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

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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 (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

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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 multicriteria 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),