste streams and processing technologies (Raafat et al. 2013);
- Triple Helix and Industrial Ecology standards for sustainability featuring technological, economic and environmental performance (Trokanas et al. 2013);
- dynamics associated with resource properties, i.e. resource availability, strength and relevance of matches (Trokanas et al. 2014);
- profiles and roles of participating companies and other users.

An ontology excerpt for Industrial Symbiosis (subsumption) is shown in Figure 3 which accounts for the plastic options presented in Figure 2. The ontology differentiates between types of materials and users and is typical of the ontologies used in IS. They include detailed classifications and characterisations of resources, i.e. waste streams and processing technologies with the latter supplemented by ontologies for methods, units of measurements, commercial names, and geospatial references.

Figure 3 Excerpt of IS ontology related to plastics

The ontology models are inferred by processing axioms. The inference reclassifies the models so that to suit particular requirements of IS operation, e.g. finding or reporting resources in confined geographical, environmental and economic clusters, or in providing justification for selected matches. In essence, the ontology inference generates new knowledge useful for decision making at all service levels and at all stages of IS operation.

In the process of instantiation, the pool of IS participants increases, and so does the volume of explicit knowledge available. More importantly, the instantiation of an ontology integrates IS tacit knowledge embedded in the ontology structure with explicit knowledge from IS participants. In consequence, an instantiated ontology enables identification of patterns relevant for IS, i.e. the availability for regional and/or seasonal resources as well as the potential for economic and environmental gains. As detailed in Section 4, in the paradigm of this paper data properties are selected to characterise individual instances with respect to Triple Helix performance against technological, economic and environmental aspects.

eSymbiosis ontology is designed in English using established vocabularies of standardised classifications, e.g. European Waste Catalogue (EC 2002), and established scientific and commercial terms for materials and technologies (Raafat et al. 2013). Classes and properties are also labelled with terms in different languages allowing for multilingual operation and with synonyms to account for the heterogeneity of the databases used in the background, to cope with the jargon and the syntactic interpretations of keywords for industry and waste. In the current implementation of eSymbiosis ontology multilingual aspects includes Greek with assumption that terms in one language are related to a single term in the other. Implementation of multiple term relationship is the subject of an on-going research.

The matching process between instances enables formation of IS networks (Trokanas et al. 2014). Although direct matching between instances is possible, the proposed paradigm converts instances into individual user description ontologies describing each IS participant and respective resources. This approach enables

supplementary description of IS participants and their resources, use of commercially available matchmaking engines and future inclusion of process models for better performance assessment. User description ontologies are all stored in a purposely designed repository assuring data security and a fast access.

3.2 The Concept of the eSymbiosis Service

The multilingual eSymbiosis service, as illustrated in Figure 4, is implemented as a web service accessible through web portals. The service shares proprietary and to some extends public information using ontologies that invite links between partners ranging from SMEs and large industries to government agencies and the general public.

Figure 4 eSymbiosis service structure

Constitutive parts, namely users and IS practitioners, communicate with the eSymbiosis service through a web portal that integrates the functionalities illustrated in Figure 5: user registration, input – output matching, reporting and auditing of the ontology updates.

The domain ontology for Industrial Symbiosis is implemented using Web Ontology Language (OWL), which is an established and widely used language enabling the service to expand, share and reuse other ontologies over the Internet. The domain ontology coordinates the whole process of IS as it does

- navigate the process of user registration by parsing and populating referenced class properties: at the end of the registration process, the ontology is instantiated by the user profile;
- assist the creation of user description ontologies stored in a repository for fast access;
- assist input – output matching: the matching process is closely related to the domain ontology and reflects IS relevance;
- format the data for reporting by parsing and inferring the ontology various reports for user and IS practitioners are provided.

Figure 5 Service functionality

Other than producing ontology instances, each user is further described by an own, separate ontology the *user description ontology* (Trokanas et al. 2014). User description ontologies are implemented using standardised Web Ontology Language for the Web Service (OWL-S). They enable matching and establish links to external datasets and/or models that detail users' operation.

As described in Section 4.2, the matching accounts for technological, economic and environmental considerations that improve the quality of proposed synergies. Such synergies, hence IS networks, are developed by matching the service description ontology of requesting user with service description ontologies of all remaining population. Synergies are produced by the purposely designed matchmaking engine (Section 4.3) which also ranks options by terms of semantic relevance and provides respective justification. The matching process compiles information from data properties, user descriptions and the embedded tacit knowledge.

Monitoring and reporting stages are initiated by the selection of a synergy. Unless the synergy is cancelled, the monitoring continues until completion. User reports are produced to summarise progress in regular time intervals. According to the data available in the transaction, each synergy is measured on the ground of economic, environmental (Trokanas et al. 2013) and social aspects as outlined in Table 1. The list follows the performance metrics produced by the National Industrial Symbiosis Programme in the UK and can be translated to performance indicators for sustainability.

Table 1 Metrics for IS benefits

Economic	Environmental	Social
Cost Savings to Business	Landfill Diversion (tonnes)	Jobs created
Additional Sales to Business	CO ₂ reduction (tonnes)	Jobs saved
	Virgin Raw Materials Saved (tonnes)	
	Hazardous waste eliminated (tonnes)	
	Water Savings (tonnes)	

4 Knowledge Modelling and Matching

4.1 IS Domain Ontology

eSymbiosis domain ontology models the tacit knowledge accumulated by IS practitioners and experts. It is structured into four layers of abstraction: meta-level, top-level, domain-level, and instantiation level, as fully explained in the reference (Raafat et al. 2013) and shown in Figure 6.

The meta-level defines general concepts independent of the domain to support general sharing and reusing. It provides an insight view for users outside the IS domain and/or unfamiliar with ontology engineering (Marquardt et al. 2010). The concept *Object* defines all the physical assets associated with the domain, whereas the concept *Property* defines attributes that describe other concepts in the ontology, both annotated with additional explanations needed for reuse and sharing. In eSymbiosis, the meta-level is also used to promote and explain links.

Figure 6 The design of the eSymbiosis ontology

The top level of the eSymbiosis ontology defines its basic structure and contains the following abstract concepts:

1. *Role*, which refers to different types of users taking part in the IS: resource (waste) providers (*ResourceProducer*), resource sinks (*ResourceConsumer*) and processing technology providers (*SolutionProvider*). This concept is the entry point for user registration;
2. *Resource* refers to materials, waste, energy, products, water and expertise that a user may offer or require. It formulates integration of various knowledge sources, i.e. general knowledge on process industry, existing classifications of resources and experiential knowledge on resources from past cases. In the eSymbiosis ontology resources are classified in four different ways:
 - Resource by source is based on the European Waste Catalogue (EWC) (EC 2002) which is the classification widely accepted by waste managing agencies and currently in use by majority of IS practitioners. EWC is a six digit code with reference to the source of the resource. Combined with

EWC STAT (EC 2010) (statistical version), it allows for a broad classification of almost all types of waste,

- Resource by characteristic classified on their key properties, such as hazardousness, processing requirements or phase (solid, liquid or gas),
 - Products classification which classifies waste per product it is based on and which refers to existing classifications (UN, 2008), aiming to allow users with all levels of expertise to classify their resource, e.g. a restaurant chain having plastic water bottles and not knowing their composition or other chemical and physical properties,
 - Resource by material type used to define the waste composition along the object property *hasComposition* and type of product along the object property *hasProduct*. This concept is used as the common reference for other parts of ontology, e.g. solutions, and concomitant input – output matching.
3. *Solution* defines the processing technologies which process resources (inputs) and produce outputs in the form of material, energy and water and in turn enables technology participation in IS. There is no standardised classification available and this part of the ontology is designed following the principle similar to the waste classifications as described by (Raafat et al. 2013):
- Solution by input based on resources a technology can process and which assumes expert knowledge from the user,
 - Solution by characteristic classified on the basis of key technology characteristics normally related to the final product,
 - Solutions by industry sector which requires a lower level of expertise from the user,
 - Solution by type based on definition in literature, e.g. thermochemical, mechanical, biochemical etc.
4. *Attributes* describe three top level concepts in relation to Triple Helix terms of economic, environmental and social properties. This concept defines properties used for input-output matching (Table 2) and to allow multilingual operation of reporting functionality with reference to the pattern of supply (*PatternOfSupply*), measurement (*UnitOfMeasurement*), location (*Location*) and quantity (*hasQuantity*).

The top level of ontology defines top-level object properties which provide relationships between the concepts and data properties characterising the concepts. The object properties are listed in Table 2 and their roles are explained in Appendix A. The property list is not exhaustive but denotes all facets of the modelled properties.

Table 2 The ontology properties

Property	Domain	Range	Feature
<i>geo:location</i>	<i>Role</i>	<i>Geo:SpatialThing</i>	Social, Operational
<i>hasResource</i>	<i>ResourceProvider</i>	<i>Resource</i>	Operational
<i>hasSolution</i>	<i>SolutionProvider</i>	<i>Solution</i>	Operational
<i>hasPatternOfSupply</i>	<i>Resource</i>	<i>PatternOfSupply</i>	Operational
<i>hasComposite</i>	<i>Products,</i> <i>ResourceBySource</i>	<i>ResourceByType</i>	Operational
<i>processInput</i>	<i>Solution</i>	<i>Resource</i>	Operational
<i>canProcess</i>	<i>Solution</i>	<i>Resource</i>	Operational
<i>needsEnergy</i>	<i>Solution</i>	<i>Energy</i>	Environmental
<i>needsWater</i>	<i>Solution</i>	<i>Water</i>	Environmental
<i>processOutput</i>	<i>Solution</i>	<i>Resource</i>	Operational
<i>hasProduct</i>	<i>Solution</i>	<i>Resource</i>	Operational, Environmental
<i>hasQuantity</i>	<i>Resource</i>	<i>float</i>	Operational, Environmental

<i>hasProcessingPrice</i>	<i>ResourceBySource</i>	<i>float</i>	Environmental, Economic
<i>hasAnnualCost</i>	<i>Materials</i>	<i>float</i>	Environmental, Economic
<i>validFrom</i>	<i>Resource</i>	<i>date</i>	Operational
<i>validTo</i>	<i>Resource</i>	<i>date</i>	Operational

The axioms or restrictions on properties define lower levels of abstraction and hence modelling of tacit knowledge. An example of the restriction defining the composition of waste with EWC code EWC120103 (non-ferrous metal filings and turnings) in the form $\forall EWC120103 \text{ hasComposition NonFerrousMetalsAndAlloys}$ is shown in Figure 7. The semantics of this restriction is that if an entity is a member of the class *EWC120103*, then it must have a relationship along the object property *hasComposition* to the class *NonFerrousMetalsAndAlloys*. Other types of restrictions can state necessary and sufficient conditions for the re-classification of entities or define cardinalities along the properties. Note that the names of the concepts and properties here as well as in the whole eSymbiosis ontology are self-explanatory.

Figure 7 An example of the restriction on the properties

For solutions (processing technologies) restrictions are used to define their inputs and outputs needed for input-output matching: each solution is modelled by defining the input by object property *canProcess*, auxiliary inputs by object properties *needsEnergy* and *needsWater*, and the outputs and by-products by object properties *hasProduct* and *hasByProduct* (Raafat et al. 2013). An example of restriction $\forall PETProduction \text{ canProcess Bauxite}$ is shown in Figure 8 which has semantics that PETProduction technology is capable of processing Bauxite, among other type of materials.

Figure 8 Implementation of restrictions defining solutions (processing technologies)

The domain level ontology further details concepts from the top-level by embedding waste and technology classifications and knowledge on IS obtained from IS experts and in the course of practicing IS, that is from past successful cases and which pass ontology update auditing procedure. In the present implementation,

the domain ontology contains several thousand concepts and the subsumption of the top four levels of concepts is shown in Figure 9.

The instantiation level of the ontology, as shown in Figure 6, contains all the instances of ontology, including registered users, but also members of the concept *Attributes* which are used to characterise resources and which are summarised in Table 3.

Table 3 Instances of the concepts *Attribute* to characterise resources

Concept	Instances
<i>PatternOfSupply</i>	Continuous, Batch
<i>UnitOfMeasurment</i>	kg, tonnes, m ³ , litre, acres, m ²
<i>QuantityType</i>	Liquid, Solid, Powder, Solution, Emulsion, Gas, Flake, Slurry

Figure 9 The top four levels of the eSymbiosis ontology

4.2 User Description Ontology

In the course of registration users become instances of the domain ontology. Each user is described by user description ontology translated from the respective instance and which enables input-output matching with technology, economic and environmental semantic relevance. The ontology provides means for synergy identification and the formalism embedded is based on universally recognised OWL-S framework (Martin et al. 2004). Every user is the instance of the OWL-S ontology modified to incorporate properties

related to resources, especially those used as metrics for synergy discoveries (Table 4). Each industry is characterised by sets of inputs and outputs with reference to resource types presented as data properties (Trokanas et al. 2014). The values assigned to such properties are numerical or point to a concept in the domain ontology through object properties *hasType*, *hasPatternOfSupply*, *hasApplicationIn* and *hasUserType*. These properties define the semantic content for matching as shown in Figure 10.

Figure 10 The structure of user description ontology

4.3 Semantic Matching: Identification of IS Networks

4.3.1 Concept of Matching

The identification of potential synergies between different industries, namely the input-output matching, is translated into an ontology matching process. The matching is performed using i) the explicit knowledge provided by the user in the course of the registration, and ii) the tacit knowledge captured by the domain ontology. Inference and matchmaker engines relate user description ontology of requestor to user description ontologies of all other registered users (Trokanas et al. 2014). In the present implementation of the eSymbiosis service matching process is reviewed on the basis of the metrics defined within the user description ontologies (Table 4).

Table 4 Metrics for input-output matching

Matching Metrics [Service Description Properties]	Description
Type of Resource [hasType]	Refers to the knowledge classification in the domain ontology
Quantity of Resource [hasQuantity]	The matching industry should be able to process not only the type but also the amount. This might result in multiple matches which can be combined to match the requested amount.
Pattern of supply [hasPatternOfSupply]	Whether it is supplied in batches or continuously
Availability [validFrom, ValidTo]	Presents the availability period of a resource
Location [hasLocation(Location:Latitude, Location:Longitude)]	Presents the location of each site belonging to industries, based on longitude and latitude

Semantic matching allows for suggestive matching within the eSymbiosis service: when an exact solution is not identifiable, this matching identifies solutions which are proven for similar types of resources, presenting the choices to the user together with reports of their semantic similarity. The suggestive matching is empowered by object properties such as *hasApplication* which establishes associations between resources in specific industries. The semantic matching also allows for a partial matching in cases where the registered industries satisfy the request only partially. In the case of partial matching the options are listed to select. Options are sorted with respect to relative advantages and offer room for optimisation and multi-criteria analysis.

4.3.2 Implementation of Matching

There are three types of matches supported by the eSymbiosis service: i) direct matching, ii) chain matching or backward engineering, and iii) resource decomposition.

Direct matching is applied when the input and the output from two industries match against all the semantic aspects of their resource types. The matching process interprets the relationship semantically providing evidence for the similarity between concepts and recommendations to the requester as shown in the schematic of Figure 11.

Figure 11 Direct matching

Chain matching relates to cases where a direct input-output relationship is impossible or unworthy. The matching requires pre-processing of the output from the source through enabling technologies that may account for sorting, pre-treatment or the conversion of the material/energy into alternative forms compatible with the types of sinks available to use. Hence, this type of matching requires enabling

technologies that constitute part of the knowledge domain available which are searched in an iterative process, as shown in Figure 12.

Figure 12 Chaining matching

Resource decomposition is performed when certain types of resource can be separated into smaller streams which in turn can be processed in parallel with each other. Options to separate streams can be triggered either by the system or the requester using the object property *hasComposite*. As in the chaining matches, if direct matching is not possible this option may stand as the single alternative to build synergies. The matching can be further compounded with other matches or be combined with the chaining matches described above. Such a result then leads to complex solutions and networks with one-to-many synergies. The individual steps of resource decomposition are illustrated in Figure 13.

Figure 13 Resource decomposition matching

Each type of matching consists of three distinct stages: i) elimination, ii) semantic matching and ranking, and iii) performance ranking, as shown in Figure 14.

Figure 14 Process of matching

In the course of the elimination, the matching options are reduced based on the role of the user and the regional availability of the resources. A resource producer is matched against solution providers and vice versa. The user role is extracted from the *serviceCategory* property in the user description ontology. Industries with overlapping availabilities are considered for matching. The availability is traced from data properties *validFrom* and *validTo* and their matches combine a better pair.

The purpose of the semantic relevance is set to evaluate the quality of a potential match. In the course of this work the relevance is used to combine proximity of resources (Distance Measurement in Figure 14) with properties of the resources exchanged (Attribute Matching in Figure 14). Properties used in the process are illustrated in Figure 15. The former two aspects are considered together. The object property *hasType* (ontology of each industry) relates to the resource type whereas the similarity measurements are performed directly on the graph presentation of the domain.

Figure 15 eSymbiosis matching process

As the analysis of input–output matches is concluded, users are provided with recommendations ranked by performance merits and metrics. The list provides the user with an explanation of the synergy to seek and is likely to benefit the industry for economic, environmental and social gains (Figure 16).

Figure 16 Industrial symbiosis performance factors

5 Demonstration and Case Studies

Data from the Viotia region presented in Section 2 have been selected to demonstrate performance of the service.

Case description: **Allumex Ltd.** is an aluminium casting company producing aluminium billets. The Environmental Manager explores ways of disposing aluminium waste generated by casting because of high disposal costs but also because of awareness for potential economic gains. The manager registers the company with the eSymbiosis service through a two-step process. The first step entails details that identify the profile of the company and details of the request including the identification of the company (company name, contact details, location, size) and the type of resources for disposal (billets) with optional information (secondary data) about the processing technology and the environmental standards followed so far. The step is illustrated in Figure 17.

Role

☐ I have a resource to offer
☐ I have a Technology
☐ I want a Resource

Is this information confidential? ☐ Yes ☒ No
 Industry Sector (NACE)
 Located in Region
 Needed Expertise
 Type of Resource you can Supply
 Continue

Figure 17 The initial step of registration

During the second stage of registration, the manager provides details about the waste available to dispatch. More precisely, the eSymbiosis service navigates the user through different options that classify relevant waste (aluminium) prompting answers for different questions to enrich background knowledge. The information collected from users may range from keywords to details. The workflows are assisted by available classifications (waste is classified into metals>aluminium and EWC codes are automatically assigned to the material). The user can select an available resource or differentiate from the given list; in its current form, the type of waste should be selected from the list because fuzzy descriptions of materials are not allowed. Quite apparently, the EWC code is extracted by the system and the user does not need to know about the system classification. The classification **code** for the selected waste is EWC120103 from

which the **nonferrous metal filing and turnings** is automatically extracted, as shown Figure 18. Other information about the resource can be entered, including its volume/size, e.g. **300 Tonnes/month**, the pattern of supply, e.g. **continuous or batch**, the period of availability, e.g. **March to June**, and the mode of availability, e.g. **not one-off**.

Role: I have a resource to offer [Back]

Type of Resource you can Supply

Can't find what you're looking for? [Search] ?

Classify Resource by Characteristic

Classify Resource by Source (based on EWC)

- 01 - Exploration, mining, quarrying, physical and chemical treatment of minerals
- 02 - Agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing
- 03 - Wood processing and the production of panels and furniture, pulp, paper and cardboard
- 04 - Leather, fur and textile industries
- 05 - Petroleum refining, natural gas purification and pyrolytic treatment of coal
- 06 - Wastes from Inorganic Chemical Processes
- 07 - Organic chemical processes
- 08 - Manufacture, formulation, supply and use (MFSU) of coatings (paints,
- 09 - Photographic industry
- 10 - Wastes from thermal processes
- 11 - Chemical surface treatment and coating of metals and

Availability Pattern: Continuous

Current Delivery Method: (choose)

Does it need Special Handling? ☐ Yes ☒ No

Has Current Storage Method: (choose)

Interval: Per Month

Is it Biodegradable? ☐ Yes ☒ No

Is Your Resource Hazardous? ☐ Yes ☒ No

Is your resource produced in Batches? ☐ Yes ☒ No

Physical Form: (choose)

Quantity Produced: 300

Resource Name: Aluminium Turnings

Storage Capacity for resource:

Valid From: 01/11/2014

Valid To: 16/08/2016

Unit of Measurement: Tonnes (kg*1000)

[Continue]

Figure 18 Process of registering the type of resources

Once details are entered, the matching process reviews matches with all other already registered users stored in the repository. An elimination phase precedes the semantic matching phase, as shown in Figure 14. Two criteria are used for elimination. The first is the user type – modeled in the service description by the *hasUserType* property (Figure 10). The second is the Boolean *isHazardous* property. In this case the request service description has user type *ResourceProvider*. Therefore, all other resource providers are eliminated. An indicative list with some instances before the elimination phase is given in Figure 19. Registered resource providers that have been eliminated in this phase of matching are shown in red colour. The final stage of matching with remaining users, which includes the semantic matching as well as forming the justification for matches, then takes place and the results including the similarity scores are shown in Figure 20.

Service ID	Company Name	User Type	Process	Resource Type	Quantity	Pattern of Supply	Valid From	Valid to	Latitude	Longitude
2	AutoComp	SP	Seatbelt's car sense ball manufacturing	Aluminium Alloy	20	batch	04/07/2012	23/09/2016	38.31983	23.60701
5	HES Ltd.	SP	Hydro Electricity System	Lead	3000	continuous	14/11/2014	14/04/2016	38.3257	23.60094
33	Farmex	RP	-	EWC020103	1200	continuous				
9	Ferral	SP	Aluminium Incineration	Aluminium	30	batch	01/02/2013	17/10/2015	38.32671	23.61181
12	4PS	SP	Adhesive Production	EWC12	2450	continuous	07/08/2013	17/12/2014	38.32997	23.61278
44	Treval	RP	-	EWC030308	250	batch				
1	Hartex	RP	-	Paper	480	batch				
29	Polyrom	SP	CD-ROM manufacturing	Aluminium	60	continuous	07/08/2012	08/12/2015	38.36031	23.55776
47	ElectroPower	SP	Electronic Control Unit's housing manufacturing	Aluminium Alloy	6000	continuous	09/08/2012	09/09/2016	38.34223	23.58178
27	Akter	RP	-	EWC120106	500	batch				
187	EnvID	RP	-	Aluminium Scrap	828	continuous				
89	Sider	SP	Copper Turnings	EWC120103	3500	continuous	09/08/2012	03/06/2016	38.339	23.60928
99	AluCy	SP	Aluminium Recycling	Aluminium Cans	20	continuous	14/08/2012	14/05/2016	38.34567	23.67432
124	Recycling Hellas	SP	Metal Recycling	NonFerrousMetal	1200	continuous	26/09/2015	07/10/2016	38.37899	23.50643
134	Compo	SP	Aluminium Capacitor Production	Aluminium Foil	60	batch	06/11/2012	05/07/2016	38.30999	23.59000
136	SunTech	SP	Copper Production	MetalDust	2100	batch	17/12/2012	20/01/2015	38.31958	23.62223
147	Alumex	RP	-	EWC120103	300	continuous	01/11/2014	16/08/2016	38.32222	23.53

Instead of registered members, the database may indicate members with a *potential* to show an interest. The potential is assessed on the basis of their industrial activity and trade.

Service ID	Company Name	Process	Resource Type	Quantity Total	Pattern of Supply	Distance	Valid From	Valid to	Similarity Measure
89	Sider	Copper Turnings	EWC120103	3500	continuous	6.724	09/08/2012	03/06/2016	97.34%
47	ElectroPower	Electronic Control Unit's housing manufacturing	Aluminium Alloy	6000	continuous	5.035	09/08/2012	09/09/2016	85.47%
5	HES Ltd.	Hydro Electricity System	Lead	3000	continuous	4.879	14/11/2014	14/04/2016	82.09%
124	Recycling Hellas	Metal Recycling	NonFerrousMetal	1200	continuous	7.272	26/09/2015	07/10/2016	79.58%
12	4PS	Adhesive Production	EWC12	2450	continuous	7.154	07/08/2013	17/12/2014	68.26%
134	Compo	Aluminium Capacitor Production	Aluminium Foil	60	continuous	12.855	06/11/2012	05/07/2016	67.09%
29	Polyrom	CD-ROM manufacturing	Aluminium	60	continuous	6.638	07/08/2012	08/12/2015	66.66%
2	AutoComp	Seatbelt's car sense ball manufacturing	Aluminium Alloy	20	batch	7.162	04/07/2012	23/09/2016	63.03%
9	Ferral	Aluminium Incineration	Aluminium	30	batch	6.2	01/02/2013	17/10/2015	62.86%
99	AluCy	Aluminium Recycling	Aluminium Cans	20	continuous	8.83	14/08/2012	14/05/2016	62.09%

Figure 20 Matching results

The matching results illustrate all the companies which have capacities to buy and use the resource offered by **Allumex Ltd.** Results include the technological and environmental relevance of the match as percentage of similarity (column denoted as **Similarity Measure**). More elaborated explanation of matches is also provided including i) the **Resource type** which shows the type of resources registered by each partner, that is only those relevant to the particular request, ii) information on volumes offered under headings **Quantity** and **Pattern of Supply**, and iii) geographical location in the column **Distance**. Based on the results shown in Figure 20, it is evident that the service does not restrict to exact matches but includes companies with similar rather than exact needs for the particular type of aluminum produced by **Allumex Ltd.**

In our example, even though **Allumex Ltd** did not found a partner that matches 100% the description of its resources, it may use the service to proceed further with several informed decisions. For instance, although their requirement for processing is more than what **Allumex Ltd** has to offer, the manager may decide to negotiate a synergy with **Sider**. This might give **Sider** a chance to allocate part of the resource that they require. Since **Allumex Ltd** generates aluminium waste continuously in the given period, the manager may decide instead to negotiate a synergy with **Ferral** by acquiring information about their storage capacity. At this point, the user may have to request additional information about the industries to proceed further with establishing the synergy.

Another option offered by the service is the identification of general options and alternatives to use a particular resource. In our case the **Allumex Ltd** is invited to explore alternative options to valorise aluminium. Using a search facility, the user could access additional information in the form of the results summarised in Figure 21. The results list potential uses for the particular resource (aluminum) taking into account the location and the overall industrial activity of Allumex Ltd.

Potential uses for "Aluminium":

- Aluminium Foil Production
- Bearing Steel Production
- Extruded Aluminium Profiles Production
- Iron Powder Production
- Primary Aluminium Production
- Remelting of Aluminium Scrap
- Rolled Aluminium Sheet Production
- Scrap-based Aluminium Production
- Virgin Aluminium Production

Figure 21 General information about available resources

Tracing the recommendations made through these results, the manager has explored options by searching local companies. The regional search is shown in Figure 21 along with the selected partner (Bearing Steel Production). The latter partner will be subsequently notified for the interest to establish a synergy.

Figure 22 Locations of the resources

6 Conclusion

A new paradigm is presented for Industrial Symbiosis. The paradigm uses ontology engineering to model application knowledge, local domains, and tacit knowledge available from Industrial Symbiosis experts and practitioners. The domain ontology is built as a multilingual model with four levels of abstraction. The model accounts for different resource and solution classifications and characterisations. It further accounts for different roles for the participants, as well as common operational aspects of Symbiotic practices. The approach is developed to reuse and combine data (e.g. markets, geographical locations) with knowledge (e.g. existing ontologies) that relates to the properties of waste resources (material, energy), metrics and sustainability indicators. Using ontology engineering knowledge can be shared in open communities, and it can be expanded, extended and enhanced as part of a collaborative effort. The approach has already produced a web service to systematise and automate the development of symbiotic links. Using description ontologies, the service is able to screen and prioritise links and support the discovery of uses for waste.

Moreover, there is apparent potential to expand the service towards complex scenarios of symbiosis that involve multiple partners, several enabling technologies, and additional perspectives that may relate to the strategic development of regions and application domains. The service already enjoys real-life access to data as it is demonstrated in the largest industrial prefecture of Greece.

Appendix A: Description of Object Properties

<i>Property</i>	<i>Description</i>
<i>geo:location</i>	<i>Term of a basic RDF vocabulary that provides the Semantic Web community with a namespace for representing lat(itude), long(itude) and other information about spatially-located things, using WGS84 as a reference datum.</i>
<i>hasResource</i>	<i>Link between a resource provider and the type of resource they have available.</i>
<i>hasSolution</i>	<i>Link between a solution provider and the type of solution they have available.</i>
<i>hasPatternOfSupply</i>	<i>Links resources to the PatternOfSupply attribute concept. The concept is about the pattern of the demand or availability (Continuous, Batch).</i>
<i>hasComposite</i>	<i>Relation used to provide information about the composition of products and waste types.</i>
<i>processInput</i>	<i>Relation used to link solutions to their inputs.</i>
<i>canProcess</i>	<i>Relation used to link solutions to their main inputs.</i>
<i>needsEnergy</i>	<i>Relation used to link solutions to their energy inputs.</i>
<i>needsWater</i>	<i>Relation used to link solutions to their water inputs.</i>
<i>processOutput</i>	<i>Inverse relation of canProcess. Used for tacit knowledge modelling for resource processing.</i>
<i>hasProduct</i>	<i>Relation used to link solutions to their products.</i>
<i>hasQuantity</i>	<i>The amount of resource available or required.</i>
<i>hasProcessingPrice</i>	<i>Addressing solution providers – the cost for the resource currently in use.</i>
<i>hasAnnualCost</i>	<i>Addressing solution providers – the annual cost of a resource as feedstock.</i>
<i>validFrom</i>	<i>The date the resource/solution becomes available.</i>
<i>validTo</i>	<i>The date the resource/solution stops being available.</i>

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