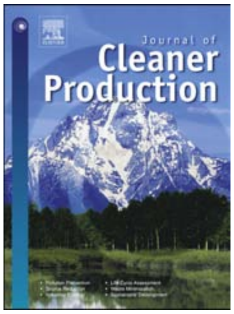

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Semantic Approach for Pre-assessment of Environmental Indicators in Industrial Symbiosis

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1. Introduction

Industrial Symbiosis (IS) is a growingly accepted paradigm for processing waste into material, energy and water with benefits to participants measured by economic, environmental and social gains. Although the practice of IS has demonstrated the need for evaluating these benefits either in the process of screening of impending options or monitoring the operation of symbiotic networks, and despite of some attempts to quantify them (Van Berkel 2010, Mattila, Pakarinen & Sokka 2010, Berkel et al. 2009), no unified metrics or methods for calculating concomitant indicators has been proposed (Eckelman, Chertow 2009, Jacobsen 2006a). Consequently, evaluation of IS networks performance has been identified as deficient (Martin et al. 2012). It is especially so for assessment of environmental performance (Eckelman, Chertow 2009). Along the same line, the existence of such metrics is not only anticipated to have impact on further promotion and advancement of IS practice, but also on ameliorating the screening process and serving as a useful decision-making tool for participation.

As identified by (Kraines et al. 2005) and (Grant et al. 2010), Information and Communication Technologies (ICT) in general and semantic technologies in particular have the potential to improve the IS process and also to evaluate their performance. So far, ICT have been used to organise data about IS (Hepp 2006), to store data and to enable its querying and retrieval (Phillips et al. 2005) or to simply enable the IS matching process by supporting the decision-making process (Chertow 2000). In general, ICT have been identified as useful tools for enabling Industrial Ecology (Zapico, Brandt & Turpeinen 2010). However, certain limitations of currently used ICT have been identified;

- they heavily focus on the expert that facilitates the synergy rather than on the participants (Grant et al. 2010);
- they mainly support the process after the input/output matching and hence after the IS synergies have been established (Cecelja et al. 2014) and with minimum or no indication on their potential;
- the lack of standardised classifications (Trokanas et al. 2013).

It has been identified that use of tacit knowledge is perhaps one of possible solutions to overcome these limitations. The first IS support ICT system addressing the challenge of tacit knowledge is the DIET system based on production rules (Grant et al. 2010) the production of which has stopped (Allen 2004). Perhaps better solution is in using tacit knowledge implemented in the form of ontologies, as reported by (Cecelja et al. 2014). The respective eSymbiosis system offers a possibility to focus on participants and their resources, a comparative ease to implement standardised (and other) classifications (Trokanas et al. 2013), as well as assessment of IS synergies prior to their operation as demonstrated in Section 3.

In this paper we propose systemisation of IS relevant environmental metrics and a semantic approach based on knowledge modelling using ontologies to facilitate "*a priori*" calculation of respective indicators. Metrics are classified to reflect the current IS practice and concomitant environmental targets. The environmental indicators, however, are calculated from explicit knowledge embedded in IS domain ontology in the form of properties characterising materials, waste streams and processing technologies participating in IS. The indicators are calculated during the stage of screening of IS options, more precisely during the input/output matching of participating resources (companies) (Raafat et al. 2013). The outcome is used for ranking the options by environmental relevance and hence for making decisions. The proposed approach was verified using real-life IS data from the municipality of Viotia in Greece.

2. Semantic Approach to Industrial Symbiosis

Input/Output (I/O) matching is the key to formation of IS networks, hence to the IS process (Raafat et al. 2012), through which process industries try to identify ways to improve their resource efficiency and minimise their waste production (Cecelja et al. 2014). The use of semantic technologies in IS practice facilitates the automation of I/O matching. Semantics in general and ontologies in particular allow for integration of tacit and explicit knowledge and its use for I/O matching. More rigorously, resources participating in IS, namely waste and processing technologies, are described semantically in the form of ontology with entities characterised by properties relevant to IS practice (explicit knowledge) and the knowledge about IS process (tacit knowledge) (Raafat et al. 2013, Trokanas et al. 2012). While tacit knowledge is embedded in ontology structure, including subsumption, object properties and respective restrictions on object properties, explicit knowledge is acquired during the registration of participating resources when concept properties, the data properties, are populated by respective values. The data properties include operational, environmental and economic characteristics. During the matching process both tacit and explicit knowledge are used (Trokanas et al. 2013) to identify basic and the most commonly used one-to-one networks in the form of direct link between two participants i and j (Figure 1), but also complex networks including more participants (Figure 2).

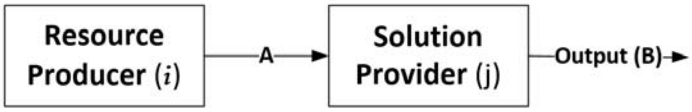


Figure 1 Direct Link

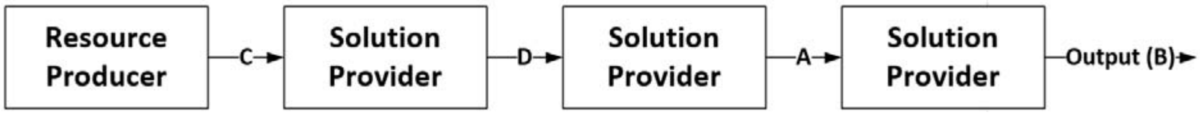


Figure 2 Complex Link

Integrated together, tacit and explicit knowledge enable i) supplementing missing data by default values determined from prior IS experience and expertise, and ii) inferring new knowledge. As tacit knowledge, we define knowledge that stems from experience. In the case of IS, it covers associations between different waste types or materials, alternative uses for certain materials and jargon terminology, among others. As explicit knowledge, we define knowledge that can be easily conveyed. In the case of IS, it covers physical and chemical properties of materials, quantities, conversion rates and others. For example, in the case of a processing technology additional inputs or outputs can be inferred and in the case of resources information about the composition of a waste can be inferred.

3. IS Domain Ontology

The IS domain ontology (Figure 3) is implemented as a conceptualisation of the IS domain with three main streams representing it, namely *Resource*, *Technology* and *Role,* along with the respective properties. Note here that names adopted for the streams and concepts in the ontology are self-explanatory.

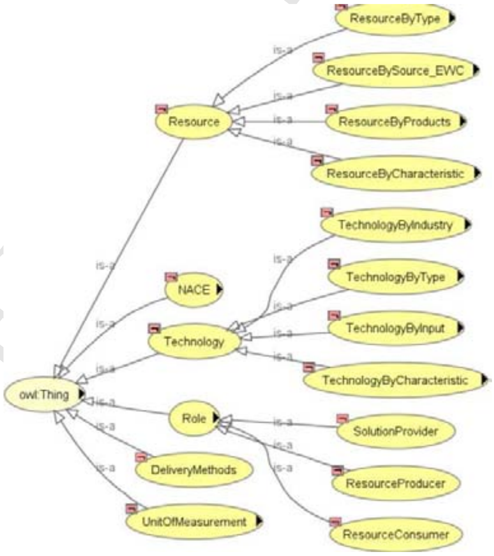


Figure 3 Excerpt of the domain ontology

Within IS practice the *Resource* stream (Figure 4) acts as the point of reference for synergy identification. It refers to materials, waste, energy, products, and water that a participant provides or requires. In the domain ontology the concept *Resource* is further classified into four sub-streams: i) *ResourcebySource_EWC*, ii) *ResourcebyType*, iii) *ResourcebyProducts* and iv) *ResourcebyCharacteristic*

(Trokanas et al. 2012). The *ResourceBySource* sub-stream is based on the existing European Waste Catalogue (EWC) (European Commission 2000) which classifies waste by their source – a combination of industry and process information. It is worth mentioning that all waste producers in the European Union (EU) are required by law to provide information based on this catalogue. Concepts of this sub-stream are related to the *ResourceByType* sub-stream via the object property *hasComposite*. The *ResourceByType* sub-stream includes three main concepts, as illustrated in Figure 4, with the key aspect being the *Materials* classification which is used as a common reference for similarity calculation (Trokanas et al. 2013). This means that most of the concepts of the domain ontology are somehow linked to the *Materials* classification (Figure 7). The *ResourceByProducts* sub-stream is based on an existing product classification (UN 2008). The concepts *ResourceByProducts* are linked to the *ResourceByType* sub-stream as well. Lastly, the *ResourceByCharacteristic* sub-stream includes concepts that are characterised by relevant properties, e.g. combustible and biodegradable resources. Concepts in this sub-stream are concepts that belong to other sub-streams and are reclassified by their properties.

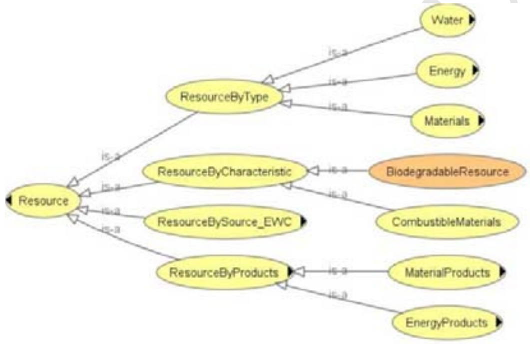


Figure 4 An excerpt of the resources classification

The stream *Technology* (Figure 5) represents processing technologies including storage and transportation services. The classification of processing technologies, which corresponds to the resource classification, includes classifications by industry (*TechnologyByIndustry*), type (*TechnologyByType*), input (*TechnologyByInput*) and characteristics (*TechnologyByCharacteristic*) of the technologies. Each technology is further characterised by its requirements and other properties. Each technology is also characterised by its inputs and outputs in terms of materials and by-products. Other characteristics include energy requirements and emissions (Raafat et al. 2013).

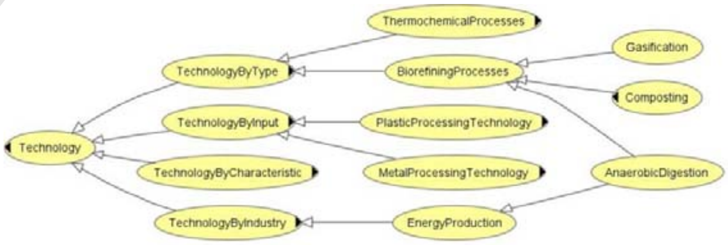


Figure 5 An excerpt of the technology classification

The stream *Role* (Figure 6) represents types of users involved in IS process, including *ResourceProvider*, *ResourceConsumer* and *SolutionProvider*.

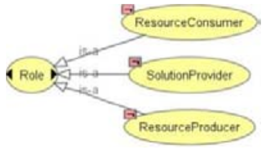


Figure 6 An excerpt of the role module

The properties, as shown in Figure 7, represent additional information which complement the IS domain. This information includes economic, operational and environmental properties. In the IS domain ontology, properties are modelled as object and data properties used to enable the identification of symbiotic networks. They also enable modelling of processing technologies and composition of waste, implemented by restriction on properties. The example in Figure 7, demonstrates property used to define the input of a technology (Technology *canProcess* Resource) and its inverse property (Resource *canBeProcessedBy* Technology). It also demonstrates the properties that link different types of roles (ResourceProducer and SolutionProvider) to Resources (*haResource*, *canUse*) and Technologies (*hasSolution*).

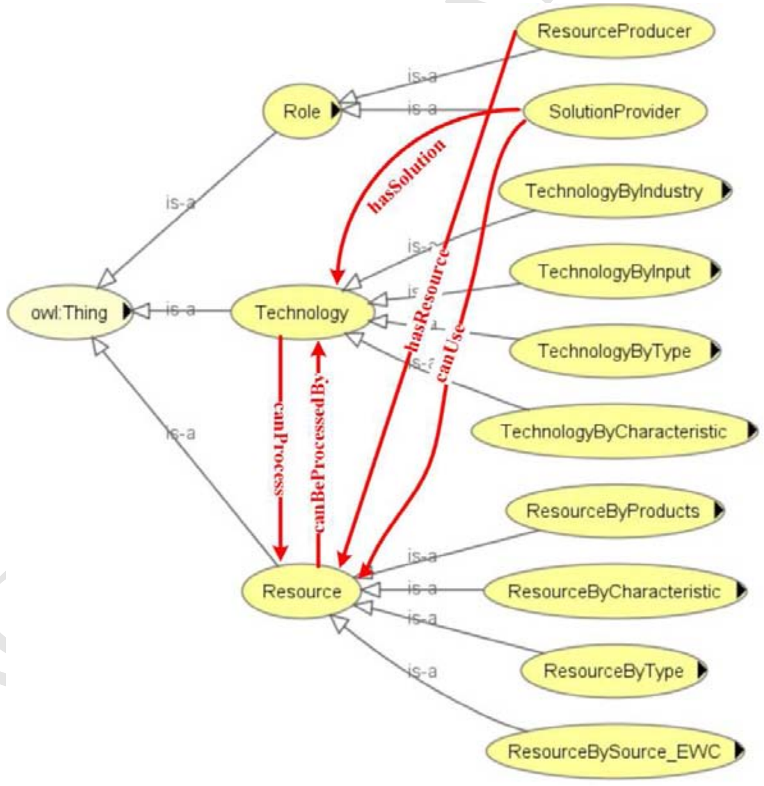


Figure 7 An excerpt of the ontology demonstrating some of the properties

Restrictions on properties allow for more granulated modelling of tacit and explicit knowledge about resources and processing technologies. Restrictions are processed by the inference engine and hence support ontology reclassification. More precisely, by processing restrictions new knowledge is generated. In relation to the IS process, restrictions enable I/O matching by defining links between instances of resource, processing technologies and with the reference to the classification of materials. The example in Figure 8, demonstrates the use of restrictions for technology modelling. In specific, it defines that all *PETProduction* technologies must have a link to the concept *Bauxite* through the *canProcess* object property.

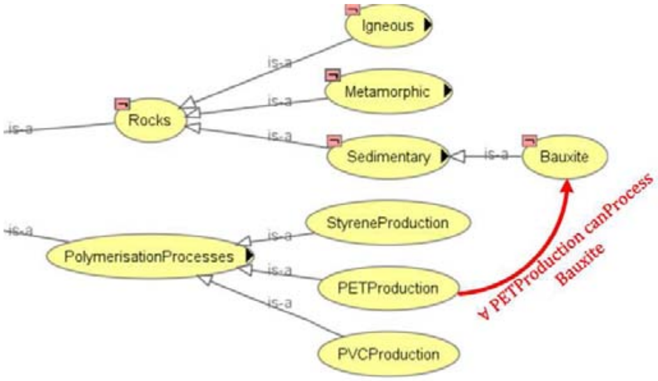


Figure 8 An example of restriction on object property

In addition, restrictions on object properties are used to model default values for data type properties when actual value is not available, i.e. the user did not provide it, as shown in Figure 9. This in turn allows for calculation of relevant metrics and respective indicators.

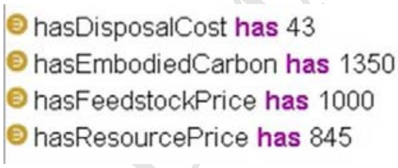

hasDisposalCost **has** 43
hasEmbodiedCarbon **has** 1350
hasFeedstockPrice **has** 1000
hasResourcePrice **has** 845

Figure 9 An example of restrictions on data type properties from the Propylene concept

4. Performance Metrics

Following the implementation of semantically supported automation of IS practice, as explained in Section 3 and reported by (Raafat et al. 2013), we employ the same technologies to pre-assess environmental effects of symbiotic networks. Semantic technologies address the erraticism and unpredictability of waste and processing technologies by allowing for modelling of explicit and tacit knowledge. The use of ontologies offers a standardised description of nonstandard and off-spec resources in a machine understandable format. This description is used as a common reference to describe resources and processing technologies, thus enabling automated I/O matching (Trokanas et al. 2013).

The pre-assessment of a synergy serves as an incentive for participation in IS. In this work we propose a methodology of calculating indicators based on environmental metrics, as shown in Figure 10. In order to quantify environmental effects, hence to enable comparison between options, all respective indicators are aggregated into a single quantity, the IS environmental indicator.

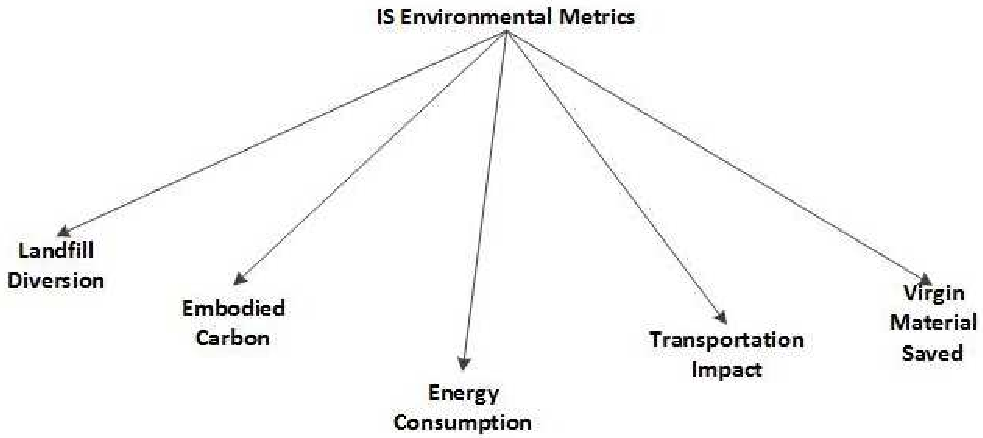


Figure 10 IS Environmental Metrics

The proposed metrics are selected as a compromise between complexity (more metrics can be introduced, i.e. emission of other gasses including green-house-gasses (GHG) in general or health effects and social perception) and effectiveness in IS practice, and along some previous studies (Chertow, Lombardi 2005, Jacobsen 2006b, Martin, Eklund 2011, Martin et al. 2012, Mattila et al. 2012) and current practice in IS (Cecelja et al. 2013). Still, the proposed framework allows for further expansion.

4.1 Embodied Carbon

Embodied carbon $EC_{network}$ (in $kgCO_2$) is calculated from the exchange of resources between participants i and j (Figure 1) as:

$$EC_{network} = \sum_{i,j}^{n_{res}}(Q_{i,j} * EC_{R(i,j)}) \qquad (1)$$

where $Q_{i,j}$ is the quantity exchanged between participants i and j, $EC_{R(i,j)}$ is the embodied carbon for the type of resource R exchanged between i and j and n_{res} represents the number of different resources exchanged in the network. In the ontology, the data property *hasQuantity* is used for the quantity $Q_{i,j}$ defined by the user and the data property *hasEmbodiedCarbon* is used for embodied carbon $EC_{R(i,j)}$ which is determined from default values predefined in the domain ontology with the use of restrictions. More precisely, the restriction used for defining the embodied carbon values is ‘Resource *hasEmbodiedCarbon has* Value’, where Value is the specific value for each resource, as demonstrated by an example in Figure 9 (Hammond, Jones 2008, ICIS 2013, Eurostat 2013).

Taking into account the carbon dioxide credit price CO_2^P, exctracted from the *CO$_2$Price* property, as formed in the boundaries of the carbon exchange scheme, the Embodied Carbon of the symbiotic network $EC_{network}$ is converted to the cost ECC as:

$$ECC = EC_{network} * CO_2^P \qquad (2)$$

4.2 Virgin Materials

Saving of virgin materials occurs when a raw material input is replaced by a by-product or a recycled material input. The amount of saved virgin materials VMS is calculated as the sum of committed resource capacities $C_{i,j}$ of participants i and j in the synergy as:

$$VMS = \sum_{i,j}^{n_{in}} C_{i,j} \tag{3}$$

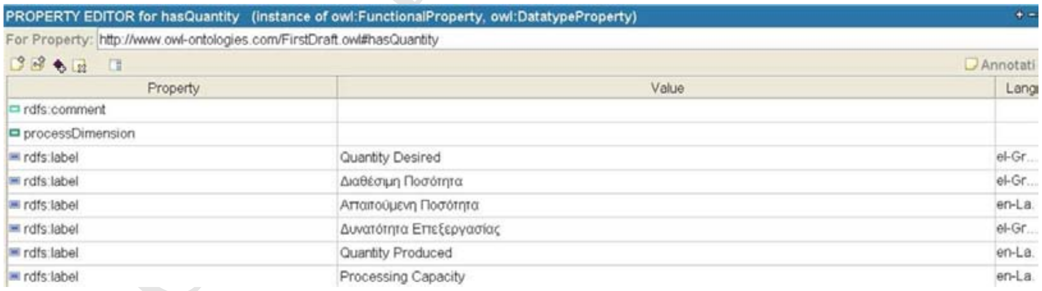
where n_{in}, is the number of inputs involved in the synergy. This indicator is calculated from the side of the participant that receives a resource for processing. Therefore and for the purpose of this indicator, every exchange is defined by the input.

The amount of the materials saved is converted to financial savings $VMFS$ using the prices of the feedstock FP used before establishing a symbiotic synergy and the resources RP used in the symbiotic synergy to replace that feedstock:

$$VMFS = \sum_{i,j}^{n_{in}} C_{i,j} * (FP_{i,j} - RP_{i,j}) \tag{4}$$

Saving of 0 is in the case when the two prices are equal which indicates that either the new resource is not a by-product/waste or that the user already uses waste thus no new saving occurs.

The main inputs are modelled in the IS domain ontology concept *Technology* (Figure 5) in the form of restrictions. An example of using restrictions to define Bauxite as the input of PET processing technologies is given in Figure 8. The value for capacity $C_{i,j}$ is extracted from the *hasQuantity* data property. Using annotations, a single property *hasQuantity* is used for both quantities and capacities (Figure 11). The $FP_{i,j}$ and $RP_{i,j}$ variables are extracted from the *hasFeedstockPrice* and *hasResourcePrice* data properties, respectively, as defined for each concept using restriction on data properties (Figure 9).



PROPERTY EDITOR for hasQuantity (instance of owl:FunctionalProperty, owl:DatatypeProperty)

For Property: http://www.owl-ontologies.com/FirstDraft.owl#hasQuantity

Property	Value	Lang
rdfs:comment		
processDimension		
rdfs:label	Quantity Desired	el-Gr...
rdfs:label	Διαθέσιμη Ποσότητα	el-Gr...
rdfs:label	Απαιτούμενη Ποσότητα	en-La.
rdfs:label	Δυνατότητα Επεξεργασίας	el-Gr...
rdfs:label	Quantity Produced	en-La.
rdfs:label	Processing Capacity	en-La.

Figure 11 Annotations for customised service

4.3 Landfill Diversion

The landfill diversion metric LDS applies in cases where a by-product/waste is re-used instead of being disposed in landfill. It is assumed that all symbiotic synergies fulfil this condition and it is calculated as the sum of the exchanged quantities $Q_{i,j}$ between participants i and j (Figure 1). Landfill diversion metric is calculated in a similar way to the metric virgin materials saved. However, not both of these metrics occur in all cases. In addition, IS aims in producing benefits to all participants and it is the full benefit that needs to be assessed, therefore both of these metrics are used in the calculations as:

$$LDS = \sum_{i,j}^{n_{res}} Q_{i,j} \tag{5}$$

where n_{res} is the number of resources exchanged in a synergy. Landfill diversion savings metric is converted to financial gains $LDFS$ by accounting for the disposal cost DC, the price of the resource RP and the landfill tax LT:

$$LDFS = \sum_{i,j}^{n_{res}} Q_{i,j} * (DC_{i,j} + RP_{i,j} + LT) \tag{6}$$

In the domain ontology the information needed for the calculation of landfill diversion are extracted from the data properties *hasQuantity* (Figure 11) for the quantity Q, *hasResourcePrice* (Figure 9) for the price of resource RP, *hasDisposalCost* (Figure 9) for the disposal cost DC and *landfillTax* for the landfill tax LT where the landfill tax value is predefined as it normally depends on environment (country) where IS operates (Figure 12).

▭ CO2Price	3.72
▭ landfillTax	64

Figure 12 CO_2 and landfill tax predefined values

4.4 Transportation

Transportation is considered in the same way as a processing technology enabling geographical dislocation. The impact of transportation TI is calculated from the distance $l_{i,j}$, between the participants i and j, the *kgCO₂* per *km*tonne* of emission represented by the transportation impact factor $TF_{i,j}$ and quantity $Q_{i,j}$ of the exchanged resources. Haversine Formula (equations (7) – (11)) is used for calculating the distance between the participants for which the latitude lat_i and longitude lon_i of the participants are extracted from the *geo:lat* and *geo:long data properties* of reused wgs84_pos[1] ontology:

$$D_{lon} = lon_j - lon_i \tag{7}$$

$$D_{lat} = lat_j - lat_i \tag{8}$$

$$a = (\sin(D_{lat}/2))^2 + \cos(lat_i) * \cos(lat_j) * (\sin(D_{lon}/2))^2 \tag{9}$$

$$c = 2 * \operatorname{atan2}(\sqrt{a}, \sqrt{1-a}) \tag{10}$$

$$l_{i,j} = R * c \tag{11}$$

---

[1] http://www.w3.org/2003/01/geo/wgs84_pos#

where, R is the radius of the earth.

$$TI = \sum_{i,j}^{n_{syn}} TF_{i,j} * l_{i,j} * Q_{i,j} \tag{12}$$

Here, TF is the $kgCO_2/tonne\ km$ value modelled in the ontology by the *hasTransportationFactor* data property (Table 1) and the quantity $Q_{i,j}$ of the exchanged resources between participants and n_{syn} is the number of pairwise exchanges in the network. The financial gains or costs of transportation TFI are calculated from the credit price of CO_2^P as (DEFRA 2012):

$$TFI = TI * CO_2^P \tag{13}$$

where LGV and HGV stand for Light and Heavy Goods Vehicle, respectively.

Table 1 kgCO$_2$ for transportation modes

Transportation Mode	**Transportation Factor** (kgCO$_2$ per vehicle km)
LGV (<3.5t)	0.272
HGV (3.5t-7.5t)	0.563
HGV (7.5t-17t)	0.747
All HGVs average (default)	0.906
Rail	0.021

4.5 Environmental Effects of Energy Consumption

The energy consumption is calculated only for energy consumed by processing technologies involved in the symbiosis and taking into account environmental energy tags for six different types of energy (in *kgCO$_2$* per *KWh*), as shown in Table 2 (DEFRA 2012).

Table 2 Energy types and their kgCO$_2$ content

Energy Type	**kgCO2 per KWh**
Electricity	0.5246
Natural Gas	0.1836
Liquefied Petroleum Gas	0.2147
Gas Oil	0.27857

Fuel Oil	0.2674
Diesel	0.2517
Coal	0.3325

The energy types are linked to the carbon content values $CC_{i,j}$ by the *hasCO2Content* data property property in the domain ontology. The total $kgCO_2$ environmental effect of energy used ECI for processes involved is calculated as the sum of the $kgCO_2$ for each energy type used multiplied by the quantity $Q_{i,j}$ of exchanged resources and assuming linear dependency:

$$ECI = \sum_{i,j}^{n_{en}} \left(Q_{i,j} * CC_{i,j}\right) \tag{14}$$

where n_{en}, is the number of different types of energy used. In majority of cases in practice only a few different types of energy are involved. The environmental cost of consumed energy $ECFI$ is calculated from the credit price of carbon dioxide CO_2^P (from the *CO_2Price* data property in the domain ontology) as:

$$ECFI = ECI * CO_2^P \tag{15}$$

4.6 Aggregated Environmental Impact

The environmental indicators, including costs and savings, are aggregated into a single metric, the weighted environmental impact $ENVI$, as the weighted average

$$ENVI = \sum_{i=0}^{pairs} \frac{(!w_{ECC} * ECC) - (w_{VMFS} * VMFS) - (w_{LDFS} * LDFS) + (w_{TFI} * TFI) + (w_{ECFI} * ECFI)}{\sum w_i} \tag{16}$$

Here $w_{ECC}, w_{VMFS}, w_{LDFS}, w_{TFI},$ and w_{ECFI} are weighting factors for each type of indicator which reflect the current IS practice but also allow for user to specify priorities. More precisely, users can choose the priority of each metric by assigning a weighting factor between 1 and 5, which correspond to normalised values 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum weighting factor is 0.2, thus no weighting factor is completely ignored. The use of default values for weighting factors aims in reducing the uncertainty stemming from user involvement by not allowing the use of extreme values that can lead to misleading results. Future implementations will include optimisation of environmental impact of each synergy. Optimisation will include general environmental impact ($ENVI$) and individual environmental costs and savings. As such, aggregated weighted environmental impact $ENVI$ enables multi-criteria decision making accounting for embodied carbon, virgin materials, landfill diversion, transportation impact and energy consumption, as well as user's priorities, and hence better reflects the IS practice.

4.7 Normalisation of Environmental Impact

The environmental impact (ENVI) is aggregated with the semantic relevance (Raafat et al. 2013, Cecelja et al. 2013) of symbiotic synergies (the semantic relevance is explained in Appendix B). This step aims in providing a single metric that represents both environmental and operational relevance of the synergies. Before aggregating the metric with the semantic relevance of the network, indicators are normalised in order to create a single and more intuitive metric with values ranging between [0,1]. This metric is compatible with the semantic relevance described in (Raafat et al. 2013). Normalisation is also useful for the cases where default values are used for the calculations. In such cases, some values might not be accurate, hence representation as a single value ranging between [0,1] is preferred. For the environmental impact, the lowest available impact is used as the base for normalisation:

$$NI_i = \frac{\max(\mathrm{ENVI}) - ENVI_i}{\max(\mathrm{ENVI}) - \min(ENVI)} \tag{19}$$

where i is the number of synergies for which $ENVI$ has been calculated. As such, the symbiotic network with the lowest impact becomes the most relevant with score 1 and the network with the highest environmental impact becomes the least relevant with score 0. All other options are scaled in between this range. Finally, the metric SIR use for final option ranking and which incorporates both environmental performance $ENVI$ and semantic similarity SR is calculated through the final step of aggregation. As semantic similarity, we define the metric that outlines the relevance of two resources in the context of IS (substitute, associated materials etc.) with a single numeric value. Similarity depends on both the properties of the two concepts that are compared as well as the relations between them. Details on the calculation of semantic similarity are given in (Raafat et al. 2013, Cecelja et al. 2013) and Appendix B:

$$SIR_i = \frac{(w_{cost} * ENVI_i) + (w_{sim} * SR_i)}{(w_{cost} + w_{sim})} \tag{20}$$

where w_{cost} and w_{sim} represent the weighting factors for $ENVI$ and SR, respectively, and index i represents the number of options identified for which environmental impact and semantic relevance have been calculated.

5. Case Study

To demonstrate the use of proposed environmental metrics, we use data on five participants registered with the system, as shown in Table 3. Demonstration is, however, restricted to information relevant to these metrics only. Each participant is characterised by a unique ID, user type, resource input/output, location coordinates, availability and pattern of supply. As mentioned in Section 3, materials stream in the domain ontology is used as a reference. Therefore, only the inputs and outputs of processing technologies are used during the matching process. Solution providers (SP) are users that can offer a solution (processing technology). Resource consumers (RC) are users that register a need for a resource. Resource producers (RP) are users that can offer a resource.

Table 3 Users' registration details

ID	User Type	Resource Output	Resource Input	Output Quantity	Lat	Lon	Valid from	Valid to	Pattern of Supply[(1)]
6	SP	Butadiene	Ethane	140	22.93	38.43	01/01/13	01/01/15	b
1	SP	Propylene	Naphtha	705	22.89	38.44	01/03/13	01/03/14	b
9	RC	-	Polypropylene	810	22.91	38.64	01/06/13	01/06/15	c
2	SP	Polypropylene	Propylene	1050	22.85	38.52	01/06/13	01/01/15	b
5	RP	PP Scrap Bags	-	900	22.82	38.51	10/09/13	01/07/14	c

(1) b – batch supply, c – continuous supply

User 6 has registered butadiene as a by-product of a cracking process (Table 3) with ethane as the main input along with specific information about quantities, time availability, geographical information and others. Cracking processes are modelled in the ontology, including their inputs and outputs (Figure 13) allowing for the inference of more information about other resources available than those registered (Table 4). Processing technologies modelling includes inputs, outputs and respective conversion rates, as well as energy and water requirements. More details on modelling and classifications of processing technology models are presented in (Raafat et al. 2013).

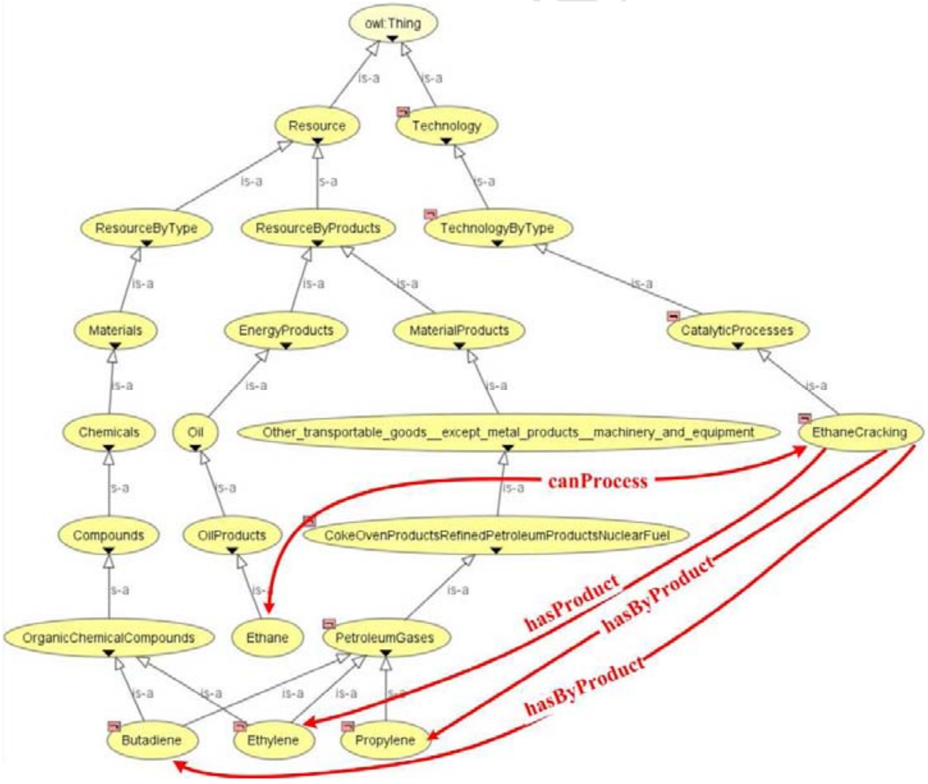


Figure 13 Ethane cracking modelling

The inferred resource propylene is registered as a feedstock and not as a by-product. For the calculation of the quantities (Table 5) we use default conversion rates of the processing technology (Andrady 2003) modelled in the domain ontology (Table 4) by respective restrictions, as demonstrated in Figure 8, Figure 9 and Figure 13.

Table 4 Knowledge modelled in the domain ontology for ethane cracking

Input	Conversion Rate	Output	Energy Quantity (MJ/kg)	Water (kg)
Ethane	1.11%	propylene	3.53	29
	80.00%	ethylene	41.05	
	14.00%	butadiene	21.38	

From the information provided in Table 3 and Table 4, it is possible to infer more information about the user 6 (Table 5). More precisely, knowledge inference is the process of identifying new relationships. In this case, properties are modelled in the ontology and inference refers to the user instance.

Table 5 Inferred information for user 6 in Table 3

Output	Input Quantity	Output Quantity	Energy in KWh
propylene	1000	11.1	784.44
ethylene	1000	800	9122.22
butadiene	1000	140	4751.11

User 1 has registered propylene as a by-product of a cracking process with naphtha as the main input (Table 3). In the same manner as with user 6, more information is inferred from ontology (Figure 13) about other available resources which are registered as feedstock and not by-products. The processing technology of the User 1 has different conversion rates than the one of User 6, but same energy requirements (Table 6).

Table 6 Cracking process (naphtha input)

Input	Conversion Rate	Output	Energy Quantity (MJ/kg)	Water (kg)
Naphtha	14.10%	propylene	3.53	29
	30.00%	ethylene	41.05	
	4.50%	butadiene	21.38	

The information provided by User 1 is used to identify the processing technology that is available and use the respective conversion rates for the inference of other available resources and their quantities (Table 7). The principle of technology modelling is demonstrated in Figure 8 and Figure 13 with more details on the integration of processing technologies provided by (Raafat et al. 2013). In both cases, ethylene is the main product and for that it is assumed that ethylene is not available, unless the user explicitly registers it as a resource.

Table 7 Inferred Information for User 1

Output	Input Quantity	Output Quantity	Energy in KWh
propylene	5000	705	784.44

ethylene	5000	1500	9122.22
butadiene	5000	225	4751.11

The performance of the identified symbiotic networks (Figure 14) is evaluated by summing the impacts of all the synergies in the network. In this case study calculation focuses on the identified symbiotic networks for the request of polypropylene given by the registration of user 9 which is a resource consumer and which needs 810 tonnes of polypropylene along with the other details given in Table 3. Excluding the information about energy consumption, Table 8 shows the explicit information used for the calculation of the environmental indicators according to the request from user 9.

Table 8 Information used in calculations

ID	User Type	Resource Output	Resource Input	Output Quantity	Embodied Carbon	FP	RP	DC	LT
6	SP	Propylene	Ethane	11.1	1.35	1000	845	43	64
1	SP	Propylene	Naphtha	705	1.35			43	64
9	RC	-	Polypropylene	810		1810			
2	SP	Polypropylene	Propylene	1050	3.9	1810		30	64
5	RP	PP Scrap Bags	-	900	1.8		600	30	64

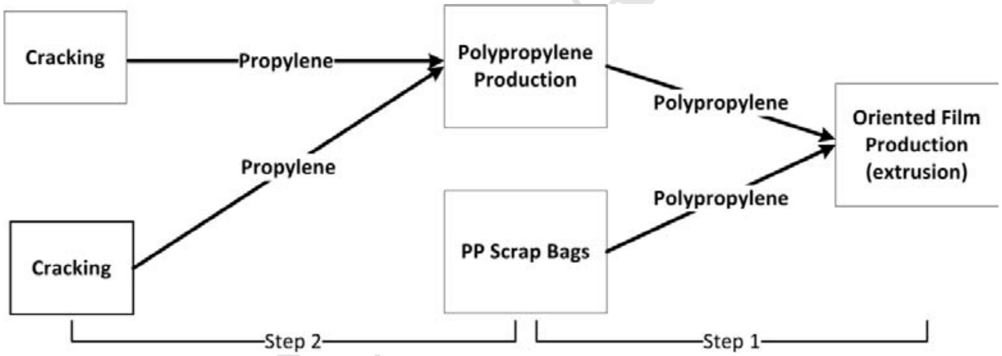


Figure 14 Identified Symbiotic Networks

Two synergies are identified as possible solutions for this request. Since the request originated by user 9, the matching algorithm follows a backward chaining approach. The first step (Step 1 in Figure 14), involves the supply of polypropylene to the requestor. Semantic matching takes into account both the tacit knowledge which is inherent in the structure of the domain ontology (Figure 8) and explicit information which is either provided by the user or modelled in the ontology as default values (Figure 9). The results of the matching are presented in Table 9 and the details on the calculation of semantic matching are given in Appendix B.

Table 9 Matching Polypropylene Request

Request	Matched	Similarity	Quantity
Polypropylene PP			810
	PP	**0.8509**	1050

	PP Scrap Bags	**0.3089**	900

The second step (Step 2 in Figure 14), involves the supply of propylene for the production of polypropylene in order to satisfy the initial request. Results are presented in Table 10. The similarity values are later aggregated with the environmental indicators as described in Section 4.7.

Table 10 Matching Propylene Request

Request	Matched	Similarity	Quantity
Propylene			1060.61
	Propylene	**0.8749**	705
	Propylene	**0.7417**	11.1

Propylene is available from the cracking process registered by the users 1 and 6 (Table 3). More details on backward matching are given in Appendix C. The embodied carbon of propylene is 1.35kgCO_2/kg (Figure 9). The satisfied capacities for the two synergies differ significantly, leading to a high variance between the two metrics. By observing equations (1) and (2) we get respective quantities as:

$$Q_{1-2} = 11\ tonnes$$

$$Q_{6-2} - 705\ tonnes$$

Therefore, the two embodied carbon metrics are

$$EC_{1-2} = 14850\ kgCO_2$$

$$EC_{6-2} = 951750\ kgCO_2$$

The same metric is calculated for the second pair. The embodied carbon for Polypropylene is 3.9 kgCO_2/kg (Table 8). The embodied carbon for the scrap bags is significantly lower (1.8 kgCO_2/kg) since it will be reused. In both cases the full capacities of requests are satisfied.

$$Q_{2-9} = 810\ tonnes$$

$$Q_{5-9} = 810\ tonnes$$

The EC metrics are then calculated according to equation (1) as:

$$EC_{2-9} = 3159000\ kgCO_2$$

$$EC_{5-9} = 1458000\ kgCO_2$$

The metrics of all the synergies are aggregated to create a single EC metric for each possible path. In this case, there are three possible options. The first two involve a symbiotic network while the third involves a single synergy (Table 11). The EC metric is converted into a cost ECC using the credit price for CO_2 (£3.72) which is predefined in the domain ontology.

Table 11 EC and ECC Metrics

Network	$EC\ (kgCO2)$	$ECC\ (£)$
1-2-9	3173850	11806722
6-2-9	4110750	15291990
5-9	1458000	5423760

To calculate the virgin materials saved VMS and its corresponding financial metric $VMFS$, the capacities that are satisfied by a by-product need to be calculated first and according to equations (3) and (4):

$C_{1-2} = 11.1\ tonnes$

$C_{6-2} = 0\ tonnes$

Therefore,
$VMS_{1-2} = 11.1\ tonnes$

$VMS_{6-2} = 0\ tonnes$

The materials saved financial metric is calculated using the prices of the feedstock *FP* and the resources *RP* (by-products) as modelled in the domain ontology and illustrated in Figure 9:

$VMFS_{1-2} = 11.1 * (1000 - 845) = £\ 6470.5$

$VMFS_{6-2} = 0$

In the same manner, the VMS and $VMFS$ are calculated for the all other resource exchanges in the network. In the case where a resource is not replaced with a by-product, $VMFS = 0$.

$VMFS_{2-9} = 810 * (1810 - 1810) = £\ 0$

$VMFS_{5-9} = 810 * (1810 - 600) = £\ 980100$

The virgin materials saved indicators for each of the networks are given in Table 12.

Table 12 VMS and VMFS Metrics

Network	VMS	$VMFS\ (£)$
1-2-9	11.1	6470.5
6-2-9	0	0
5-9	810	980100

The landfill diversion savings indicator LDS and its financial counterpart $LDFS$ are calculated according to equations (5) and (6). The former is calculated from the quantities of by-products that are used instead of being disposed in landfill:

$$LDS_{1-2} = 11\, tonnes$$

$$LDS_{6-2} = 0$$

$$LDS_{2-9} = 0$$

$$LDS_{5-9} = 810\, tonnes$$

For the financial indicator *LDFS* shown in Table 13, the above values are converted using the disposal cost, price and landfill tax, as described in Section 4.3. Default data for this calculation are extracted from the restrictions on properties in Figure 12 and Table 8.

$$LDFS_{1-2} = \sum_{i}^{Resource} Q_{1-2} * (DC_{propylene} + RP_{propylene} + LT)$$

The metric is calculated in the same way for all synergies.

$$LDFS_{1-2} = 11 * 1064 = £\, 11704$$

$$LDFS_{6-2} = 0$$

$$LDFS_{2-9} = 0$$

$$LDFS_{5-9} = 810 * (600 + 35 + 64) = £\, 566190$$

Table 13 LDFS Metric

Network	$LDFS$ (£)
1-2-9	11704
6-2-9	0
5-9	566190

The impact of transportation, hence the transportation factor, depends on the mode of transport. In the case where the user has not provided explicit information regarding the mode of transportation, we use the average for HGVs calculated in $vehicle * km$ basis. Air and water transportation are not considered due to the local nature of industrial symbiosis. By observing equations (7) – (13), the impact of the transportation is:

$$TI_{1-2} = TF_{1-2} * distance_{1-2} * Q_{1-2} = 0.906 * 13.15 * 11 = 131.05\, kgCO_2$$

$$TI_{6-2} = 5780.50\, kgCO_2$$

$TI_{2-9} = 10369.44\ kgCO_2$

$TI_{5-9} = 11991.27\ kgCO_2$

The *TFI* (Table 14) is calculated using the CO_2 credit price in Equation 13.

Table 14 TFI Metric

Network	$\boldsymbol{TFI}$ (£)
1-2-9	21990.97
6-2-9	60077.78
5-9	44607.52

The energy consumption indicators ECI and $ECFI$ apply only to the symbiotic networks that involve a processing technology. Given the details in Table 2 and by observing equation (14), we get:

$$ECI_{1-2} = 9780520\ kgCO_2$$

$ECI_{2-9} = 203124\ kgCO_2$

$$ECI_{6-2} = 11582880\ kgCO_2$$

$$ECI_{5-9} = 0\ kgCO_2$$

The financial counterpart is calculated again by accounting the CO_2 credit price and according to equation (15). The results for all the symbiotic networks are given in Table 15.

$$ECFI_{1-2} = £\ 36383.53$$

$ECFI_{2-9} = £\ 755.621$

$$ECFI_{6-2} = £\ 43088.31$$

$$ECFI_{5-9} = 0$$

Table 15 ECFI Metric

Network	$\boldsymbol{ECFI}$ (£)
1-2-9	37139.15
6-2-9	79471.84
5-9	0

After all the aspects of the environmental impact and savings have been calculated, they are aggregated to provide a single environmental metric, as shown in Table 16.

Table 16 Environmental Metrics

Network	$ECFI$ (£)	TFI (£)	$LDFS$ (£)	$VMFS$ (£)	ECC (£)
1-2-9	37139.15	21990.97	11704	6470.5	11806722
6-2-9	79471.84	60077.78	0	0	15291990
5-9	0	44607.52	566190	980100	5423760

Given the results described in Table 16 and by observing equation (16), the aggregated $ENVI$ indicator is calculated (Table 17). All weighting factors $w_{ECC}, w_{VMFS}, w_{LDFS}, w_{TFI},$ and w_{ECFI} are here set to 1.

Table 17 ENVI Metric

Network	$ENVI$
1-2-9	2,369,536
6-2-9	3,086,308
5-9	784,415.5

This aggregated metric $ENVI$ is then normalised by observing equation (19) in order to conform to the semantic relevance score (Table 18).

Table 18 Aggregated and Normalised Impact Score

Network	$ENVI$	NI
1-2-9	2,369,536	0.31
6-2-9	3,086,308	0.00
5-9	784,415.5	1.00

Eventually, the semantic relevance and impact score are aggregated (Table 19), and according to equation (20) with results are presented to the user as a single score for each option. In current implementation, the default values for the weighting factors used in the aggregation are $w_{cost} = 0.4$ and $w_{sim} = 0.6$. They have been established through experience from current IS practice. However, the participants have the option to alter the weighting factors according to their priorities.

Table 19 Final Semantic Relevance Score

Network	*SR*	*NI*	*SIR*

1-2-9	0.7963	0.31	***0.60***
6-2-9	0.8629	0.00	***0.51***
5-9	0.3089	1.00	***0.58***

Based on the results in Table 19, available options are re-ranked in terms of environmental and semantic relevance *SIR*. The option **1-2-9** has the highest score (0.60), option **5-9** comes second with a score of 0.58 and lastly, option **6-2-9** has the lowest *SIR* score of 0.51. If the user had set environmental performance as a priority by setting higher weighting factor for the *NI* (Table 19), option 5-9 would have come first with $SIR = 0.72$ (for $w_{cost} = 0.6$ and $w_{sim} = 0.4$).

4 Conclusions

The use of a single metric supports an intuitive way for comparison of symbiotic networks. By transforming all impacts into a cost IS performance is made more relevant to the user. The proposed metric can be further enhanced by other metrics transformed into a cost, such as toxicity, hazardousness and the social perception of environmental effects which are currently investigated.

It is apparent that the results depend on the weighting factors provided by the user. Yet, the use of weighting factors in the aggregation of proposed metrics and respective indicators provide higher flexibility, more customised results and better reflection of current IS practice. The system is easily customisable to address certain environmental issues of an area by using predefined weighting factors.

This approach has been successfully implemented in the web platform described in (Cecelja et al. 2014). It has been in operation and tested by a high number of companies in Viotia, Greece.

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Appendix A - Nomenclature

IS	Industrial Symbiosis
ICT	Information and Communication Technologies
I/O	Input/Output
EC	Embodied carbon of the symbiotic network
$Q_{i,j}$	Quantity of resource exchanged between industries i and j
$EC_{R(i,j)}$	Embodied carbon of resource exchanged between industries i and j (extracted from the hasEmbodiedCarbon data type property)
ECC	Embodied carbon cost for the symbiotic network
CO_2^P	Price of CO_2 as formed in the boundaries of carbon exchange scheme
VMS	The amount of virgin materials saved
$VMFS$	*VMS* transformed into a financial metric (savings)
$FP_{i,j}$	The price of the feedstock that is replaced by a resource between industries i and j
$RP_{i,j}$	Price of resource exchanged between industries i and j
$C_{j,i}$	Capacity of industry j satisfied by industry i (for resource consumers and solution providers – linked to *hasQuantity* property)
LDS	The amount of waste diverted from landfill
$LDFS$	*LDS* converted to a financial metric (savings)
$DC_{i,j}$	Disposal cost for resource exchanged between industries i and j
LT	Landfill tax for region
lon	Longitude
lat	Latitude

TI	Transportation impact
$TF_{i,j}$	Transportation factor between industries i and j
TFI	Transportation Impact in financial terms (cost)
ECI	Energy consumption impact
CC	Carbon content of energy type
$ECFI$	Energy consumption financial impact (cost)
$ENVI$	Total environmental impact of symbiotic synergy
$NI_i^{networks}$	Normalised impact of network *i*
$\min(I_i)$	The minimum impact of all available option for symbiotic networks
w_{ECC}	Weighting factor for ECC
w_{VMFS}	Weighting factor for $VMFS$
w_{LDFS}	Weighting factor for $LDFS$
w_{TFI}	Weighting factor for TFI
w_{ECFI}	Weighting factor for $ECFI$
w_{cost}	Weighting factor for environmental impact
w_{sim}	Weighting factor for semantic similarity
PP	Polypropylene
SR	Semantic relevance
SIR	A metric aggregating the semantic similarity and the impact of the networks
n_{syn}	The number of pairwise exchanges in the symbiotic network
n_{in}	The number of inputs involved in the symbiotic network
n_{res}	The number of resources exchanged in the symbiotic network

n_{en}	The number of different types of energy required in a symbiotic network
$l_{i,j}$	The physical distance between users i and j

Appendix B – Semantic Matching

The semantic matching is used to establish the technological relevance between IS participants and respective resources and hence to enable formation of IS networks. The matching algorithm (Raafat et al. 2013) is designed using a multi-level approach (Figure B.1); i) elimination level (E), ii) resource matching level (RM) and iii) the aggregation level (A). The resource matching level itself contains three phases, including graph modelling (GM), distance measurement (DM) and property matching (PM).

The inputs of the matching process include the domain ontology, the registered industries' semantic profiles and the requestor's semantic profile. The output of the matching is a set of similarity measures between the request and the matched profiles of registered participants.

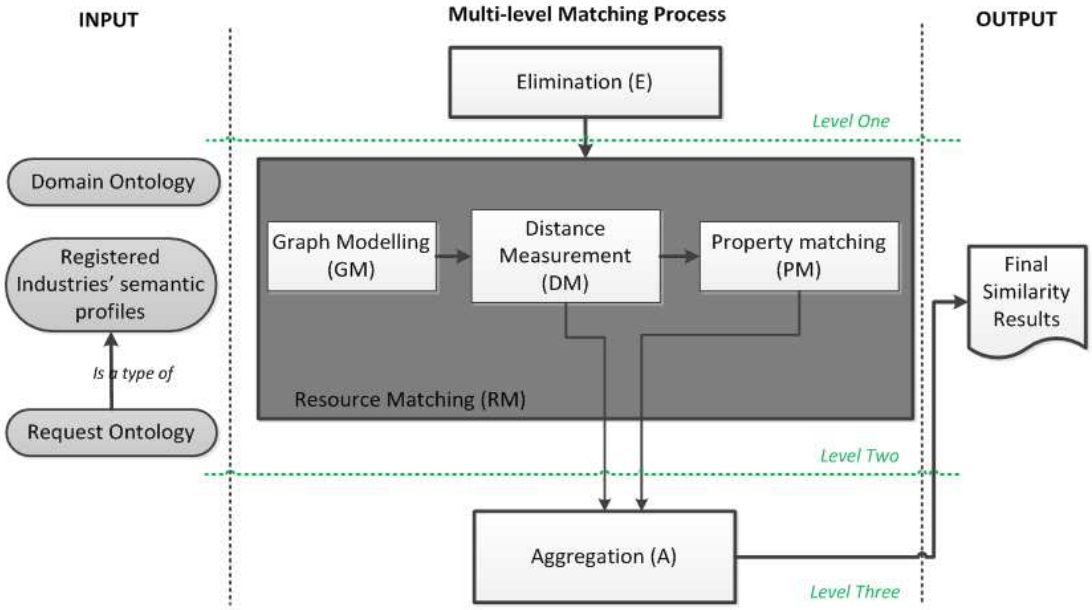

Figure B.1 The multi-level matching process

The process of elimination is introduced to minimise redundant matching and hence to computationally speed up the process. Three metrics have been introduced for the elimination phase: i) elimination based on user's role, ii) elimination based on the nature of the resource in terms of hazardousness, and iii) elimination based on availability of resource.

The resource matching (Figure B.1) calculates a semantic similarity measure over the resource classification of the domain ontology. Semantic similarity between resources is quantified by the distance measurement h_k^C between respective concepts and through the vector similarity h_k^V of resource properties associated with this phase. The whole process is performed in three phases, namely Graph Modelling (GM), Distance Measurement (DM) and Property Matching (PM).

The Distance Measurement (DM) phase measures the similarity between the type of the resources specified as the input and output of the resource provider and the solution provider using the graph model of the ontology. The distance is measured using the shortest path algorithm for distance measurement which operates over any directed graph model. Modified Dijkstra shortest path algorithm is used as the foundation of distance measurement between resource types showing the dissimilarity degree between two nodes which is then normalized and converted into a similarity measure.

The distance $\delta'\left(S_i^I, S_C^I\right)$ between two classes is calculated as the dissimilarity function and the similarity measure h_k^C, is then calculated using the normalized dissimilarity δ'. Normalization of the dissimilarity ranges the value to an interval of real numbers between 0 and 1 and is calculated by dividing the dissimilarity measure over the longest logical path between the two nodes. Using the normalized dissimilarity measure the similarity degree is a number between 0 and 1 with 1 being maximum similarity and 0 representing no similarity:

$$h_k^C = (1 - \delta')$$

In the Property Matching phase the properties characterizing the resource and industry are matched. Only industries which pass a threshold similarity at the Distance measurement (DM) phase are considered. The threshold t is application dependent and can be adjusted to optimize results of matching taking into account application's requirements. The property matching is performed by using a node based similarity measure, the vector space modelling (VSM). Vector space modelling allows for measuring the similarity between two vectors in an *n*-dimension space and it can be adapted to account for attributes of nodes with no limitations to type or number of attributes and therefore allows comparison of resources by several properties. Similarity is calculated as an average of the cosine similarity measure ($h_k^{V,c}$) and the similarity measure calculated using Euclidean distance ($h_k^{V,E}$).

$$h_k^V = \left(h_k^{V,c} + h_k^{V,E}\right)/2$$

The results of the matching phases distance measurement (DM) and property matching (PM) are aggregated at the third level of the multi-level matching algorithm and using the fuzzy weighted average.

$$\mathrm{h}_k = \frac{\alpha h_k^C + \beta h_k^V}{\alpha + \beta}$$

Where α and β are weighting parameters; in the current implementation we use α=0.6 and β=0.4 to reflect IS practice.

Appendix C – Backward Matching

Chain matching (Raafat et al. 2013) expands direct matching between two industries by introducing additional participants in the network which play the role of enablers, mediating linear relationships. The concept of enabler refers to a process or technology that breaks the linear relationship of a direct match and provides access to alternative solutions. The enabler is capable of processing a resource and producing an output which matches the targeted input of the request. The chaining is integrated by a backward matching with resource consumers playing the role of a requestor, as shown in Figure C.1. The resource consumer (which can itself be a solution provider) places a request for a type of resource as input. In the case where there is no direct match available or to broaden the identified synergy possibilities, an intermediate solution provider will act as an enabler. The backward matching performs two direct matching between the resource consumer and the enabler, and then between the enabler and the resource provider. The final similarity between the resource consumer and the resource provider is calculated as aggregation of the similarities between each direct match in the chain.

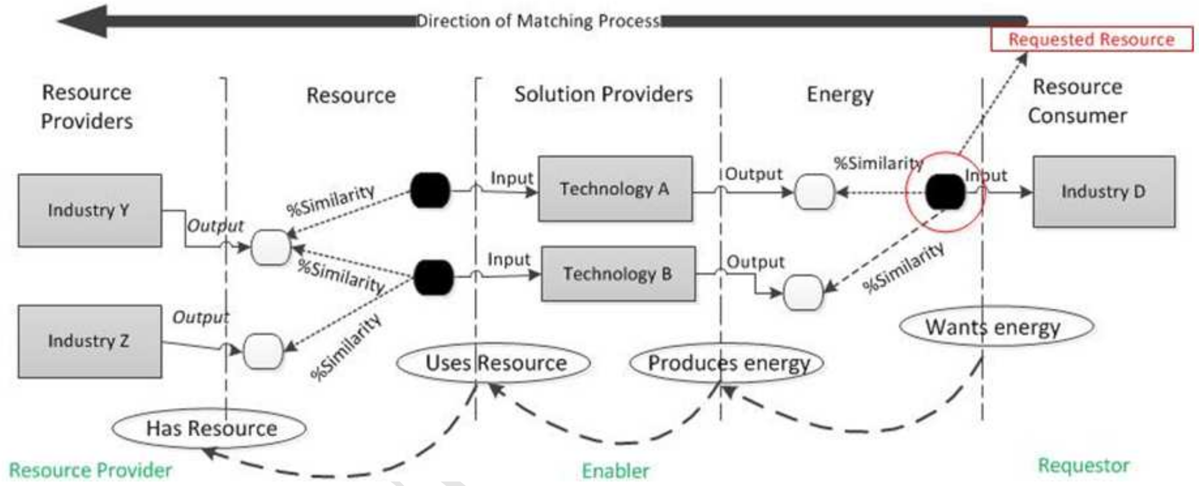

Figure C.1 Chain matching

Industrial Symbiosis (IS) is a growingly accepted paradigm for processing waste into material, energy and water with benefits to participants measured by economic, environmental and social gains. Despite of some attempts to quantify them no unified metrics or methods for calculating concomitant indicators have been proposed. This paper presents a systemisation of IS relevant environmental metrics and a semantic approach based on knowledge modelling using ontologies to facilitate "*a priori*" calculation of respective indicators. The approach and metrics are presented and verified with a case study.

Industrial Symbiosis, Performance, Metrics, Semantics, Ontologies, Knowledge Modelling