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Smart eco-industrial parks: A circular economy implementation based on industrial metabolism

Alejandro M. Martín Gómez[a, *], Francisco Aguayo González[b]

[a] *Design Engineering Dept. University of Seville, Virgen de África 7, 41011, Seville, Spain*
[b] *Mechanical Engineering and Industrial Design Dept. University of Cadiz. Avd. Universidad de Cádiz 10, E-11519, Puerto Real, Cadiz, Spain*

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ABSTRACT

In order to conserve natural environments, the Circular Economy (CE) is considered as a suitable way to carry out the transition from current economic models to models of a more sustainable nature. From the biological perspective however, industrial systems are generally inefficient. Manufacturing systems from the biological perspective therefore require the incorporation of tools to support decision making, thereby enabling organizations to improve their functions and competitiveness in a global and integrated perspective. Accordingly, at meso level, eco-industrial parks are gaining importance as an approach towards ensuring CE. In this work, an ontological framework for CE, based on industrial metabolism, is developed as the technology for information and knowledge models to share the circularity of resources through industrial ecosystems, based on ecological, economic, and social criteria. The ontology developed is modelled using Ontology Web Language and integrated in an architecture based on bio-inspired Multi-Agent Systems (MAS). Moreover, a quantitative method, Ecological Network Analysis, is incorporated into MAS knowledge to analyze and establish relationships and metabolic pathways between companies, which can increase the circularity of technical nutrients and reduce biological nutrient extraction. The integrated model is applied to a case study on the product life cycle for the establishment of its metabolic pathway through an eco-industrial park. The subsequent incorporation of MAS thereby establishes the Smart Eco-Industrial Park.

1. Introduction

The intensification of human activity in specific areas, such as large cities and industrial parks, poses problems from the ecological and environmental point of view, especially as a result of rapid economic development in certain areas (Geissdoerfer et al., 2017). In fact, industrial parks are used, in the current socio-economic model, to concentrate industrial activity in a specific area for economic purposes, sometimes proving contradictory from the point of view of environmental protection (Fan et al., 2016). Regarding circularity levels of CE, industrial parks are situated at the meso level, with cities to nations at macro level, and single companies or customers at the micro level (Elia et al., 2016). Industrial parks are being considered as a way to build the CE concept for the analysis of industrial systems (Ghisellini et al., 2016). Furthermore, Industrial Metabolism (IM) can provide a suitable basis for the optimization of processes and improvement of environmental and economic performance (Fan et al., 2016).

From among the alternatives under development, the transition of production and consumption models based on a Linear Economy (LE) to a CE (Yuan et al., 2006) is highlighted. For example, ecological network analysis (ENA) (Zhang et al., 2017) has been applied in the study of urban metabolism (based on the analysis of multiple paths and nodes), and it imitates the process of urban material and material flow by constructing network models in accordance with input-output analysis. This and other models are characterized by helping to improve productivity, eco-efficiency, and environmental management reform, and by seeking closed cycles. This solution is conceived by taking nature as a model based on analogical relations (Pomponi and Moncaster, 2016).

Conceptions such as Smart City (Roscia et al., 2013) and Smart Industrial Park (Song et al., 2014) provide the implementation of intelligent distributed architectures that support the management of cities and industrial parks based on the principles of industrial ecology, thereby increasing the use of urban services to achieve efficiency

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* Corresponding author.
Email addresses: ammartin@us.es (A.M.Martín Gómez); faguayo@us.es (F.A. González)

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(Ahvenniemi et al., 2017). This situation is also present in the concept of the eco-industrial park (Côté and Cohen-Rosenthal, 1998), whereby industrial parks are developed that are part of the natural systems, and are built to minimize environmental impacts and reduce associated costs (Van Bueren et al., 2012). Accordingly, the interest to achieve the integration of the different parts that constitute the CE is identified. A CE approach based on IM involves the perspective of intelligent sustainable manufacturing (Thomas and Trentesaux, 2014). Its implementation through systems based on intelligent agents and MAS (Romero and Ruiz, 2014) enables the integrated management of material flows, substances, energy, and water resources associated with the needs of products and processes (Jensen et al., 2011).

However, the practical implementation of circularity concepts in industrial parks is not exempt from difficulties (Pomponi and Moncaster, 2016). These obstacles include relationships and interactions between companies, environmental impacts, lack of confidence, deficiencies in transmission and lack of reliability of information and the need for gradual implementation (Romero and Ruiz, 2014). Currently a formulated model of a Smart Eco-Industrial Park (SEIP) that integrates the potentialities of ENA is lacking. Specifically, this model would integrate knowledge modelling for the establishment of ENA and for the determination of parameters for the assessment of product design and processes from CE. MAS technology enables its implementation, since it is able to operate on the web.

The aim of this paper is to develop an architecture based on MAS for the management of CE issues relating to IM of an SEIP, from the informational point of view. The paradigmatic framework on which this work is built falls within the scope corresponding to IM in the context of CE, from the quantitative approach that makes ENA possible.

This paper is organized as follows. Section 2 presents an introduction to the main concepts developed. Section 3 describes the model developed for the management of IM based on CE. Section 4 sets out a case study for product design and manufacturing. Finally, Section 5 presents the conclusions and future work.

2. CE implementation at meso level (SEIP)

The circular economy is a concept, introduced by David Pearce in 1990, that has its conceptual roots in industrial ecology. This concept strives to convert an open-ended system into a circular system where the relationship between resource use and waste is considered. In accordance with the first law of thermodynamics, the planet is seen as a closed system. Thus, circulating matter and energy within the economic system would reduce the quantity of inputs and limit the increasing entropy (Andersen, 2007). Here, the concept of circularity (Lieder and Rashid, 2016) acquires a special character in terms of closed resource loops.

In recent years, there has appeared growing interest in the use and implementation of CE concepts at eco-industrial parks level (Dong et al., 2016). Its approach to industrial parks is reflected in the concepts of eco-industrial park, eco-industrial network, and industrial symbiosis (Winans et al., 2017), where the main goal of CE is the assessment of resources within a closed-looped system, oriented towards reducing raw materials, while reducing waste generation (Winans et al., 2017). In order to carry out this assessment, it is also necessary to define multi-criteria decision making (Zhao et al., 2016) so that the benefit of eco-industrial parks can be evaluated from the point of view of circularity. However, CE implementations still remain in the early stages of development, because CE implies the adoption of sustainable enterprise standards, use of renewable materials, and policies of a more sustainable nature (Ghisellini et al., 2016).

One major difference between industrial and natural ecosystems is that the efficiency is a spontaneous process as the result of evolution, while in industrial systems it has to be conceived artificially through the design process (Liwarska-Bizukojc, 2009). In other words, to achieve the circularity of resources in industrial and urban systems, it is necessary to develop and manage relationships among participating organizations. Obviously, the design and management differ for the various types of CE approach. The proposed approach considers nature as a model, teacher, and mentor and strives to encounter solutions in bio-inspired design and smart management.

CE implementation at micro level (products and companies) requires the adoption of eco-design (Ghisellini et al., 2016) assisted by Life Cycle Assessment (LCA). Eco-design has considered all the environmental impacts of products since its conception, so it provides a way to improve the CE through the improvement of resource use. At meso level, eco-industrial parks initiatives are considered. These initiatives adopt the perspective of industrial symbiosis among companies (Wen and Meng, 2015), and C2C (cradle-to-cradle) is sometimes included since CE and C2C are strongly connected, in an effort to achieve circularity of resources (Fischer and Pascucci, 2016). However, market conditions (price of by-products) make it difficult to carry out the industrial symbiosis, thereby verifying that the economy perspective may be decisive in the circular perspective of product design and manufacturing, and hence policy intervention through economic incentives and regulatory frameworks is required (Elia et al., 2016). Finally, at macro level, interesting approaches, such as eco-cities, zero-waste programs and CE indicators, are considered (Elia et al., 2016).

2.1. *Design and framework of the CE*

Design and framework for designing and managing the life cycle of technical systems at micro, meso and macro level should be oriented towards producing less impact on natural systems, since it is insufficient to attend current demands. The design and framework approaches that can be articulated at the macro, meso and micro levels to configure CE include:

At micro level, Green Design (Dangelico and Pontrandolfo, 2010), which is a term that implies a direction for improvement in the design, involves continuous improvement that is oriented towards generalized ideals and incurs no damage to the environment. Restorative Design (Kellert, 2012) is an approach that guides the activities of design to restore the ability of local natural systems to a healthy state of self-organization. Design of reconciliation (Lyle, 1999) believes that humans are an integral part of nature, in that human and natural systems are the same thing. Regenerative Design (Reed, 2007) is a systems theory approach to design, based on the design of products that carry out processes that can be "regenerated", which means the materials they are made of and their own sources of energy can be restored, renewed and revitalized. Cradle to Cradle (C2C) (Braungart et al., 2007) conceives products and materials as biological nutrients or food types (organic materials that can be deposited in any natural environment as food for other organisms) and technical materials (non-digestible synthetic materials lacking toxicity agencies that can be reused uncontaminated). The design of materials as nutrients enables metabolic pathways, both natural and industrial, to be linked. While natural nutrient cycles incite biological metabolism, engineered materials can lead to an industrial metabolism that mimics the biological model.

At meso level, Liwarska-Bizukojc (2009) proposes an industrial ecosystem model that establishes an industrial ecosystem mimicking the natural ecosystem. This model provides the structure of the ecosystem, the classification of the companies as producers, consumers and decomposers, mass and energy flows, and types of interactions. Romero and Ruiz, (2014) propose an analytical model to convert industrial areas into industrial eco-systems that integrates a knowledge database and supports the process of identification of cooperative strategies in industrial areas.

At macro level, social metabolism or socio-economic metabolism (González de Molina and Toledo, 2014) identifies the interactions between society and the natural environment, thereby allowing the analysis and quantification of the flows of materials and energy therein.

These approaches constitute an major contribution to the future development of CE, at various levels.

2.2. IM as an approach to the CE

According to the definition of IM presented by Wernik (2001), "Industrial metabolism considers human societies as systems for transforming materials by describing the exchange of materials and energy between human society and nature in a way analogous to the description of material and energy balances in natural organisms and ecosystems".

In the field of biology, metabolism is understood as the set of biochemical reactions that take place in a living cell or body. However, this processing substance need not take place exclusively at the cell level. The definition of metabolism can be extended beyond the processes of cell anabolism and catabolism, including materials and energy flows occurring at various functional levels of living systems (Wassenaar, 2015). While biology develops knowledge of metabolism at the individual level, industrial ecology has led to the expansion of this analogy to the level of industrial ecosystem. It is therefore possible to study the metabolism of an industrial ecosystem.

Industrial metabolism is also defined as the use of materials and energy flowing through industrial systems for processing, and later for its disposal as waste. It is aimed at understanding the movement of material flows, water and energy (and stocks) linked to human activity, from their extraction to their inevitable reintegration into global biogeochemical cycles, or technical cycles in the technosphere (Ayres, 1994). In this analogy, which incorporates biological metabolism enzymes that catalyze biochemical reactions, the metabolic processes associated to industrial manufacturing, distribution, use, logistics and end of life are composed of resources, machines or workstations that provide added value to the input material (Becker et al., 2013). These processes consider the processes of anabolism and catabolism to be the same, and call them metabolic steps.

Thus, various approaches to IM can be identified. This research strives to provide an overview of the main approaches to IM. Certain contributions consider IM from a biological analogy view in industrial ecology while others take a social metabolism approach (Wassenaar, 2015; González de Molina and Toledo, 2014). Such approaches are based on manufacturing cells, trophic chains, and metabolic networks (Fan et al., 2016). In addition, there are approaches that consider the ecosystem level and its analogy in the implementation in industrial eco-parks, and also cases of use of IM application in eco-industrial parks (Fan et al., 2017).

Regarding quantitative methods, ENA is applied mainly by building the ecosystem into a network of nodes, paths between nodes, and flows along those paths. The incorporation of this knowledge within a model makes it possible to analyze the paths and flows related to each node in the network, and this can then provide an overview of the system. Since ENA is used to identified and analyze flows and paths, it has also been applied for the analysis of industrial metabolic pathways (Zhang et al., 2016).

2.3. MAS

Recent research in the field of industrial ecology through the various approaches using MAS have resulted in the promotion and better understanding of models of individual and collective behaviour of companies from a specific point of view, and of the interactions between the different organizational levels, mainly from the informational perspective of sustainability. It is possible to adopt a number of perspectives based on the organization, function, information and resources, through the identification of the elements that make up 1manufacturing, production, and service systems, and hence shape urban and industrial ecosystems.

According to the definition of Wooldridge and Jennings (1995), an agent is a computer system that interacts with its environment and that can have autonomy, sociability, reactivity, and proactivity. Agents can be classified (Hinchey et al., 2006) into categories (reactive, cognitive and deliberative) based on their similar characteristics, despite the fact that agents constitute a heterogeneous population.

The evolution of manufacturing systems, which constitute IM, presents a growing trend in the use of distributed information technology based on MAS (Andreadis et al., 2014), which enables the transmission of information to be reduced and anonymity, where established to be ensured. Regarding the methodologies for the development of MAS, the majority have been proposed on the basis of extensions or improvements in line with other already existing methodologies. Thus, it is possible to perform a three-fold classification of these methodologies: the object-oriented methodologies; the methodologies of the legacy of knowledge engineering (e.g. as further (conceptual modelling of MAS) and MAS-COMMONKADS methodology (MAS Common Knowledge Acquisition and Design System)); and the methodologies based on the paradigm of agents (which include Cassiopeia, HLIM (High-Level and Intermediate Models), Prometheus, SODA (Societies in Open and Distributed Agent spaces), Tropos, and Gaia). With regard to the technology that enables the knowledge of the manufacturing systems of IM to be mapped, there are various execution platforms for the development of communities of intelligent agents, and these include JADE (Java Agent Development Framework), FIPA-OS (Foundation for Intelligent Physical Agents Open Source), Jackal, and OAA (Open Agent Architecture).

Recent work proposes models and architectures based on intelligent agents that support various aspects of the industrial ecology (Wang et al., 2012; Bichraoui et al., 2013; Lee et al., 2014; Romero and Ruiz, 2014). These studies describe certain features, such as the properties that the agent must possess, typology of actors and capabilities, and criteria for decision-making under the framework of industrial ecology.

From among the methodologies discussed above, the object-oriented methodology and JADE technology are considered to be the most suitable for the problem of supporting knowledge of the ENA formulation, and for the integration of agents into the product design and manufacturing process. This enables the CE to configure circulating resources on the technosphere and natursphere.

2.4. Ontology

Although it is possible to find numerous definitions of ontology, all researchers tend to agree on the importance of ontology in the representation, distribution and reuse of knowledge of a particular domain. One definition of ontology is that offered by Weigard and Hoppenbrouwers (1998), where an ontology is a database that describes the most important concepts of the world or a certain domain, a number of their properties, and how these concepts are related to each other. However, the most frequent definition of ontology is offered by Gruber (1993), who states that ontology is a formally represented body of knowledge based on a conceptualization. Gruber (1993) establishes a set of entities that can typically model a knowledge domain: classes, attributes or properties, and relationships. It is important to highlight that the ontologies designed allow the exchange of knowledge, and reuse this knowledge among entities within a specific domain.

An ontology enables knowledge in the field of sustainability to be modelled and formalized (Wijesooriya et al., 2015); this knowledge includes the classification and accounts for material consumption, energy, water, waste, effluents, air emissions, substances and toxicity parameters, symbiotic relationships among companies, etc.

Regarding the representation of ontologies, hierarchies are predominant for two main reasons (Spyns et al., 2002). First, hierarchies are similar to the way people organize the mental models of the world around them. And secondly, hierarchies enable the establishment of mechanisms of generalization and specification in processing and information management. For the development of the ontology for the establishment of LCA, product design and manufacturing within each of the domains, it is necessary to define the components of ontology based on its own semantic set (Raafat et al., 2013; Lee et al., 2014). Furthermore, it is necessary to define the description and properties based on each of the components.

3. Model of SEIP based on IM

In the field of waste management, the re-use, recycling and recovery of waste is the main objective in the current Waste Framework Directive of the EU (2008/98/EC). By 2020, the proportion of domestic, commercial and industrial waste to be destined for reuse and recycling categorised into paper, metals, glass, plastic, or other bio-recyclable fractions is predicted to reach at least 50% of its total weight. Specific systems for each of the categories of waste are also predicted. To this end,approaches are being developed (Maria and Micale, 2014) to determine a system of integrated social, environmental, and economically sustainable waste.

Based on the requirements and guidelines of the current legislation, and on the incorporation of the concept of IM above, a model of distributed IM is defined: see Fig. 1, which contains the fundamental elements and relationships between metabolisms of various production and service sectors. Moreover, based on MAS, this model can be formulated from the same architecture as that used to efficiently manage their dynamics and to facilitate decision-making under principles of industrial ecology (Roberts, 2004).

As is shown in Fig. 1, the concept of global IM, in general, includes the productive and service sectors as identified in accordance with the International Standard Industrial Classification of All Economic Activities (ISIC Rev. 4), which was internationally established by the United Nations. These sectors have a specific metabolism that enables the inputs, transformations, cycles, and outputs of materials and energy to be identified and analyzed. It is therefore possible to establish the integration of the various metabolisms in the product life cycle and to seek the circularity of resources.

As regards the existence of successful experiences of eco-industrial parks, Kalundborg, Ora Eco-Park, and By-product Synergy provide examples, although practical implementation thereof is not without difficulties. Relationships and interactions between companies, environmental impacts, the need for gradual implementation (Romero and Ruiz, 2014) as well as the search for integration may 1lead to the appearance of conflicts of interest, lack of cooperation, and the withholding of information relating to processes in order to obtain resources to share (Bichraoui et al., 2013).

3.1. MAS architecture for IM management

In the conceptual model, each company is regarded as a living organism, which cooperates in an SEIP, paying special attention to the flows of material and energy (cyclicity), types of substances (toxicity), and the way in which materials, energy and water are used (efficiency). Each company has its own metabolism, meaning the set of individual operations within an industrial operation, either at the cell manufacturing plant level, at the industry level, or globally at the complex, estate, park or industrial district level.

According to the bio-inspired model of eco-industrial parks based on trophic chains, there are four main agent classes in the industrial ecosystem (Liwarska-Bizukojc, 2009): Producers, energy producers,

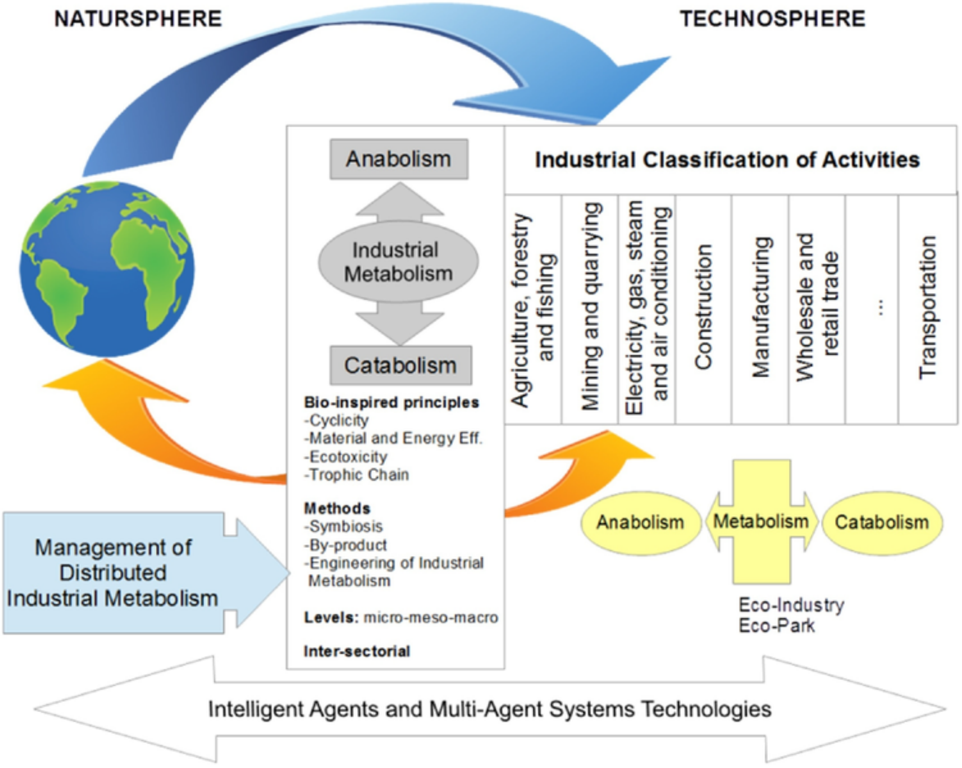

Fig. 1. Framework for CE implementation based on IM.

consumers, and decomposers. Those represent the different levels of the trophic chain. Producers are companies that produce goods of market value (including energy) and generate by-products and waste. Furthermore, various producer levels can be established depending on the trophic chain. Energy producers are a specific group because energy is a crucial resource. This class provides energy to producers, consumers, and decomposers. Consumers use the products manufactured by producers including water and energy. According to their metabolism, their outputs are solely used products and waste. Finally, decomposers are the companies that transform, recycle, recover and neutralize by-products and waste that have been generated by producers and consumers in the industrial ecosystem.

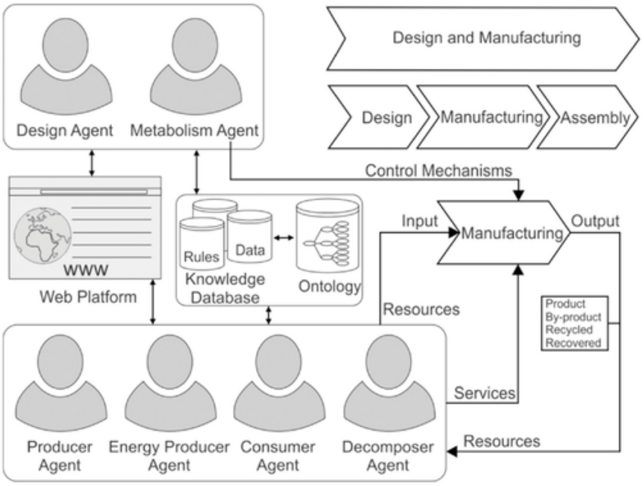

Fig. 2. Multi-Agent architecture for CE based on IM.

In order to create a model for CE based on IM, the MAS architecture shown in Fig. 2 has been implemented. This architecture allows database knowledge, rules and common ontology to be shared among the agents, which can operate on the web. Furthermore, the product life cycle is incorporated into this model in order to represent the relations among agents. In this way, the processes of a product life cycle (design, manufacturing, assembly, etc) have inputs, outputs, control mechanism and services. This architecture enables resources and services (processes) to be shared under the use of the common ontology in order to achieve the circularity of resources among organizations and the assessment of resources from the perspective of efficiency and environmental compatibility. Fig. 3 illustrates the interaction between each class of agent at the eco-industrial park level.

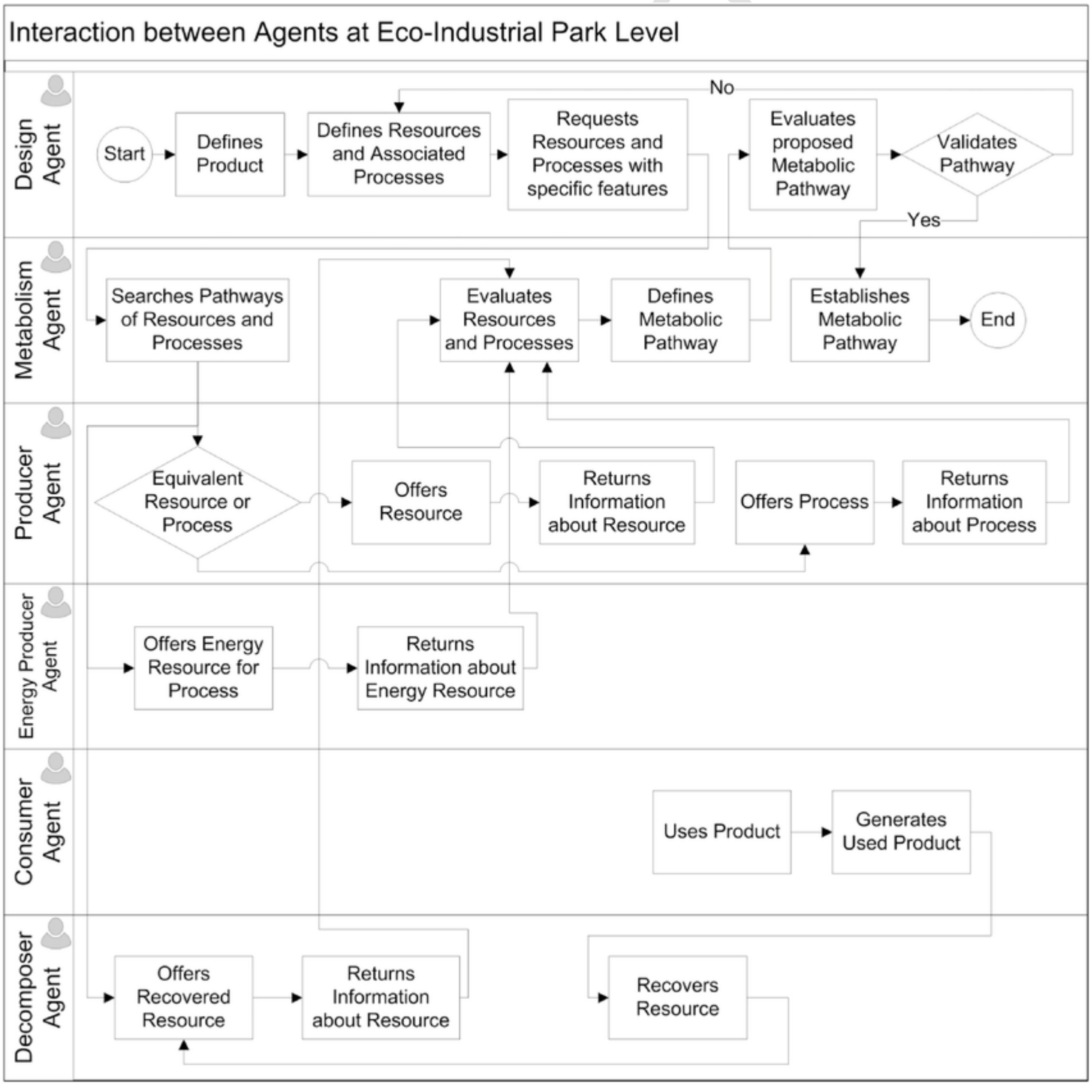

Fig. 3. Main interaction between agents at Eco-Industrial Park.

The general architecture is composed of 6 agents: the Design Agent, the Metabolism Agent, the Producer Agent, the Energy Producer Agent, the Consumer Agent, and the Decomposer Agent.

- Design Agent: The Design Agent starts the process of the definition of the product design and manufacturing process, selects materials, requests resources and carries out the process associated to the Metabolism Agent. The information returned by the Metabolism Agent enables the assessment of the proposed pathway on the basis of ecological, economic and social criteria.
- Metabolism Agent: This agent establishes metabolic pathways according to the product life cycle and criteria. This agent uses the knowledge database that contains the resources and processes enabled in the SEIP in real time, as well as their characteristics structured on the common ontology. With respect to the rules, this agent evaluates the possible ENA and provides a metabolic pathway.
- Producer Agent: This agent produces resources. Moreover, it offers resources and processes to other agents, and their related information according to the common ontology.
- Energy Producer Agent: This agent produces the energy resource and offers it to other agents, together with its related information according to the common ontology.
- Decomposer Agent: This agent recovers resources from used products. In addition, it offers these resources together with their information (through the ontology) to other agents.
- Consumer Agent: This agent establishes product necessities, consumes previously generated resources, and may represent the end user.

3.2. *Ontology*

The analysis set out above justifies the interest in establishing ontology-based knowledge to support the metabolism of industrial ecosystem and its circularity, so that knowledge can be managed, edited, released and reused.

The ontology for product definition and manufacturing in the domain of CE based on IM is implemented in Protégé (Horridge et al., 2007) using the Web Ontology Language (OWL). This language is widely recognized and employed to publish, share and transfer data using ontologies in web services. In addition, the generated OWL file is in fact an XML file that can be easily used in Multi-Agent platforms, such as JADE. Moreover, OWL has recently been utilised to create ontologies in the field of industrial ecology (Raafat et al., 2013; Borsato, 2017).

The proposed ontology is defined with the basic structure shown in Fig. 4, and its main expressions are presented in Table 1. This ontology contains the following abstract classes and sub-classes:

- *Resource*: related to the resource which cycles within the industrial ecosystem. It has the following sub-classes:
  - *ResourceByType*: related to the materials, water, and energy.
  - *ResourceByNutrient*: related to the characterization of the resource regarding its reinstatement into biological or technical cycles.
  - *ResourceByObtaining*: related to the different phases of how the resource is obtained.
  - *Composition*: related to the substance types and their percentage of the total weight.
  - *Properties*: related to the resource attributes: quantity, cost and location. It should be noted that the cost is a value that can be either positive or negative, and depends on whether the organization charges or pays for its removal.
  - *Eco-properties*: refers to the attributes of the resource from the perspective of industrial ecology, in terms of its cyclicity, toxicity and efficiency. These sub-classes have the following composition:
    - *Cyclicity* identifies the capacity of circularity of the resource, according to its metabolism (biological or technical).
    - *Toxicity* establishes a percentage scoring of toxicity based on the characterization of the substances that form the resource, regarding exposure and risk that could be harmful to humans or the environment.
    - *Efficiency* represents the efficiency in energy and water use. The concept has the following composition:
      - *EnergyUse* is an indicator that identifies and characterizes the energy incorporated into the resource (MJeq/kg) in the phase where it is obtained.
      - *WaterUse* is an indicator that quantifies the water incorporated into the resource (l/kg) in the phase where it is obtained.
      - *CarbonFootprint* is an indicator that quantifies the mass of CO2 released into the atmosphere per unit mass of resource (kg/kg).
- *Process*: related to the process that adds value to the resource. Since the *properties* and *eco-properties* of a resource depend on the process where it is obtained (embedded characteristics), the resource and process classes share both these subclasses. Moreover, it also has the following subclasses:
  - *AssociatedHumanWork*: related to workers hours in units of mass of resource processed (h/kg).
  - *ManufacturingUnitProcess*: related to unit process (e.g. cutting, machining, injection moulding, assembly).
  - *AuxiliaryManufacturingProcess*: mainly related to supply chain operations.
  - *ProcessParameter*: is used to thoroughly describe manufacturing processes.
- *Pathway*: related to the pathway to ensure the circularity of resources, it is composed of resources and processes.
- *Agent*: represents the agents that establish the system and interact to achieve a common objective.
- *Role*: each instantiated agent may have one or more roles in the industrial ecosystem, based on the trophic chain.

The ontology presented is employed to manage qualitative and quantitative information for both the requested and offered resources and processes. Fig. 5 presents a better visualization of the resulting relationships regarding classes. Relationships in the ontology define associations between the concepts. For example, the relationship *defines* establishes the type of resources and processes associated to the product. All the relationships applied here are listed and their semantics explained in Appendix A.

3.3. *Knowledge of metabolism agent*

The CE can be analyzed by its analogy with the exchange of resources in a natural ecosystem. Based on this analogy, the relationship between a pair of nodes can be: exploitation, control, competition, or mutualism. Accordingly, the knowledge of ENA is incorporated into the Metabolism Agent, which uses ENA to conduct flow and analyze the metabolic pathways. Tools of analysis can therefore be used to analyze the ecological relationship among agents that form the network (Fath, 2007). The direct-flow matrix $\boldsymbol{F}$ is completed with direct relationships (f_{ij}). T_i is defined as the sum of the flows from the nodes of the network (agents) to node i and the external flow inputs (z_i) into node i.

$$T_i = \left(\sum_{j=1}^{n} f_{ij}\right) + z_i \tag{1}$$

Fig. 4. Top class hierarchy.

The direct-flow intensity matrix (***D***) can now be assembled. This matrix represents the intensity of flow from node *j* to node *i* over one unit of path length and thus represents a local perspective of flow. The matrix element is therefore d_{ij}.

$$d_{ij} = \left(f_{ij} - f_{ji}\right)/T_i \tag{2}$$

The integral-flow intensity matrix (***N***) is completed by adding the boundary (D^0), direct (D^1), and indirect (D^m) flow intensity matrices. ***N*** is a convergent series that has an exact solution and can be computed.

$$N = D^0 + D^1 + D^2 + \ldots + D^m = \left(D^0 - D\right)^{-1} \tag{3}$$

According to *N*, it is possible to analyze the sign of any element in order to identify the relationship between a pair of nodes. If (n_{ij}, n_{ji}) = (+,-), then node *i* exploits node *j*. If (n_{ij}, n_{ji}) = (-,+), then node *i* is exploited or controlled by node *j*. Although this may benefit one of the two nodes, it could create industrial symbiosis in the future. If (n_{ij}, n_{ji}) = (-,-), then node *i* competes with node *j*, thereby decreasing resource efficiency. Finally, if (n_{ij}, n_{ji}) = (+,+), then the two nodes represent a mutualism relationship and both nodes benefit.

The Metabolism Agent can analyze various perspectives of the ENA generated according to the key indicator for CE: Ecological (based on cyclicity, toxicity and efficiency); social (based on human work associated to the process); and economic (based on costs). This perspective will depend on the indicator priority for each analysis.

4. Case study

This section describes a simplified application of the proposed model. Accordingly, a model of SEIP is developed. This case study is related to the process of design and manufacturing of 1000 units of workbenches through their life cycle. Although the architecture allows

Table 1
Ontology-related concepts for CE: Glossary and expressions.

Concept			Expression
Composition			$[Rc] = [rc_1, rc_2, ..., rc_m, ..., rc_n]$ $rc = \{SubstanceByType, WeightPercentage\}$ m = 1,...,nm = 1,...,n
Properties	Quantity		$[Rq] = [rq_1, rq_2, ..., rq_m, ..., rq_n]\ rq_m?N$ $m = 1,...,n$
	Cost	$m = 1,...,n$	$[Rco] = [rco_1, rco_2, ..., rco_m, ..., rco_n] rco_m?R$
	Location	rl = {Latitude, Altitude} $m = 1,...,n$	$[Rl] = [rl_1, rl_2, ..., rl_m, ..., rl_n] rl_m?R$
Eco-properties	Cyclicity		$[Rcl] = [rcl_1, rcl_2, ..., rcl_m, ..., rcl_n] rcl_m \in [0, 1]$ $m = 1,...,n$
	Toxicity		$[Rtx] = [rtx_1, rtx_2, ..., rtx_m, ..., rtx_n]\ rtx_m \in [0, 1]$ $m = 1,...,n$
	Efficiency	Energy Use	$[\mathrm{Re}] = [re_1, re_2, ..., re_m, ..., re_n] re_m?N$ $m = 1,...,n$
		Water Use	$[Rw] = [rw_1, rw_2, ..., rw_m, ..., rw_n] rw_m?N$ $m = 1,...,n$
		Carbon Footprint	$[Rcf] = [rcf_1, rcf_2, ..., rcf_m, ..., rcf_n] rcf_m?N$ $m = 1,...,n$

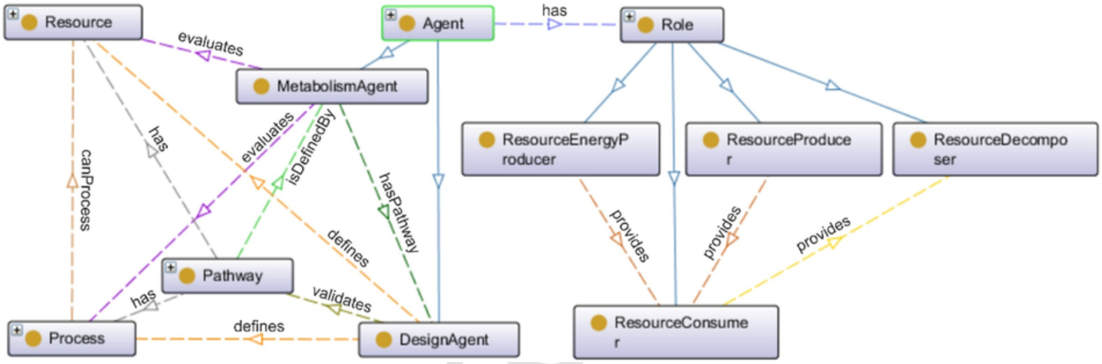

Fig. 5. Top-level hierarchy of CE Ontolgy.

metabolic pathways to be assessed under economic (cost), social (workers h) and ecological (cyclicity, toxicity and efficiency) criteria, this case is simplified to assessed the metabolic pathway from the cyclicity perspective. Thus, the main objective of the proposed case is to show the circularity of resources through metabolic pathways within the industrial and natural ecosystem. Note that the application is represented in a simplified way in order to illustrate the model operation without losing comprehensibility.

In accordance with the agents defined in the previous architecture, agents in an SEIP can be identified based on industrial ecosystem approach. Firstly, the Metabolism Agent and the Design Agent are identified. The producer agents are subsequently instantiated. Several Manufacturing Agents are instantiated in order to create the levels of producers (1°, 2°, 3°,…), such as Extractive Plant (1° Producer). The Energy Producer is then instantiated as the Energy Agent, which provides renewable energy needed to perform other processes in the network. The next step involves the instantiation of the consumer as the User Agent. Finally, Decomposer Agents are instantiated several times in order to create the levels of decomposers (1°, 2°, 3°,…). Thus, the Transformation Agent manages waste collection by optimizing transport for further treatment. The Treatment Agent directs each classified waste to be sent to the specific agent with the ability to process that type of waste. The Reverse Logistics Agent directs the recovery operations and supply components to reincorporate them into new products. The Recycling Agent manages the process of recycling and offers recycled resources. The Landfill Agent accepts and coordinates the process of eco-friendly waste disposal.

Based on the analogy model of the circularity of resources through the trophic chain, Fig. 6 schematically presents the agents that form the industrial ecosystem. Moreover, this model reveals the process of product design through the life cycle (raw material acquisition, product design and manufacturing, logistics, consumer use, and end of life), the services associated to each process of the life cycle, and the flows that can be established among different agents.

The process is initiated by the Design Agent. Once the Design Agent completes the process of product design, the information shown in Table 2 is returned in accordance with the ontology. Here, resources to be incorporated into the product are identified. Fig. 7 presents the use case diagram of the agents, according to the principles of UML applied to the product design and manufacturing, and shows in detail the various activities of the intervenient agents in the SEIP. This use case diagram describes the circularity of resources among companies and assesses the metabolic pathways from the circularity perspective.

Once the product has been defined, the process for the establishment of the metabolic pathway through the eco-industrial park can begin. From the resource information provided by the Design Agent and the possible relationships at eco-industrial park level (see Fig. 6), the Metabolism Agent can assemble the matrix flows. Table 3 shows direct flows (***F*** matrix). Flow(t) values represent the flows from the nodes

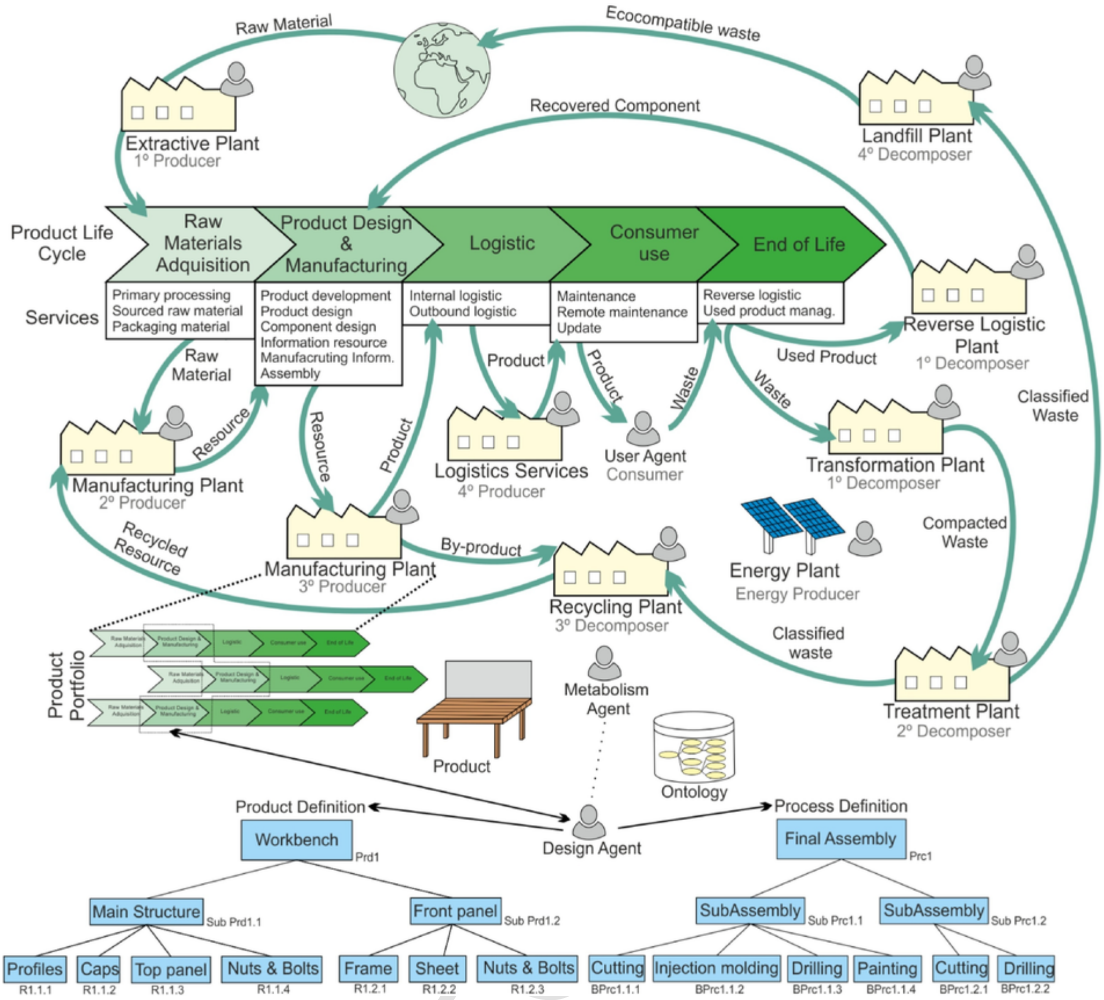

Fig. 6. Analogy model of circularity through the trophic chain for the SEIP.

Table 2
Product specifications according to the ontology.

Resource	Properties	Composition		Eco-properties	Resource By Nutrient	Resource By Type
	Quantity	SubstanceByType	WeightPercentage	Cyclicity		
	Rq	*Rc = {SubstanceByType, WeightPercentage}*		*Rcl*		
Aluminium 1200	1,310 kg	Al/Mg/Mn/Cr/Cu/Zn/Zr/Li	3.87%	0.75	Technical	Material
S 275JR	16,510 kg	Fe/C	48.75%	0.84	Technical	Material
Butyl Rubber	460 kg	$(CH_2\text{-}C(CH_3)\text{-}CH\text{-}(CH_2)_2\text{-}C(CH_3)_2)_n$	1.36%	0.25	Technical	Material
Pinewood	15,590 kg	Cellulose/Hemicellulose/Lignin/H_2O	46.02%	0.50	Biological	Material

listed across the top of the table to the nodes in the first column of the table.

Based on the direct flows among all pairs of nodes and with the external environment (see Table 3), the direct and integral intensity can be calculated (Tables 4 and 5). Of the 26 pairs that have direct-flow intensity, 11 have a wide gap between the magnitudes (absolute values) of the direct-flow intensity: 1 → 2, 2 → 3, 3 → 4, 4 → 5, 5 → 6, 6 → 7, 7 → 8, 7 → 10 and 8 → 2. This reflects the direct-flow intensity among nodes that set the main pathway. This pathway starts at the Extracting Plant (A_1) and finishes at the Landfill Plant (A_{10}). The pathway between the Recycling Plant (A_8) and the Manufacturing Plant (2° Producer), 8 → 2, should be highlighted.

Based on the positive and negative signs for each element in the matrix $\boldsymbol{N}$, (Table 5), the main ecological relationships among agents can be determined, in accordance with the intensity. Exploitations are therefore related to nodes: 2 $(n_{21}, n_{12}) = (+,-)$, 2 $(n_{28}, n_{82}) = (+,-)$, 3 $(n_{32}, n_{23}) = (+,-)$, 3 $(n_{39}, n_{93}) = (+,-)$, 4 $(n_{43}, n_{34}) = (+,-)$, 5 $(n_{54}, n_{45}) = (+,-)$, 6 $(n_{65}, n_{56}) = (+,-)$, 7 $(n_{76}, n_{67}) = (+,-)$, 8 $(n_{87}, n_{78}) = (+,-)$, 9 $(n_{95}, n_{59}) = (+,-)$, and 10 $(n_{107}, n_{710}) = (+,-)$. Inverse pairs return nodes that are exploited or controlled by nodes: $(n_{ij}, n_{ji}) = (-,+)$. This corresponds with the traditional linear economy. Re-

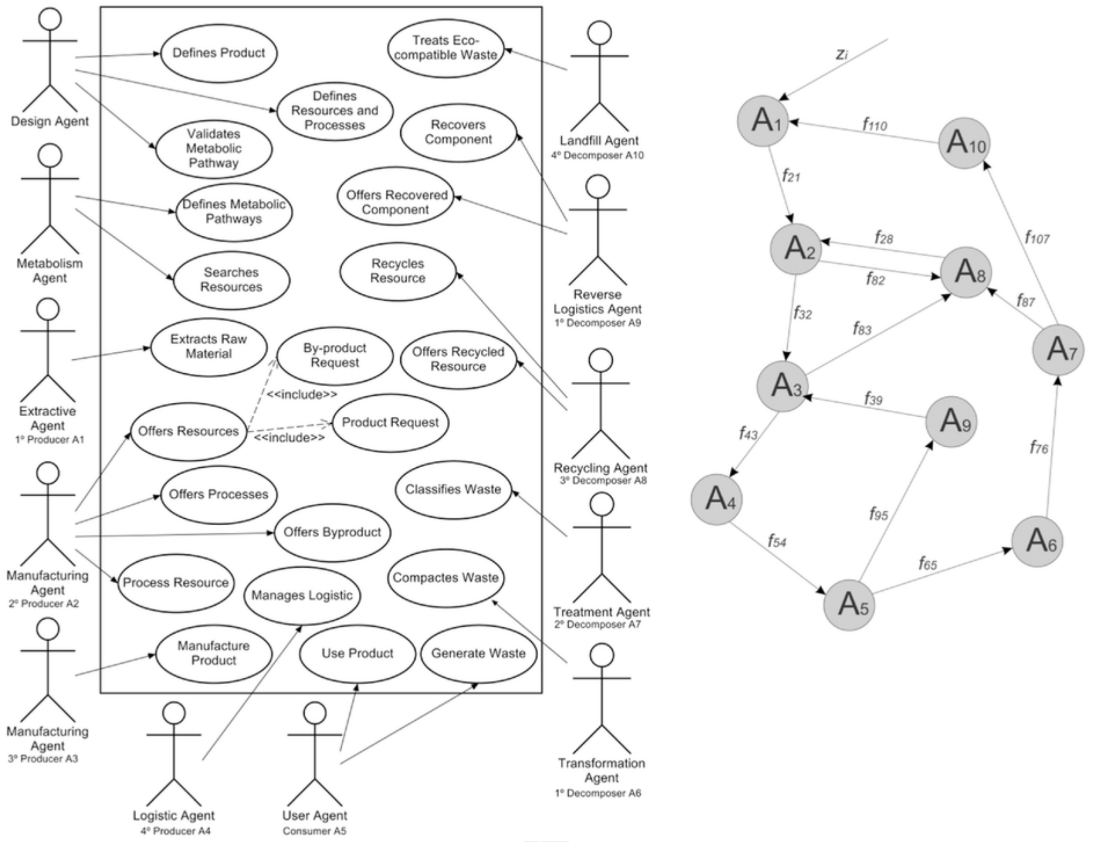

Fig. 7. Use case diagram of a Smart Eco-Industrial Park (left) and metabolic network (right).

Table 3
Direct flows among all pairs of nodes (agents) and between nodes and the external environment.

Flow(t)	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	z_i
A_1	0	0	0	0	0	0	0	0	0	0	40,000
A_2	40,000	0	0	0	0	0	0	22,991	0	0	0
A_3	0	35,000	0	0	0	0	0	0	460	0	0
A_4	0	0	33,780	0	0	0	0	0	0	0	0
A_5	0	0	0	33,870	0	0	0	0	0	0	0
A_6	0	0	60	0	33,870	0	0	0	0	0	0
A_7	0	0	0	0	0	33,780	0	0	0	0	0
A_8	0	5,000	1,070	0	0	0	22,991	0	0	0	0
A_9	0	0	0	0	460	0	0	0	0	0	0
A_{10}	0	0	0	0	0	0	22,991	0	0	0	0

Nodes: A_1 Extractive Plant − 1° Producer. A_2 Manufacturing Plant − 2° Producer. A_3 Manufacturing Plant − 3° Producer. A_4 Logistics Services − 4° Producer. A_5 User Agent − Consumer. A_6 Transformation Plant − 1° Decomposer. A_7 Treatment Plant − 2° Decomposer. A_8 Recycling Plant − 3° Decomposer. A_9 Reverse Logistics Plant − 1° Decomposer. A_{10} Landfill Plant − 4° Decomposer.

garding the main mutualism relationships, the related nodes are: 3 $(n_{31},n_{13}) = (+,+)$, 3 $(n_{35},n_{53}) = (+,+)$, 3 $(n_{37},n_{73}) = (+,+)$, 3 $(n_{38},n_{83}) = (+,+)$. This reveals that a positive relationship exists between Manufacturing Plant (3° Producer) (A_3) and Recycling Pant (A_8), since this pathway is better than that of (A_1) through (A_2)·The main competitions between nodes are: 1 (n_{18}, n_{81}) = (-,-) and 9 (n_{910}, n_{109}) = (-,-), 9 (n_{92}, n_{29}) = (-,-). Extractive Plant (A_1) and Recycling Plant (A_8) compete to supply resources to the network.

This analysis reveals that a main metabolic pathway exists that can achieve the circularity of resources for the aforementioned manufacture of the workbenches. This circular pathway is: 2 → 3, 3 → 4, 4 → 5, 5 → 6, 6 → 7, 7 → 8, 8 → 2. This pathway reinforces the mutualism relationship and prevents the unnecessary extraction of raw material.

5. Conclusion

This paper proposes an ontology for CE, based on IM, for product design and manufacturing. This proposal provides significant advantages over the current management of these systems, which lacks a global view. The integrated use of MAS to achieve the SEIP, enables it to operate in real time, thereby not only decreasing the time of flow management, but also ensuring anonymity of the organizations involved in the exchange process, while establishing a common ontology that helps in the identification, analysis and circularity of resources.

Significant benefits can be obtained through the incorporation of a smart information management system that allows the management and integration of the information processes with the purpose of enabling the decision-making under CE perspective. Available and acces-

Table 4
Direct-flow intensity matrix (**D**).

D	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_1	0	−1.0000	0	0	0	0	0	0	0	0
A_2	0.6350	0	−0.5556	0	0	0	0	0.2856	0	0
A_3	0	0.9870	0	−0.9526	0	−0.0017	0	−0.0302	0.0130	0
A_4	0	0	1.0000	0	−1.0027	0	0	0	0	0
A_5	0	0	0	1.0000	0	−1.0000	0	0	−0.0136	0
A_6	0	0	0.0018	0	0.9982	0	−0.9956	0	0	0
A_7	0	0	0	0	0	1.0000	0	−0.6806	0	−0.6806
A_8	0	−0.6191	0.0368	0	0	0	0.7911	0	0	0
A_9	0	0	−1.0000	0	1.0000	0	0	0	0	0
A_{10}	0	0	0	0	0	0	1.0000	0	0	0

Nodes: A_1 Extractive Plant − 1° Producer. A_2 Manufacturing Plant − 2° Producer. A_3 Manufacturing Plant − 3° Producer. A_4 Logistics Services − 4° Producer. A_5 User Agent − Consumer. A_6 Transformation Plant − 1° Decomposer. A_7 Treatment Plant − 2° Decomposer. A_8 Recycling Plant − 3° Decomposer. A_9 Reverse Logistics Plant − 1° Decomposer. A_{10} Landfill Plant − 4° Decomposer.

Table 5
Integral-flow intensity matrix (**N**).

N	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
A_1	0.7002	−0.4721	0.1527	−0.1035	0.0419	−0.0634	−0.0213	−0.1250	0.0014	0.0145
A_2	0.2998	0.4721	−0.1527	0.1035	−0.0419	0.0634	0.0213	0.1250	−0.0014	−0.0145
A_3	0.1953	0.3076	0.5216	−0.3039	0.1930	−0.1161	0.0778	0.0192	0.0041	−0.0529
A_4	0.1081	0.1702	0.3348	0.4336	−0.2475	0.1799	−0.0670	0.0841	0.0077	0.0456
A_5	0.0870	0.1370	0.1863	0.2618	0.4393	−0.2952	0.1444	−0.0648	−0.0035	−0.0983
A_6	0.0226	0.0356	0.1530	0.1642	0.3099	0.4776	−0.2123	0.1500	−0.0022	0.1445
A_7	0.0649	0.1022	0.0341	0.0971	0.1295	0.2286	0.3581	−0.2156	−0.0013	−0.2438
A_8	−0.1271	−0.2001	0.1407	0.0015	0.1355	0.1373	0.2730	0.7528	−0.0000	−0.1858
A_9	−0.1083	−0.1706	−0.3352	0.5657	0.2463	−0.1791	0.0666	−0.0839	0.9923	−0.0453
A_{10}	0.0649	0.1022	0.0341	0.0971	0.1295	0.2286	0.3581	−0.2156	−0.0013	0.7562

Nodes: A_1 Extractive Plant − 1° Producer. A_2 Manufacturing Plant − 2° Producer. A_3 Manufacturing Plant − 3° Producer. A_4 Logistics Services − 4° Producer. A_5 User Agent − Consumer. A_6 Transformation Plant − 1° Decomposer. A_7 Treatment Plant − 2° Decomposer. A_8 Recycling Plant − 3° Decomposer. A_9 Reverse Logistics Plant − 1° Decomposer. A_{10} Landfill Plant − 4° Decomposer.

sible organized information can thereby be provided which facilitates the identification of the relationships among flows and improves evaluation under the ecological, economic and social criteria.

A quantitative method, ENA, is incorporated into knowledge of the Metabolism Agent to describe and quantify the ecological relationships among agents at eco-industrial park level, and to identify the pathways provided by these relationships. In this paper, the perspective of circularity of resources is analyzed through the eco-industrial park, principally since it simplifies the analysis and demonstrate how the system works. In order to further improve this approach, future research must be directed towards the integration of the triple perspective: ecological, economic and social.

Appendix A. The set of relationships.

Relationship	Description
defines	Defines the type of resources and processes associated to the product
evaluates	Searches resources and processes to establish the pathway
validates	Confirms the pathway proposed
provides	Links a resource provider and resource consumer
canProcess	Defines type of inputs and the associated outputs
hasPathway	Links agent for integration regarding the use of resources and processes in different industries
isDefinedBy	Receives a definition of the type of resources and processes associated to the product

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