Semantic input/output matching for waste processing in industrial symbiosis

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ABSTRACT

Industrial symbiosis (IS) is a subdiscipline of Industrial Ecology that aims to bring together companies from different sectors to share resources, namely energy, materials, and water. The main goal of IS is to improve resource (materials, waste, energy) efficiency and lead to mutual environmental, financial and social benefits to participants.

In this paper we present a semantic approach for IS input/output matching. This approach is based on knowledge modelling and ontologies.

Ontologies are used to model all resources – waste, water, energy – along with details about their composition, characteristics (chemical and physical) and tacit knowledge about their flow.

The input/output matching algorithm presented enables the valorisation of resources through industrial symbiosis networks.

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1. Introduction

Industrial symbiosis (IS) is a subdiscipline of Industrial Ecology that aims to bring together companies from different sectors to share resources, namely energy, materials and water (Chertow, 2004; Jacobsen, 2006). The main goal of IS is to improve resource (materials, waste, energy) utilisation and provide mutual environmental, financial and social benefits to participants (Van Berkel, 2010). Benefits are generated by the reduced intake of virgin materials, reduced amount of waste (Chertow, 2007) being landfilled, reduced emissions (Jacobsen, 2006), job creation (Chertow, 2007) and/or innovation (Van Berkel, 2010).

As demonstrated, IS is a knowledge-intensive discipline (Davis, Nikolic, & Dijkema, 2010). One of the key barriers in promoting IS is the difficulty in identifying new uses of waste (Chertow, 2007). Other main pieces of information required in promoting IS are the information about the composition of waste streams and the documentation of material flows (Allen, 2004). Consequently, the input/output matching is a significant tool in IS practice referring to formation of symbiotic networks (Chertow, 2000).

Tacit and explicit knowledge in a knowledge base about IS have been identified as a pre-requisite for the thriving evolution of IS into

common practice (Grant, Seager, Massard, & Nies, 2010). Semantics and hence the opportunities offered by web technologies have been identified as potential solutions to mentioned barriers (Davis et al., 2010; Grant et al., 2010; Kraines et al., 2005).

In this paper we present a semantic approach for IS input/output matching. The approach is based on knowledge modelling and ontology engineering (Gruber, 1993). The use of ontologies allows modelling both tacit and explicit knowledge. It also offers standardisation in an off-market and off-spec subject, such as waste. The approach is formalised as a service and implemented as an automated web service (Cecelja et al., 2013), thus reducing costs for participants. Along with an appreciated comfort in using the service, automation also aims in motivating the participation of more industries and especially SMEs.

More specifically, ontologies are used to model the resources, i.e. waste, water, energy, along with details about their composition, properties (chemical and physical) and tacit knowledge about respective flows. Here, tacit knowledge is referred to as the knowledge captured from experience and professional intuition in waste treatment and industrial symbiosis by IS professionals. Material flows are identified from previous experience and domain expertise including IS, chemical engineering and process engineering, among others. Ontologies are also used for integrating processing technologies into a IS process in the form of the symbiotic network (Raafat, Trokanas, Cecelja, & Bimi, 2013). Knowledge modelling also allows for the pre-assessment of some of the environmental indicators of IS, hence enabling better screening and serving as a

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Fig. 1. IS ontology design.

useful decision making tool that further motivates participation (Trokanas, Cecelja, & Raafat, 2013).

2. Concepts and definitions

Ontological engineering is employed to model and formalise the knowledge in the domain of IS. The proposed ontology consists of three high level modules (Fig. 1): (i) IS matching process ontology, (ii) IS domain ontology and (iii) IS service description ontology. The three modules form the IS meta-ontology. This work proposes a fully functional IS domain ontology adjusted to description of respective resources participating in IS as well as matching of resources to form IS networks.

The IS domain ontology has four levels of abstraction (Singh et al., 2007; Sokka, 2011), as illustrated in Fig. 2. These levels contribute to ontology design levels as defined in Ratafia-Brown, Manfredo, Hoffmann, and Ramezan (2002) and include (i) meta-level which defines general purpose concepts of the ontology that can be applied universally and have no dependence on specific domains, (ii) top level providing abstract concepts of the domain as well as the top-level relationships between these concepts, (iii) domain level which specifies the domain of IS, and (iv) instantiation level which is application specific level with the user profile instances linked directly to the IS semantic service description ontology.

The IS matching process ontology (Fig. 1) incorporates concepts relevant to the process of screening the symbiotic networks, in particular algorithms and mathematical techniques adapted and created to fulfil requirements of semantic matching for potential synergies.

In order for the algorithms to perform, all participants need to be semantically described. For that the IS service description ontology is employed. More precisely, all IS participating resources have a semantic profile presented as instances of IS domain ontology which is then implemented as instantiation of the service description ontology.

2.1. Semantic description of resources

In order to accurately reflect IS practice, the *Resource* concept in the IS domain ontology (Fig. 2) acts as the point of reference for all semantic service profile descriptions and the synergy identification activities. To this end, the concept *Resource* refers to materials, waste, energy, product and water that a user provides or requires. The *Resource* concept consists of four different classification streams: (i) classification *bySource*, (ii) classification *byType*, (iii) classification *byProduct* and (iv) classification *byCharacteristic*. Classification *bySource* is implemented using both existing classifications, e.g. The European Waste Catalogue (EWC) (European Commission, 2000) and purpose-made classifications representing specific types of waste imposed by the application. These classifications are used for the registration of a waste as a *Resource* or by-products of a processing technology. The nonstandard nature of waste makes it difficult to compare different types, hence imposing the use of a more standardised classification defining the composition of the waste. Classification *byType* itself includes three categorisations: (i) *Materials*, (ii) *Energy* and (iii) *Water*.

Materials category is used to address the problem of standardisation. This classification was developed such that it inherently invokes similarity for concepts that have structural proximity in the ontology. For example, different types of biomass are

Fig. 2. Domain ontology structure.

interchangeable for biorefinery processes. However, *Wood* which is a type of *LignocellulosicBiomass* is more similar to *Paper* than other types of biomass such as *PotatoPeel* which is a type of *StarchyBiomass* (Fig. 3).

The *Materials* classification is also used to define the composition of waste and products as well as to define inputs, by-products and in some cases, products and by-products of processing technologies.

The *Energy* classification is specified as a resource but is also used to define energy requirements for processing technologies, whereas *Water* classification is used to define input or pre-processing conditions for some processing technologies.

The classification *byProduct*, is used to define the outcome (product) from processing technologies. It is also used by resource producers allowing for resource classification as products when the composition is not known. This classification is based on both existing product classifications, i.e. the *United Nations Standard Products and Services Code*[®] (UNSPSC[®]), Central Product Classification (CPC) (UN, 2008), and on bespoke product classifications which depends on application. As with waste classifications, product classifications do not provide composition information and it is for that reason that the composition of products is defined through reference to materials classification.

The classification *byCharacteristics* refers to groups of concepts which share similar characteristics at a higher level in the ontology. This classification is designed to realise the benefits provided by the capability of the IS domain ontology to be inferred.

2.2. Semantic description of processing technologies

The concept *Solutions* represents processing technologies capable of material and energy conversion as well as all intermediary services such as transportation and storage (Fig. 2). This classification is analogous to the resource classification. It includes classifications by product, type, input and characteristics of the processing technologies. Each technology is characterised by its requirements and other properties as presented in Raafat et al. (2013). Again, the material classification acts as a reference through the definition of inputs and outputs of each processing technology. By introducing the concept *Solutions* in the ontology allows for the integration of processing technologies into the IS network, and hence enabling the development of complex symbiotic networks (Raafat et al., 2013).

Fig. 3. Structural proximity of concepts.

Table 1
The first two levels of the resource classification.

By type	By product
Energy	Emissions
Cooling	CO
Electricity	CO2
FuelGas	NOx
Heat	Particles
LiquidFuel	SO2
SolidFuel	EnergyProducts
ThermalEnergy	Biofuels
Material	Biomass
Ceramic	Coal
Chemical	NaturalGas
Composite	Oil
Metal	OilShale
Mineral	Peat
OrganicMatterAndBiomass	MaterialProducts
Plastic	AgricultureForestryAndFishingProducts
Rock	ConstructionProducts
Water	FoodProductsBeveragesTobaccoTextiles
RainSurfaceWater	MetalProductsMachineryAndEquipment
SpringWater	OresMineralsElectricityGasAndWater
TapWater	OtherTransportableGoods
UndergroundWater	
WasteWater	

2.3. Classification and characterisation of resources

The classification of resources offers a common reference for comparing resources and identifying semantic similarities needed for input/output matching. Following the same principles as in Raafat et al. (2013) for processing technology classifications, the goal is to create an exhaustive, relevant, easy to use and homogeneous classification (Cherubini et al., 2009; McCarthy, 1995). As presented in Section 2.1, we use four classification streams for resources. Because of the large size of the ontology (more than 1600 concepts for resources), this paper only presents the first two levels of the streams *ByType* and *ByProduct* (Table 1). The third classification *BySource* is fully based on EWC classification (European Commission, 2000), while the fourth, *ByCharacteristic*, contains resources that have been reclassified based on certain characteristics such as biodegradability and hazardousness.

Along with classification of resources, this paper also proposes their characterisation. Each resource is characterised in terms of its economic, environmental and operational properties (Trokanas, Raafat, Cecelja, & Kokossis, 2013). For the characterisation of resources we use both object and data type properties. Object properties are used for modelling of the tacit knowledge about the resources such as their composition (*hasComposite*) and industrial sectors (European Commission, 2008) that traditionally produce it (*wasteProducedByIndustry*). Data type properties are used for modelling of explicit knowledge describing resources. Here, data type properties have a twofold purpose: (i) collecting information from the participant and (ii) modelling the default values for known cases. Restrictions on properties are used to enable the latter. An example of restrictions on data type properties which define the embodied carbon, feedstock price and resource price of *Polypropylene* is shown in Fig. 4.

More details on the use of restrictions and their modelling and implementation are available in Trokanas, Raafat, Cecelja,

Kokossis, and Yang (2012) and Raafat et al. (2013). Some indicative data type and object properties along with their values¹ are given in Table 2. This table illustrates the types of resources along with financial information (*FeedstockPrice*, *RecyclatePrice*) (letsrecycle.com, 2013), environmental information (*EmbodiedCarbon*, *isBiodegradable*) and IS-related operational information (*hasComposite*, *wasteProducedByIndustry*) (Alcorn & Wood, 1998; Hammond, G., & Jones, C., 2008).

3. Input/output matching

3.1. Semantic profile for resources and technologies

Semantic profile for resources and technologies and the process of ontology instantiation have been completed through the registration, a semantic profile of the user is created and implemented using OWL-S web service description framework (Martin et al., 2004). A user's profile contains all the information required for the matching process. The architecture of the semantic profile is given in Fig. 5. It contains the type of the resource (*hasType*), type of user (*hasUserType*), location (*hasLocation*), pattern of supply (*hasPatternOfSupply*) and other explicit information (*isHazardous*, *validFrom*, *validTo*, etc.).

Note that the semantic profile does not account for the processing technology. Instead, it contains a combination of resources identified as inputs and outputs of the registered processing technology, capitalising on the use of the *Materials* classification as a reference (Section 2.1).

3.2. Algorithm for input/output matching

The input/output matching is the process of establishing the semantic relevance between the profiles of the participants and hence to form symbiotic links. It is quantified by the similarity measure, which is calculated as a function of the explicit knowledge of a profile (quantity, location, availability) and the tacit knowledge (composition, associations, relevance, etc.). In consequence, the process of input/output matching is not only bound to identify direct matches. It can also semantically interpret the relationships that different concepts have with each other and it is therefore capable of suggesting alternative resources, identifying technologies that process similar types of resource or proposing different application for a resource.

In the current implementation, the process of input/output matching is performed in three stages (Fig. 6): (i) the stage of elimination, (ii) the stage of calculating the similarity measures including graph modelling, distance measurement and property matching and (iii) the stage of aggregation.

The elimination stage is introduced to minimise redundant matching and hence to computationally speed up the process. Three categories of elimination are introduced: (i) elimination based on requestor role, (ii) elimination based on the nature of the resource in terms of hazardousness, and (iii) elimination based on availability of resources. The requestor role is defined as one of: (i) resource provider, (ii) resource consumer and (iii) solution provider. All instances belonging to the requestor's group are logically eliminated from matching. Considering the fact that different user roles are defined by disjoint classes² in ontology, every industry which is capable of both providing and processing a resource has to define two separate profiles under each role. Additionally, if the requestor is providing or asking for a hazardous material, all

Fig. 4. Restrictions used to define default values.

¹ <http://www.recycleinme.com/scrapresources/PriceHome.aspx>,

<http://www.letsrecycle.com/prices>, <http://www.pricesofscrapmetal.co.uk/>.

² Disjoint classes are classes that cannot share any instances.

Table 2
Indicative properties of resources.

Resource	Datatype properties				Object properties	
	Feedstock price (£/tonne)	Recyclate price (£/tonne)	Embodied carbon (kgCO ₂ /kg)	isBiodegradable (boolean)	hasComposite	wasteProduced ByIndustry
Type						
<i>Plastics</i>						
Thermoplastics				False		
Polypropylene	1810	600	3.9	False	–	–
Polyethylene	965	230	1.94	False	–	–
PVC	1360	700	2.41	False	–	–
<i>Metals</i>						
NonFerrousMetals				False		
Aluminium	1092	500	8.24	False	–	–
Copper	4400	1800	3	False	–	–
Product						
PetroleumGases				False		
Propylene	1000	845	1.35	False	–	–
Butadiene	1120	–	–	False	–	–
Ethylene	950	–	–	False	–	–
Waste^a						
EWC0201						
EWC020102	–	–	–	True	AnimalBiomass	
EWC020103	–	–	–	True	HerbaceousBiomass	
EWC0303						16, 17, 31
EWC030301	–	15	0.2	True	Wood, bark	16, 17, 31
EWC030307	–	55	1.00	True	Paper, cardboard	16, 17, 31

^a EWC 02 01 02 – animal-tissue waste, EWC 02 01 03 – plant-tissue waste, EWC 03 03 01 – waste bark and wood, EWC 03 03 07 – mechanically separated rejects from pulping of waste paper and cardboard.

Fig. 5. Semantic profile architecture.

Fig. 6. Process of input/output matching.

instances which are not categorised as hazardous are eliminated. Availability, which is characterised by properties *isValidFrom* and *isValidTo*, is measured by the time overlap between the requestor and matched instances. Elimination occurs when there is no overlap.

The profiles which are not eliminated in the first stage, qualify for the stage 2, entailing the calculation of semantic similarity (Fig. 6). Semantic similarity determines comparison between requestor and other participants based on both tacit knowledge in the domain of IS provided by the IS experts and embedded in the ontology and explicit knowledge acquired from them in the course of instantiation of ontology. Semantic similarity consists of two quantifiable parts: (i) the distance measurement which depends on the structure of the ontology (Figs. 3 and 7), therefore incorporates tacit knowledge, and (ii) the vector similarity which is based on the values of properties (Fig. 4), therefore incorporates explicit information.

For the distance measurement (Fig. 6), the ontology is translated into a graph where concepts are represented by nodes and properties by arcs. The shortest distance between the two concepts is calculated from the graph by calculating the number of edges between them (Fig. 3). Distance is then converted to a similarity

measure to allow for aggregation with the property similarity. It has to be mentioned here that IS relevant object properties between respective concepts are also accounted for the distance calculation. More specifically and in order to better represent IS practice, different weighting factors have been allocated to different object properties (Raafat et al., 2013). For example, the *hasComposite* property carries a weight of 0.6, while the *is-a* property (hierarchy) carries only 0.5 (Fig. 7). Note that at this stage weights represent distance and therefore, higher weights imply higher distance and less similarity between the two concepts.

For calculation of the property similarity (Fig. 6) between requestor and user instances, four data properties are used (Table 3). In the present implementation, data properties are represented as vectors and property similarity is then calculated as a mean average of vector similarity combining cosine similarity and Euclidean similarity. As such, the absence of a property value, normally replaced by 0, is not penalising calculated similarity more than semantically justifiable.

Given the data properties in Table 3, each profile is converted into a four-dimensional vector {Quantity, Distance, Availability, Pattern of Supply}. The cosine similarity is calculated as a cosine of angle between the request vector and other user vectors. To relax

Fig. 7. Object properties example.

Fig. 8. Suggestions based on tacit knowledge.

the deviation introduced by the absence of a property, the distance and property similarity are aggregated together as a fuzzy weighted average as

$$\text{Similarity} = \frac{\alpha \times \text{Distance} + \beta \times \text{Property similarity}}{\alpha + \beta} \quad (1)$$

where α and β are weighing parameters. In the current implementation, weighting parameters have been set to experiential values of $\alpha = 0.6$ and $\beta = 0.4$ to reflect IS practice, previous experience and area of application.

3.3. Environmental performance of symbiosis

A detailed characterisation of waste (Table 2) allows for deduction of even more information about a potential symbiotic synergy. More specifically, given the environmental nature of IS, the presented framework also enables the calculation of some environmental aspects of IS. Calculations rely on user input. However, when no user input is available, the already modelled values are used. Results are then re-ranked based on the environmental performance of the symbiosis.

Carbon savings are measured from the embodied carbon of the exchanged materials. By-products and re-used materials have lower embodied carbon values (Table 2) (Hammond, G. P., & Jones, C., 2008; Monahan & Powell, 2011). The replacement of a raw material with a by-product yields significant savings in carbon

emissions. Landfill diversion occurs in cases where a by-product is re-used instead of being landfilled. It simply refers to the quantity of the exchanged materials in these cases. Virgin materials saving occurs in cases where a raw material is replaced by a by-product.

4. Case study

Industry 1 is a pulp manufacturer that has 300 tonnes of waste per year. Instead of registering it following the EWC classification, they register it as a wood resource. Registration entails providing information that instantiate the ontology and create a service request. Along with the resource information, the user also provides information about their location and industry. The results that the user gets are presented in two stages: (i) first stage takes place before semantic similarity has been calculated, entails suggestions for waste valorisation and industrial collaborations, (ii) the second stage takes place after the calculation of semantic similarity and involves the presentation of semantic results to the user. Both stages are explained as follows.

Given the information about the industry and the location, the user receives feedback on possible partners in the local area. This information is extracted from the tacit knowledge embedded in the IS domain ontology and it is based on associations stemming from previous experience. This information is presented as a map (Fig. 8).

After providing details about the available resource, the user also gets suggestions on waste valorisation. In more detail, the user is presented with some of the modelled processing technologies that can process the registered resource (Fig. 9). For the user that has registered *Wood*, the suggestions include *Anaerobic Digestion* and *Incineration Technologies*. This step aims in promoting the reuse of resources even in cases when a symbiotic synergy is not formed. It can serve as a decision making or planning tool.

The second stage presents the results of the semantic matching process which includes all profiles already registered. Registered information used in matching (Table 3) includes the user type,

Table 3
Properties participating in vector matching.

Data property	Value type	Description
Quantity	Float	The exact value used in the vector
Location	Longitude and latitude	Measured as geographical distance to the requester
Availability	Date	Is measured as the percentage of overlap with the availability specified by the requestor
Pattern of supply	Predefined text	Takes the value 1 for continuous and 2 for batch type of supply

Potential uses for "wood":

- Anaerobic Digestion Technology
- Incineration Technologies

Fig. 9. Resource valorisation suggestions example.

Table 4
Details of registered users.

User ID	User type	Resource/solution	Quantity	ValidFrom	ValidTo	Latitude	Longitude	Pattern of supply
1	RP	Wood	300	07/06/2013	06/04/2017	38.330	23.674	B
2	RP	EWCO30301	440	21/02/2014	10/10/2017	38.320	23.622	B
3	RC	EWCO30104	230	21/10/2014	13/09/2016	38.310	23.558	C
4	RC	Wood	700	18/02/2016	25/10/2018	38.339	23.609	C
5	RP	EWCO30305	190	03/03/2015	10/07/2017	38.360	23.612	C
6	RP	Wooden packaging	250	05/10/2015	05/06/2018	38.342	23.601	C
7	RC	EWCO30307	560	16/10/2015	24/07/2018	38.326	23.506	C
8	SP	Anaerobic digestion	1200	23/10/2015	11/12/2017	38.327	23.590	B
9	RP	EWCO30101	100	10/12/2013	12/05/2017	38.346	23.607	C
10	SP	Wood incineration	1000	26/07/2013	08/06/2016	38.322	23.613	B

Table 5
Profiles matched to User 1.

User ID	User Type	Resource/solution	Quantity	ValidFrom	ValidTo	Latitude	Longitude	Pattern of supply
3	RC	EWCO30104	230	21/10/2014	13/09/2016	38.310	23.558	C
4	RC	Wood	700	18/02/2016	25/10/2018	38.339	23.609	C
7	RC	EWCO30307	560	16/10/2015	24/07/2018	38.326	23.506	C
8	SP	Anaerobic digestion	1200	23/10/2015	11/12/2017	38.327	23.590	B
10	SP	Wood incineration	1000	26/07/2013	08/06/2016	38.322	23.613	B

Table 6
Similarity results.

User ID	Resource/solution	Similarity
10	Wood incineration	0.88
8	Anaerobic digestion	0.81
4	Wood	0.78
7	EWCO30307	0.78
3	EWCO30104	0.71

type of resource, available or required quantity, availability dates, location co-ordinates and pattern of supply (Table 4).

The profile of the request user is matched against existing profiles. The first step of the matching process is elimination as described in Section 3.2. The profiles that qualify for the next step for User 2, who is also the requestor, are shown in Table 5. These include only profiles with different user type and with availability dates (*validFrom* and *ValidTo*) that overlap.

Initially, the distance between the input and output concepts are calculated and translated to similarity. The values of the data properties (Table 5) are used to create vectors which are consequently compared as described in Section 3.2. The two similarity scores are aggregated giving the results provided in Table 6.

As for the environmental aspects of the proposed synergies, the available details allow for the calculation of CO₂ savings. These

calculations are based on the embodied carbon values of the resources (Table 2). For synergies where an alternative resource is suggested the difference in tonnes of CO₂ is presented to the user (Table 7). Also for these synergies, the amount of resource exchanged (quantity exchanged) is multiplied by the embodied carbon of the requested resource (EC of requested resource) and the embodied carbon of the suggested resource (EC of suggested resource). The difference (CO₂ saving) is presented to the user.

Given these results the potential synergies are re-ranked (Table 8) based on their environmental performance as described in Section 3.3.

The re-ranking of results aims in promoting waste processing by giving priority to synergies that offer environmental benefits.

5. Conclusions

The input/output matching algorithm presented enables the valorisation of resources through industrial symbiosis networks. Detailed modelling of resources and the use of semantics and ontology engineering offers numerous opportunities for better valorisation of resources. It also ameliorates the IS process. Semantic description of users allows for an automated input/output matching. Additional advantage of this approach is ability of partial matching. Synergies are assigned a semantic similarity score which

Table 7
Environmental indicators.

User ID	Suggested resource	Requested resource	Quantity exchanged	EC of suggested resource	EC of requested resource	Total EC (requested)	Total EC (suggested)	CO ₂ saving (tonCO ₂)
4	Wood waste	Wood	440	0.2	0.46	202.4	88	114.4
7	Wood waste	EWCO30307	440	0.2	1.00	440	88	352

Table 8
Environmental results re-ranked.

User ID	Resource/solution	Similarity	CO ₂ saving	Landfill diversion	Virgin materials saved
7	EWCO30307	0.78	352	–	–
4	Wood	0.78	114.4	440	440
10	Wood incineration	0.88	0	–	–
8	Anaerobic digestion	0.81	0	–	–
3	EWCO30104	0.71	0	–	–

is calculated from information provided by the user and modelled in the ontology. Partial matching enables the identification of waste/resources processing opportunities beyond established practice and which would otherwise be ignored. Standardisation of a resource classification has been proposed and demonstrated. The presented ontology provides a common vocabulary. The level of information integrated in the ontology also allows the calculation of environmental, economic and operational indicators that serve as a useful tool for decision making.

Appendix A. Properties characterising resources

Relationship	Description
hasPatternOfSupply	Batch or continuous operation of the technology
hasApplicationIn	Link between resources and industry sectors for the integration of tacit knowledge about the use of resources in different industries
canUse	Inverse relation of hasApplicationIn, used for intelligent recommendations
hasQuantityType	Links resources to the QuantityType attribute concept. The concept is about the physical form of the resource (solid, liquid, etc.)
hasComposite	Relation used to provide information about the composition of products and waste types
isCompositeOf	The inverse of the above
canBeProcessedBy	Inverse relation of canProcess. Used for tacit knowledge modelling for resource processing
wasteProducedByIndustry	Links resources to industry sectors that traditionally produce them
hasEmbodiedCarbon	Data type property that defines the embodied carbon of resources
hasResourcePrice	Data type property that defines the recycle price of a resource
hasFeedstockPrice	Data type property that defines the material price of a resource
isBiodegradable	Boolean property that defines whether a resource is biodegradable or not
isHazardous	Boolean property that defines whether a resource is hazardous or not
isValidFrom	The date the resource/solution becomes available
isValidTo	The date the resource/solution stops being available
hasQuantity	The amount of feedstock required by the technology or available quantity of a resource
geo:Lat, geo:Long	The geographic location of the industry, using WGS84 as a reference datum
hasUnitOfMeasurement	Links resources to the UnitOfMeasurement attribute concept. The concept is about the unit of measurement of the resource (kg, Tonnes, etc.)

Appendix B. Materials classification

Concepts	Description
Resource	Resource in IS contains materials, wastes, water, energy, etc.
ResourceByType	Resources that can be naturally classified by their type
Materials	The substance or substances out of which a thing is or can be made
Plastics	This concept ranges from synthetic plastics and elastomers to natural biopolymers
RubberAndElastomers	All rubber and elastomer materials
Thermoplastics	Polymers that become moldable or pliable above a certain temperature and returns to a solid state upon cooling
Thermosets	Polymers that irreversibly cures
Metals	Solid materials which are typically hard, shiny, malleable, fusible, and ductile, with good electrical and thermal conductivity. Includes ferrous and non-ferrous metals and alloys
NonFerrousMetalsAndAlloys	Metals and alloys that contain iron

Concepts	Description
FerrousMetalsAndAlloys	Metals and alloys that do not contain iron
Ceramics	Inorganic, non-metallic materials generally made using clay and other earthen materials through heat and cooling
CementAndConcrete	Cement and concrete materials
Clay	All clay minerals
Glass	All types of glass
Chemicals	Any material with a definite chemical composition
ChemicalElements	Classification of all chemical elements
Compounds	Chemical substances consisting of two or more different chemical elements
InorganicChemicals	Chemicals that lack carbon and hydrogen atoms
InorganicConstituents	Constituents that lack carbon and hydrogen atoms (e.g. ash)
OrganicChemicals	Chemicals that contain carbon
Minerals	A mineral is a naturally occurring inorganic solid, with a definite chemical composition, and an ordered atomic arrangement
Composites	Naturally occurring or engineered materials made from two or more constituents
OrganicMatter	Matter that comes from a once living organism such as plants and animals
AnimalBiomass	Biomass originating from animals
AqueousBiomass	Biomass originating from the ocean
HerbaceousBiomass	Biomass originating from plants
Rocks	The solid mineral materials forming part of the surface of the earth and other planets
Igneous	Rocks formed through the cooling and solidification of magma and lava
Metamorphic	Rocks formed from the transformation of existing rock types
Sedimentary	Rocks formed by the deposition of materials
Energy	Usable heat or power
Electricity	The supply of electric current to a house or other building for heating, lighting, or powering appliances
Heat	The transfer of energy from one body to another as a result of a difference in temperature or a change in phase
Water	A clear, colourless, odourless, and tasteless liquid, H ₂ O
ResourceBySource(EWC)	Based on EWC – waste classification based on the source process
Products	The totality of goods that can be made available by industries
EnergyProducts	Goods that can be used for the generation of energy
Biomass	Organic matter used as a fuel
Biofuels	Fuels derived directly from living matter
Coal	A combustible black or dark brown rock consisting mainly of carbonised plant matter, found mainly in underground deposits and widely used as fuel
NaturalGas	Flammable gas, consisting largely of methane and other hydrocarbons
Oil	A viscous liquid derived from petroleum
OilShale	Fine-grained sedimentary rock from which oil can be extracted
Peat	A brown, soil-like material, consisting of partly decomposed vegetable matter
MaterialProducts	All other goods, not included in class EnergyProducts
ResourceByCharacteristic	Resources classified based on important physical or chemical properties
BiodegradableResource	Resources that are capable of decaying through the action of living organisms
CombustibleResources	Resources that are capable of igniting or burning

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