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A holonic framework for managing the sustainable supply chain in emerging economies with smart connected metabolism

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ABSTRACT

Since their origins, human societies have integrated into the natural environment, where social metabolism that identified the interactions between society and nature was established. This social metabolism enables the flows of energy and materials between social and natural environments to be analyzed and quantified. However, in the last century, many societies have undergone a transformation from an agricultural to an industrial system. Thus, labour, as a generator of economic capital through the supply chain, has provoked a loss of natural and social capital, especially in emerging economies, thereby generating the metabolic rift. This situation can be mitigated and reversed through a circular economy, the use of digital and technological enablers of Industry 4.0 and the incorporation of an organizational enabler such as the holonic paradigm. The integration of these enablers has given rise to the development of the cyber-physical holon, which incorporates inherently sustainable concepts and allows the analysis of distributed complex systems. This paper proposes a holonic framework for multiscale and multilevel Adaptive and Integrated Sustainable Supply Chain Management (AISSCM). This framework supports a smart connected social metabolism integrated within the natural environment and oriented towards mitigation and reversal of the metabolic rift, through the processes of adaptation and integration to enable the co-evolution of the supply chain within the environment. The framework developed is applied to a family of products through their sustainable supply chain based on circularity. This proposal is developed to enable the necessary transition towards sustainable societies.

1. Introduction

The localization in emerging economies of a large part of activities that constitute the supply chain (SC), such as extraction, production and manufacturing, makes it necessary to recognise those countries as key elements in carrying out sustainable development initiatives (Jia et al., 2018). However, the development and implementation of sustainable supply chains (SSC) in emerging economies involves many difficulties, owing largely to the existence of several barriers (Katiyar et al., 2018), such as technological, economic, political and resource barriers and the lack of sustainable innovation (Kusi-Sarpong et al., 2018) and of infrastructure that supports the reverse SC, such as reverse logistic and recycling processes (Govindan et al., 2015). The triple bottom line (TBL) is a concept that has emerged to help towards achieving sustainability, where social, economic, and ecological aspects are integrated and assessed across the SC (Ahi and Searcy, 2015). Along these lines, sustainable supply chain management (Seuring and Müller, 2008) is understood as the management of material, economic, and informational flows with the aim to integrate the TBL perspective into organizations, reduce negative consequences and generate opportunities in economic, ecologic and social capital (Genovese et al., 2017; Gómez-Luciano et al., 2018; Jia et al., 2018).

The SSC has been addressed from many approaches, including those of life cycle assessment (LCA) (Matos and Hall, 2007), C2C (Kalogerakis et al., 2015), material flow analysis (MFA) (Zaghdaoui et al., 2017), input-output (Kjaer et al., 2015) and symbiosis (Leigh and Li, 2015). According to these studies, and taking into account their characteristics and complexity, the study of sustainability needs to be approached from a holistic perspective, by considering emergent areas, such as the circular economy, social metabolism and metabolic rift (bioinspired analogy).

One subject open to research is that of the goodness of analogy as a form of inspiration in the natural field of solutions to technical problems (Golubiewski, 2012; Isenmann, 2003; Wells, 2006), which enjoys a great tradition from several domains: physical, molecular, biomolecu-

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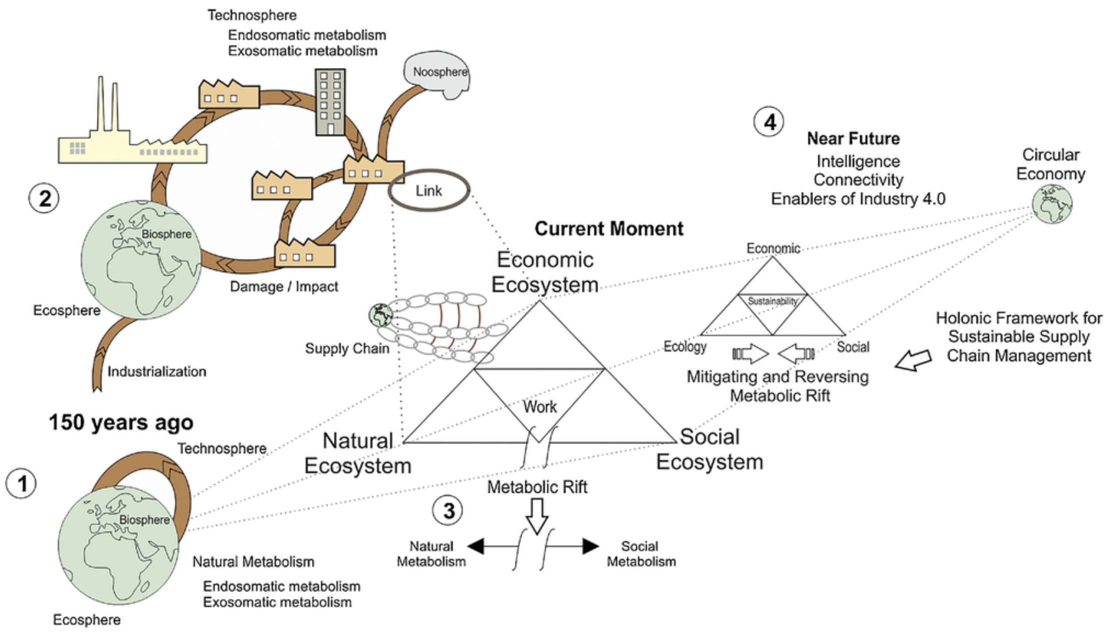

Fig. 1. Strategy for mitigation of the metabolic rift.

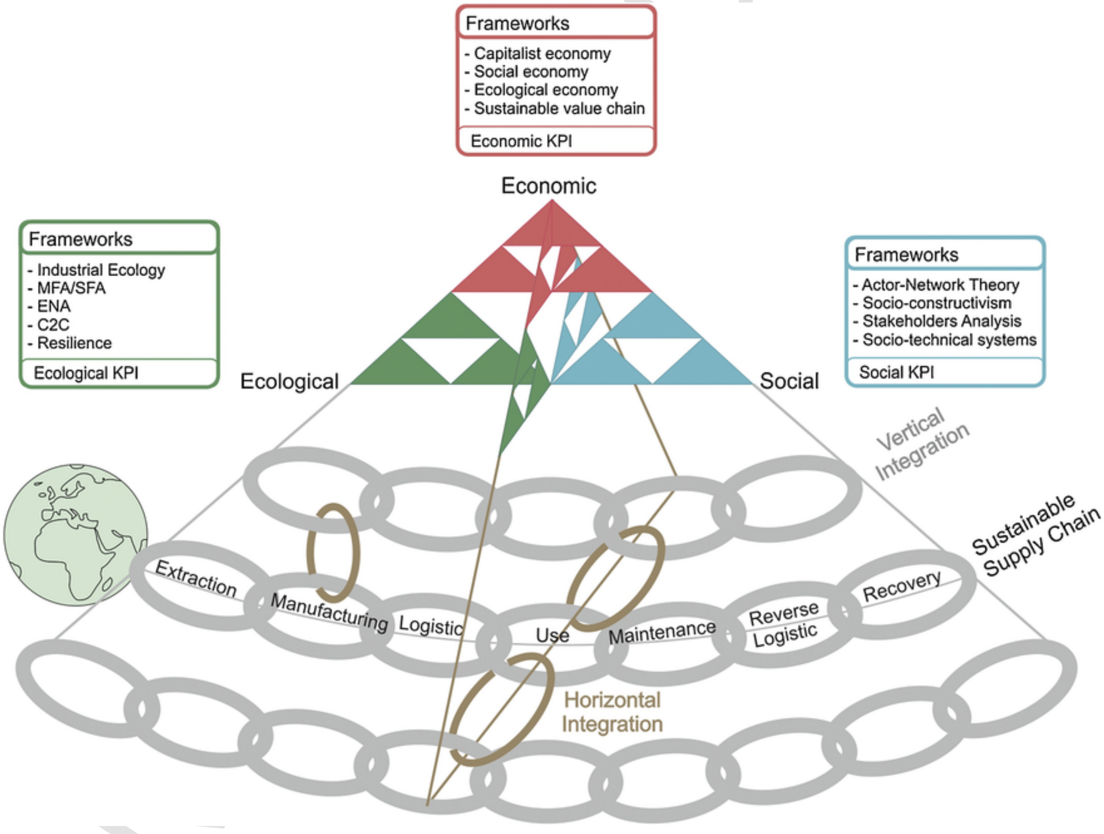

Fig. 2. Framework for integration through the sustainable supply chain.

lar, biological, social and ecological. All of these fields present high complexity as sources of inspiration (isomorphic and holomorphic in the algebraic sense). This determines many possibilities for the mapping of solutions in the domain of design inspired by the natural domain (given its complexity) and justifies the interest of its evaluation in terms of validity, uncertainty, imprecision, optimality and time dependency (Azevedo et al., 2014; Kropat et al., 2016; Kropat and Weber, 2018; Mahapatra et al., 2013; Pervin et al., 2018), which may be addressed with computer tools such as approximate sets (uncertainty), probabilistic methods (vagueness), classic techniques and soft computing for optimization. Based on this interpretation, the interest in organizing the production of the SC from the holonic paradigm as a bioinspired model is identified, thereby allowing the creation of opportunities from the TBL under the principles of the circular economy.

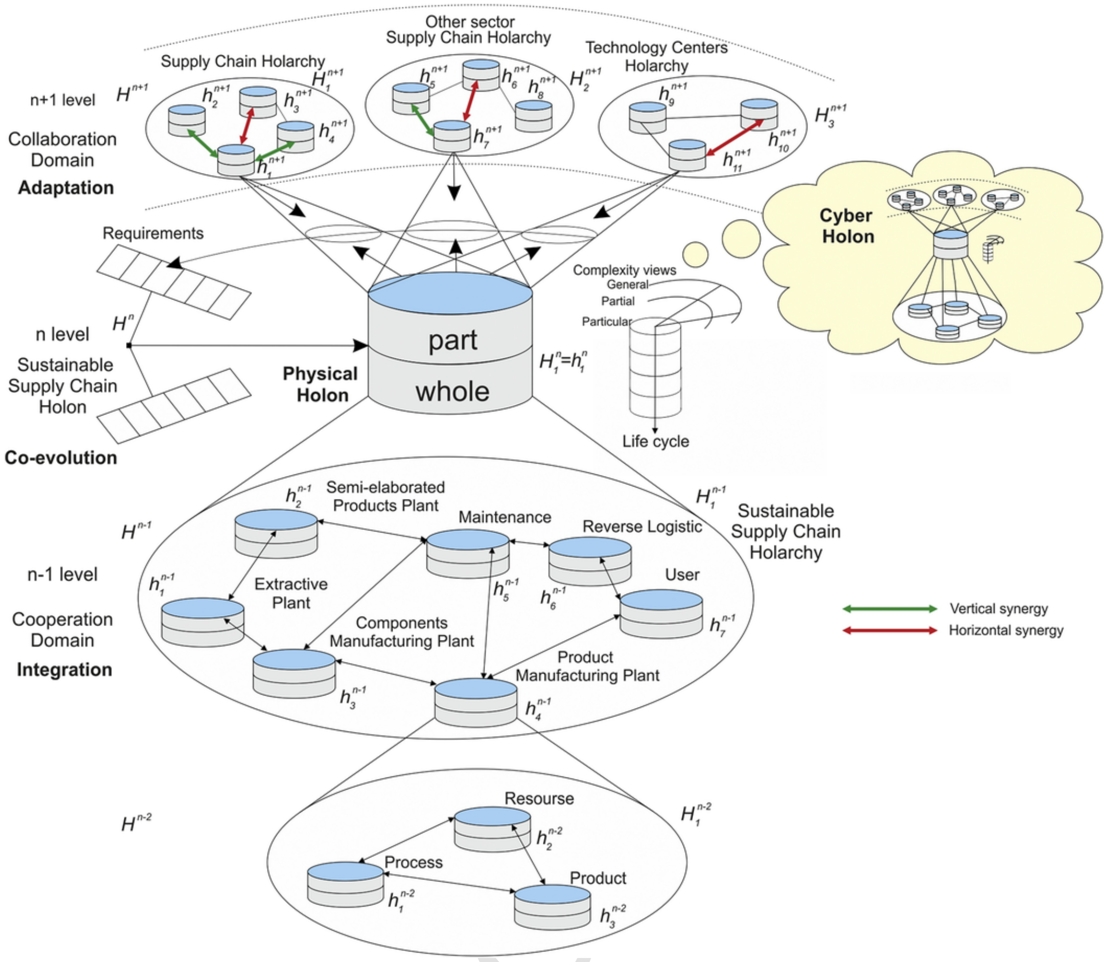

Fig. 3. Holonic framework for the Adaptive and Integrated Sustainable Supply Chain Management.

The concept of social metabolism (Marx, 1976) considers the relationship between mankind and nature through work as the engine that determines the exchange of materials and energy of the productive conglomerates from the economic and productive importance of the capitalist system (Ayres and Ayres, 2002). This concept determines a separation between natural and social capital that is initially metabolically bound, thereby giving rise to the metabolic rift (Foster, 2000, 1999) between the biosphere and the socio-sphere, which is mediated and determined by the technosphere that constitutes industrial capital. The metabolic rift generated means a loss of social and environmental capital.

Social metabolism, based on the biological and physiological notion of metabolism, is applied to the research of the relations between nature and society, through the characterization and quantification of substance and energy flows that are exchanged between a specific territory and society (González de Molina and Toledo, 2014). From this analogy, the SC is viewed as a way of organizing the various elements through the synthesis and degradation of materials and substances. This concept regarding its application to industrial sectors is named industrial metabolism (Ayres, 1994; Wassenaar, 2015).

Currently, a global transformation is under way which includes a significant increase of the metabolic profile of the global economy (material and energy flows) and considerable changes in worldwide extraction systems towards new locations (mainly in developing countries) (Muradian et al., 2012; Pauliuk and Hertwich, 2015). The study of social metabolism identifies the relationship between the socio-environmental and economic strife in territories of resource extraction, particularly in regions with ecologically sensitive ecosystems (Krausmann et al., 2008). The circular economy can contribute towards reducing the rift between underdeveloped resource-rich regions and the developed regions, thereby creating possibilities for the improvement of the distribution of economic resources at different levels and scales (Schroeder et al., 2018; Zeng et al., 2017). Opportunities from the circular economy ensure that all processes in the SC are oriented towards seeking minimization of the negative externalities, in addition to providing local community development (Oliveira et al., 2018). The adequate understanding of the cost of externalities (Prieto-Sandoval et al., 2018) permits environmental, economic and social externalities to be integrated into decision-making (Breure et al., 2018), on different geographical scales (developed, developing and underdeveloped economies) and levels of operational granularity (macro-supply chain, meso-industrial park and micro-plant).

Therefore, this paper addresses the following research questions: (i) How can the SSC contribute towards mitigating and reversing the metabolic rift? (ii) Which are the requirements, from the circular economy, the holonic paradigm and Industry 4.0, for the successful management of the SSC?

The main contributions of this research include: identification of the requirements to achieve an SSC; establishment of a conceptual framework for management of the SSC from the circular economy, with the aim of mitigating and reversing the metabolic rift existing in emerging economies; and the development of a holonic framework for multiscale and multilevel AISSCM that supports social metabolism integrated within the natural environment, from the informational perspec-

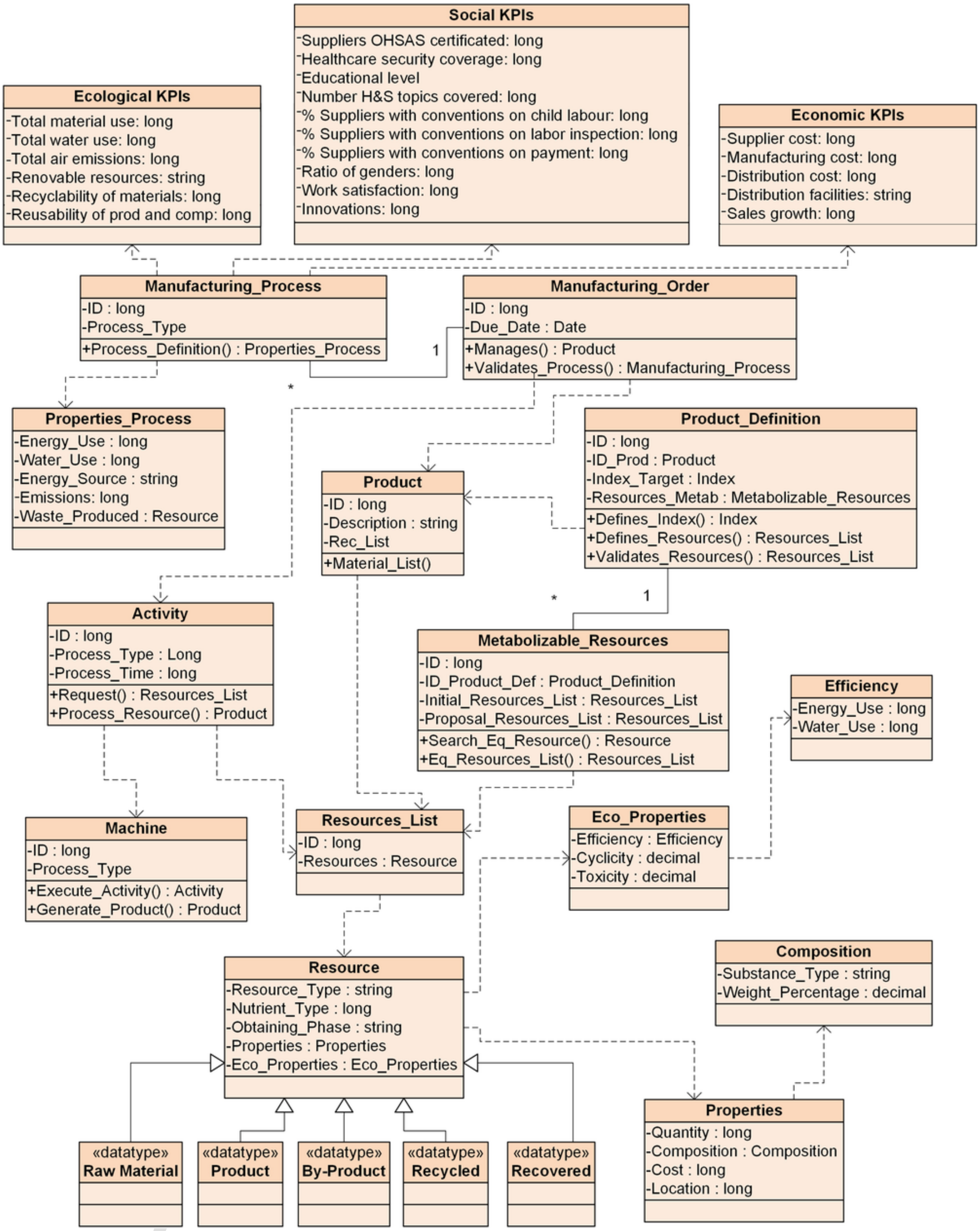

Fig. 4. Common ontology for sustainable supply chain.

tive and the opportunities of Industry 4.0 (Stock and Seliger, 2016). This research is unique, compared with other studies, (e.g. (Giret and Salido, 2017), since it considers the holonic paradigm as an organizational enabler to manage the complexity of the SSC and contributes towards research on SSC and emerging economies (Kusi-Sarpong and Sarkis, 2017).

This work is organized as follows. Section 2 provides the main concepts developed and their relationships with the SC for the characterization of the framework proposed. Section 3 describes the conceptual framework and its requirements for the support of the AISSCM. Section 4 describes the holonic framework developed to achieve the AISSCM. Section 5 sets out a case study, based on the framework above, in which metabolic pathways are identified according to the life cycle of the products, through the SC. Finally, Section 6 presents the conclusions and outlook.

2. Background of the literature

In this section, a review is carried out of the main concepts taken into account in this work. The aim is to identify the requirements, the organizational paradigm and enablers employed for the establishment of a conceptual framework for the SSC.

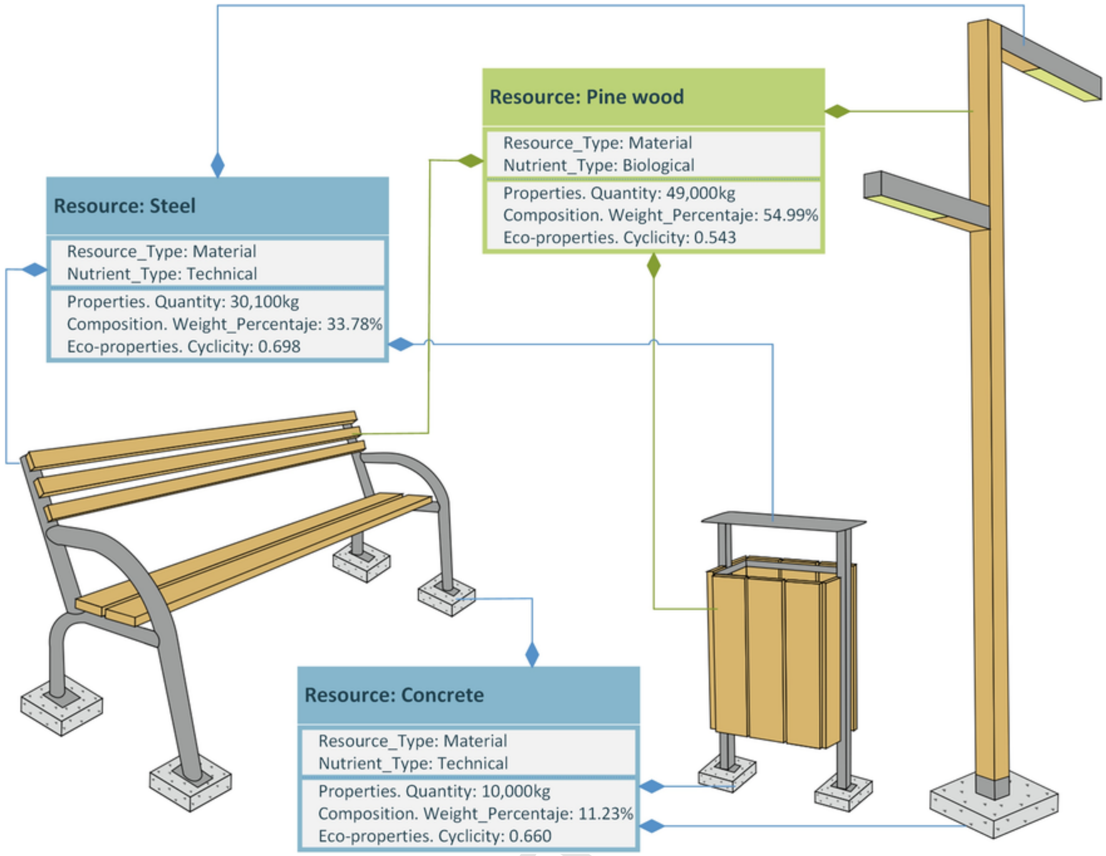

Fig. 5. Common ontology applied to a family of products.

Table 1
Integral flow intensity matrix (*N*).

N	h_1^0	h_8^0	h_9^0	h_{14}^0	h_6^0	h_{15}^0	h_{12}^0	h_{13}^0	h_{11}^0
h_1^0	0.7265	−0.4332	0.1355	−0.0918	0.0204	0.0179	−0.0920	−0.0865	0.0188
h_8^0	0.3146	0.4981	−0.1558	0.1056	−0.0234	−0.0206	0.1057	0.0995	−0.0216
h_9^0	0.1438	0.2277	0.5787	−0.2440	0.2350	0.0477	−0.0584	0.1304	0.0119
h_{14}^0	0.1190	0.1885	0.2936	0.4982	−0.2588	0.1002	0.1432	−0.0445	−0.0293
h_6^0	0.0248	0.0392	0.2850	0.2578	0.4937	−0.0525	−0.2016	0.1749	0.0412
h_{15}^0	−0.1190	−0.1885	−0.2887	0.4976	0.2587	0.9006	−0.1485	0.0487	0.0304
h_{12}^0	0.1476	0.2337	0.0829	0.1761	0.2447	−0.0342	0.4682	−0.2864	−0.0957
h_{13}^0	−0.1670	−0.2644	0.2387	0.0705	0.2681	−0.0136	0.3625	0.6142	−0.0741
h_{11}^0	0.0738	0.1168	0.0414	0.0880	0.1223	−0.0171	0.2341	−0.1432	0.9521

Nodes: h_1^0 Wood Holon (extractive). h_8^0 Component Manufacturing Holon. h_9^0 Product Manufacturing Holon. h_{14}^0 Outbound Logistics Holon. h_6^0 Consumer Holon. h_{15}^0Reverse Holon. h_{12}^0 Classification Holon. h_{13}^0 Recycling Holon. h_{11}^0 Dump Holon.

Table A1
Direct flows between each pairs of holons and between holons and the external environment.

Flow(t)	h_1^0	h_8^0	h_9^0	h_{14}^0	h_6^0	h_{15}^0	h_{12}^0	h_{13}^0	h_{11}^0	z_i
h_1^0	0	0	0	0	0	0	0	0	15,000	100,000
h_8^0	100,000	0	0	0	0	0	0	58,358	0	0
h_9^0	0	90,000	0	0	0	17,642	0	0	0	0
h_{14}^0	0	0	89,100	0	0	0	0	0	0	0
h_6^0	0	0	0	89,100	0	0	0	0	0	0
h_{15}^0	0	0	0	0	17,820	0	0	0	0	0
h_{12}^0	0	1,000	900	0	71,280	178	0	0	0	0
h_{13}^0	0	0	0	0	0	0	58,358	0	0	0
h_{11}^0	15,000	0	0	0	0	0	15,000	0	0	0

Nodes: h_1^0 Wood Holon (extractive). h_8^0 Component Manufacturing Holon. h_9^0 Product Manufacturing Holon. h_{14}^0 Outbound Logistics Holon. h_6^0 Consumer Holon. h_{15}^0Reverse Holon. h_{12}^0 Classification Holon. h_{13}^0 Recycling Holon. h_{11}^0 Dump Holon.

Table A2
Direct flow intensity matrix (D).

D	h_1^0	h_8^0	h_9^0	h_{14}^0	h_6^0	h_{15}^0	h_{12}^0	h_{13}^0	h_{11}^0
h_1^0	0	−0.8696	0	0	0	0	0	0	0
h_8^0	0.6315	0	−0.5683	0	0	0	−0.0063	0.3685	0
h_9^0	0	0.8361	0	−0.8277	0	0.1639	−0.0084	0	0
h_{14}^0	0	0	1.0000	0	−1.0000	0	0	0	0
h_6^0	0	0	0	1.0000	0	−0.2000	−0.8000	0	0
h_{15}^0	0	0	−0.9900	0	1.0000	0	−0.0100	0	0
h_{12}^0	0	0.0136	0.0123	0	0.9717	0.0024	0	−0.7955	−0.2045
h_{13}^0	0	−1.0000	0	0	0	0	1.0000	0	0
h_{11}^0	0	0	0	0	0	0	0.5000	0	0

Nodes: h_1^0 Wood Holon (extractive). h_8^0 Component Manufacturing Holon. h_9^0 Product Manufacturing Holon. h_{14}^0 Outbound Logistics Holon. h_6^0 Consumer Holon. h_{15}^0Reverse Holon. h_{12}^0 Classification Holon. h_{13}^0 Recycling Holon. h_{11}^0 Dump Holon.

2.1. Social metabolism of emerging economies

In order to achieve a sustainable transition in emerging economies, it is necessary to delve into the current metabolic transition and its potential. The global transition from an agricultural model to an industrialized model is both connected to a huge increase in resource use (Krausmann et al., 2018) and to an increase in local and global environmental pressure (Krausmann et al., 2009). The industrialization of the regions triggers an expansion in the size of the socioeconomic metabolism and provokes a characteristic alteration in the patterns of use of materials, independently of the political and economic conditions (Krausmann et al., 2016). Several proposals are identified from among the various theoretical proposals on ecosystem management of the ecosphere, which make use of the multiscale and multilevel analysis of socioecological systems to formulate sustainability (Liu et al., 2011; Li et al., 2016).

Regarding the methods for the analysis of complex systems, analogies derived from the various domains and levels that determine specific phenomenology and emergent properties can be explored. Thus, from the biological domain, different kinds of networks can be found. On the one hand, at microscopic level, there are genetic regulatory networks (Luo et al., 2017), protein networks (Sharan and Ideker, 2006), neural networks (Khoshroo et al., 2018), micro-architectured networks (Kropat et al., 2018), regulatory networks (Özmen et al., 2017), and dynamic gene-environment networks (Kropat et al., 2011), among others, whose structures, properties and evolutionary dynamics in interaction with the environment are modelled through formalisms. On the other hand, at a higher level of organization, one can find communication and information networks (internet network, telephone networks, etc.) (Ahmed et al., 2017), social networks (friendships, sexual contacts, scientific collaborations, spread of diseases, etc.) (Scott, 2017; Wasserman and Faust, 1994), and economic networks (Özmen et al., 2013), among others. Likewise, methods based on stochastic optimal control (Savku and Weber, 2017; Temoçin and Weber, 2014), system dynamics (Pedamallu et al., 2012) and optimization through gene-environment networks (Uğur and Weber, 2007) treat the complexity of the systems from the interaction of diverse components for their application in engineering, global financial networks, biological networks, food networks, and manufacturing systems. According to this review, this research focuses on the selected modelling formalisms derived from the biological domain at ecosystem level in line with the frameworks of recent research in industrial metabolism and industrial ecology (Meerow and Newell, 2015; Saavedra et al., 2018), and hence relevant studies in social metabolism that are significant in the modelling of SSC are analyzed below.

Social metabolism is analyzed using quantitative and qualitative methods. One of the first approaches to understand and analyze metabolisms is through the use of indicators at national, regional, or industrial park level (Dai et al., 2012). These indicators are developed based on assessment methods (Viglia et al., 2017) such as MFA, LCA, emergy analysis, embedded energy, CO2 emissions and input-output models, whereby quantification of the metabolic process is sought. This allows metabolic profiles to be identified of a region (extractive patterns, commerce and use of resources), whose aim is to analyze the state and inertia of the global metabolic system in the face of sustainable transition (Schaffartzik et al., 2014). However, these indicators alone or together do not provide a model for the assessment of the complete system and for the closure of the loop and feedbacks that are inherent in the circular economy. Additionally, social and economic factors of the system cannot be omitted from the analysis (Robalino-López et al., 2015; Yao et al., 2015).

Relating to qualitative methods, Yao et al. (2015) consider social, natural and economic subsystems of a larger system with multiple connections, where regional metabolism complexity is analyzed through a qualitative network model. Another quantitative and qualitative method identifies various factors of the natural, economic and social domain to analyze the metabolism from the perspective of network complexity (Wang et al., 2011). Likewise, Ecological Network Analysis (ENA) (Fath, 2007) is employed at industrial level to model the industrial ecosystem as a network of nodes, pathways between those nodes, and flows along those pathways. Therefore, ENA is applied for the identification and analysis of metabolic paths at industrial ecosystem level (Martín-Gómez et al., 2018; Zhang et al., 2017). Along these lines, and based on network analysis, the SC constitutes a key element for the monitoring and management of the complexity of the elements of the system, in accordance with its structural complexity and diversity (Cheng et al., 2014).

According to the aforementioned studies, the necessity of integrating social, ecological, and economic perspectives of the TBL approach across SCs is identified (Das, 2018; Herczeg et al., 2018; Padhi et al., 2018). Likewise, mechanisms of management for sustainability are incorporated that promote SC effectiveness, such as costs, risks, transactions, stakeholder issues (Dubey et al., 2018), and the relationship between local communities and SC (Jia et al., 2018). This allows to be addressed, since proposed models where there are defined metrics (Zhang et al., 2018a, 2018b) and indicators to evaluate the management of sustainability (Gómez-Luciano et al., 2018). Furthermore, the continuous changes in the environment in which the SC is developed means that it must possess the capacity to adapt (Jadhav et al., 2018), so that it can co-evolve with the environment, thereby enabling its survival (Morita et al., 2018).

Although the concept of socioeconomic metabolism was elaborated in the context of MFA, this concept could be employed as a paradigm for the analysis of the biophysical bases of society (Pauliuk and Hertwich, 2015). This enables the combination and integration of sustainable interdisciplinary development strategies. The SSC is required to understand, model and manage the flows of social metabolism on different levels and scales (Zhang et al., 2018a, 2018b).

2.2. Enablers for SSC

In order to achieve the integration, adaptation and management of the SSC, connectivity is necessary to collect and process data through various links of SSC (Man and Strandhagen, 2017). Industry 4.0 reflects the digital transformation of the manufacturing environment, whereby digital value chains enable the connectivity among smart factories, smart products and the environment (Dallasega et al., 2018). Continuous advances in information and sensor technologies promote the linkage between the cyber and the physical environments. The cyber-physical system (CPS) is designed to handle the system itself in the physical environment while at the same time monitoring it in the cyber environment (Monostori et al., 2016). At manufacturing level, a cyber-physical production system (CPPS), which makes the factory more adaptable (Wang et al., 2015), will enable that industry to develop networks that include processes, products, machineries, warehouse and SC in the form of a CPPS (Martín-Gómez et al., 2017).

According to Babiceanu and Seker (2016), with respect to the cyber system, virtualization in a manufacturing system is viewed as a process of interconnection where the physical manufacturing process has a virtual copy in the cloud, and hence several virtual platforms can collaborate across different physical environments. Therefore, the Industry 4.0 initiative provides enormous opportunities for the fulfilment of a high degree of customization of products and services, for flexibility, optimization of decision-making, efficiency in the use of resources, and creation of new business opportunities, that are linked to the evolution of society and market competitiveness (Kagermann et al., 2013).

At manufacturing level, Industry 4.0 requires the incorporation of the following characteristics (Stock and Seliger, 2016; Tjahjono et al., 2017): (i) horizontal integration across the SC; (ii) vertical integration and networked manufacturing system; (iii) digital integration of engineering through the SC; (iv) through-life engineering support through the SC; and (v) adaptation by exponential technologies. Thus, to achieve connectivity in the AISSCM, Industry 4.0 can be applied to enable its implementation in emerging economies (Luthra and Mangla, 2018). The current situation, which lacks authentic implementation, must be managed with the inclusion of technological and digital enablers (Lu, 2017), such as the Internet of Things, CPS, cloud computing, big data, embedded computing, information and communications technologies, ubiquitous technologies, and organizational enablers such as fractal, holonic and bionic paradigms.

Recently, the opportunities of Industry 4.0 in several sectors and the advances in its implementation have been highlighted in sectors, such as logistics management (Hofmann and Rüsch, 2017), industry (Stock and Seliger, 2016), the construction industry (Oesterreich and Teuteberg, 2016) and SC (Ivanov et al., 2016). In line with these advances, their evolution towards connected SC, which links sectors under the same framework, may be carried out through digital, technological and organizational enablers (such as the holonic paradigm), in the context of CPPS, which already exist in the diverse sectors that form social metabolism.

2.3. Holonic paradigm as an organizational enabler

The principles of the holonic paradigm were defined by Koestler (1967). The most remarkable principles are that a holon is simultaneously part and whole and is part of a holarchy formed by holons; holarchies are naturally oriented towards collaboration and a holon is the union of a physical and an informational part.

The literature includes a large variety of approaches of Koestler's concepts. In the field of manufacturing systems, at micro level, two main architectures have been proposed: PROSA (Van Brussel et al., 1998), which is basically an interholonic architecture, defines the classes of holons required for any production system as order, product, and resource holons; and ADACOR (Leitão and Restivo, 2006), which developed a holonic approach oriented towards dynamic adaptation in flexible manufacturing systems where disturbances exist. In addition, there is an evolution of the ADACOR architecture (Barbosa et al., 2015) inspired by biological and evolutionary theories, regarding the use of concepts of self-organization. Another approach is that of the HCBA (Chirn and McFarlane, 2000), whose product holon can contain a physical part and a controlling part.

Within CPPS, Wang and Haghighi (2016) present an approach for the implementation of CPS using the combined strength of holons, agents, and function blocks, with the aim of easing system execution in a decentralized environment. Another approach is related to an implementation framework of cloud-based holonic control architecture for CPPS (Quintanilla et al., 2017). In yet another study, an adaptive holonic architecture for distributed manufacturing control is developed (Gräßler and Pöhler, 2017).

Holonic architecture is identified as an adequate paradigm for modelling the SC owing to its capacity for organization (Dev et al., 2014) and management of complexity (Peters and Többen, 2005). Holonic architecture has largely been applied, in the SC, to improve flexibility and efficiency in manufacturing environments (Marcellino and Sichman, 2010; Ulieru et al., 2002) and for transportation and warehousing (Tuzkaya and Önüt, 2009), although certain studies are also dedicated to green SC (Giret and Salido, 2017). However, to the best of our knowledge, there is no research on holonic SSC from TBL.

In general, studies on holonic sustainable architectures remain in an emergent stage. Among them can be cited the Go-green holon concept (Trentesaux and Giret, 2015) and its implementation as Go-green ANEMONA (Giret et al., 2017), which provides sustainability features in manufacturing operation control architectures. Another interesting study is that involving the reference holonic architecture for sustainable distributed manufacturing enterprises (Ávila-Gutiérrez et al., 2017), which is a holonic architecture that integrates economic, social, and environmental aspects. Additionally, architectures based on structures of social and biological inspiration have been developed (Esmaeili et al., 2017).

3. Conceptual framework for AISSCM

Based on the review carried out, the SSC presents an adequate level of aggregation (Genovese et al., 2017) to achieve the necessary equilibrium of social, natural, and economic performance from circular economy principles (Kazancoglu et al., 2018; Zeng et al., 2017). This motivates the establishment of a conceptual framework for the mitigation of the metabolic rift from the paradigm of the circular economy through the integration of the links of the SC with other SCs (Herczeg et al., 2018), thereby providing itself with mechanisms of self-regulation from the pillars of sustainability (Barbosa-Póvoa et al., 2018), which in turn allow co-evolution with the natural and social environment. To this end, an integrated social metabolism on the biosphere and the technosphere (Pauliuk et al., 2015) must pursue a triple sustainable objective (Céspedes Restrepo and Morales-Pinzón, 2018), while taking into account principles under the flows, type of the substances, their intensity and scalar or synthesis principles. These can be stated as: *cyclicity* (waste equals raw material), on the biosphere (biological metabolism), on the technosphere (technical metabolism), *harmlessness* of substances that integrate the flows or absence of toxicity, enabling the highest rate of biological metabolism and *efficiency* of water, energy and material flows (Bach et al., 2018; Braungart et al., 2007).

Supply chains provoke the metabolic rift, as is shown in Fig. 1, owing to the co-evolutionary growth and development with the environment through metabolic processes without integration through human action, such as the ability to relocate operations of the SC in emerging countries, which includes vulnerability of these regions and their citizens (Belal et al., 2015). This determines: (i) a separate metabolism of natural and social ecosystems; (ii) a loss of value of the natural ecosystems (natural capital) and social ecosystems (social capital) in the creation of an ecosystem of economic value (industrial capital), with an emphasis on exchange value; and (iii) a loss of resilience of ecosystems owing to loss of diversity, efficiency, adaptability and cohesion.

Sustainability, as an aspect of an ecosystem, maintains its identity, stability, growth and development in a co-evolutionary way with the environment through integrated metabolic processes. The circular economy (Geissdoerfer et al., 2017), as a paradigm to achieve the sustainable development of the SC management (Geissdoerfer et al., 2018), establishes a set of integrated frameworks and strategies from the TBL (Kalmykova et al., 2018). According to those authors, the circular SSC contributes towards the development of emerging economies in a quadruple way: (i) by improving the products and services associated with the SC in its economic, social and environmental aspects, which are in demand in the markets of developed countries, thereby permitting business opportunities for the emerging economies; (ii) by mitigating the metabolic rift by obtaining productive, logistic and reverse manufacturing systems with less consumption of non-toxic materials, energy and water and a greater social and economic well-being per product unit generated by emerging economies; (iii) by avoiding or reducing the cost of externalities incurred by the economies of developed countries with the consumption of raw materials from developing countries; and (iv) by establishing a local culture of sustainability through practices of consumption and uses of products and services socio-environmentally integrated, through cyclicity, harmlessness, efficiency and diversity. All the aforementioned aspects must be considered while taking nature as a model, measure and mentor in the interaction between natural and artificial ecosystems (Benyus, 1997).

Digital and technological enablers (big data, internet of things, ubiquitous computing, cloud computing, smart sensors, connectivity, M2M, etc.) configure delocalized, distributed, heterogeneous and diverse ecosystems in an analogous way that are compatible with natural ecosystems. The potential of these technologies, characterized as interoperability, decentralization, virtualization, modularity, real-time capability and service orientation (Kamble et al., 2018), is focused in the way of conceiving value from a linear or scarcity economy to a circular or resource abundance economy (Lieder and Rashid, 2016). Digital and technological enablers together with organizational models of productive systems under fractal, holonic and bionic orientation, allows ecosystems to be designed in the technosphere. Not only can this ecosystem cooperate in the creation of economic, ecological and social value through the SSC, but it can also be managed dynamically thanks to its monitoring in real time, in a way that allows the quality of the sustainability to be improved from the principles of continuous improvement (Luthra and Mangla, 2018).

It is necessary to have a framework, see Fig. 2, to carry out the engineering of SSC under the TBL perspective with sustainable key performance indicators (KPI) (Popovic et al., 2018), established from the circular economy, for the configuration of a resilient integrated metabolism. This resilient metabolism requires the capacity of integration and cohesion of the internal environment and the co-evolution and adaptation to the external environment.

According to the review carried out, the requirements to ensure the success of a SSC are detailed below:

- *Management.* Determination of mechanisms and procedures aimed at mitigating and reversing the metabolic rift from TBL. This management must be oriented towards sustainable product design, environmental procurement, customer collaboration, internal sustainable management, diversity management, community development and safety management.
- *Integration.* The necessary integration of procedures, metrics, information technologies for the improvement of sustainability and business performances and for addressing collaborations through SSC. It requires the definition of collaborative strategic projects and knowledge transfer (common ontology).
- *Adaptation.* Reactive mechanism that ensures the adaptation of the SC to the environment by allowing its co-evolution. From the biological analogy, adaptive capacity is determined by genetic diversity, whose main pillar is innovation, in the form of the variety of the product, innovation in the product, open innovation, culture of innovation, or technological innovation.
- *Connectivity.* This is a fundamental requirement to achieve vertical and horizontal integration through SSC, with the ubiquitous data collection from the extraction of resources to their recovery at their end of life, and through exploitation of the data available.

The holonic paradigm presents an integrated process of interconnectivity. The information flow is distributed across the holons in CPPS. Thus, holonic architecture provides a suitable paradigm to deal with the complexity of social metabolism under the Industry 4.0 perspective and to establish a multilevel and multiscale framework that allows the creation of a platform to develop the fourth industrial revolution, with the aim of mitigating the metabolic rift.

4. Holonic framework for AISSCM

It should be borne in mind that ecosystems need to be created in the technosphere which is integrated in the natural and social context. This requires a framework to conceive the production and service systems in a way that cooperate with the natural systems in obtaining the TBL. Hence, they are not only compatible statically but also evolutionarily. Moreover, they must support the processes of evolution and improvement of production systems and acquire a compromise between effectiveness and efficiency (Cheng et al., 2014; Reed, 2007).

All these reasons, linked to enablers of Industry 4.0, justify the proposal for a holonic framework for the connected AISSCM with a bioinspired orientation, which supports the multiscale and multilevel aspects of sustainability. This can therefore enable the evolutionary compatibility between the technosphere and the biosphere. The reference holonic architecture for sustainable distributed manufacturing enterprises (Ávila-Gutiérrez et al., 2017) is considered as the foundation for the development of the holonic framework for the connected AISSCM.

4.1. Holonic principles

Entities are articulated to form holonic structures based on fundamental principles:

- *The reality consists of holarchies*. Holarchies are structures that refer to any bio-social organization with a certain degree of coherence, dynamic stability and harmony; they present an order in which, in general, certain principles or laws are applied at every level of its holarchical organization and the entities that constitute said organization are called holons. A holarchy is an open multilevel structure self-regulated between processes and products. Holarchy is formalized, through BNF notation, by holons as whole or dual basic entities (*holon/w*), by relationships between holons as part of an entity

(*holon_relationships/p*) and the rules and behavioural strategies that constitute the canon, along with the strategy of the whole holarchy (*str_c*). A holarchy is defined as *<holarchy>::= <<holon/w> <holon_relationships/p><str_c>*.
- *Holons are twofold entities.* Each element of the network is constituted by an entity called a holon, which is simultaneously a whole entity and a part, which, in turn, is part of a holarchy formed by holons.
- *Every holarchical matrix is fractal.* The holon and its relations with other holons constitute the holarchical matrix to which it belongs. The basic entity is represented by the holon at level n, holarchy of level $n+1$ and of level $n-1$, as shown in Fig. 3. Holarchy has a fractal character as the product, process and resource. It is integrated by the entities (product), the strategies and procedures (processes) to encapsulate the complexity, and machinery, equipment, facilities and infrastructures (resources), together with the relations of collaboration between holons of level n and holarchy of level $n+1$, determined by different flows. These three entities compose each link of the SC.
- *Multiscale and multilevel.* In the characterization of hierarchical structures of complex systems, relationships are established in: (i) levels of granularity of the structural organization, such as *micro* level (products, processes and organizations), *meso* level (eco-industrial parks and industrial district) and *macro* level (SC), whereby emerging relationships appear between the different levels; and (ii) geographical scales, that distinguish between city, region, nation and beyond and from industrialized countries to emerging economies (Kirchherr et al., 2017; Liu et al., 2017; Pulido Barrera et al., 2018).

4.2. Holon properties

Every holon is characterized by a set of properties:

- *Whole and part*: a holon (at '*n*' level of analysis) can be part of another holon or it can integrate different holons or holarchies in harmonic interaction, which constitute domains of collaboration (*Dcollab*, at level $n+1$) or cooperation (*Dcoop*, at level $n-1$). This is defined as *<holon>::=<<holon/w><holon/p>>*.
- *Autonomy*: a holon possesses the capacity to generate and manage the execution of its own strategies in a self-regulated way.
- *Collaboration*: a holon can be integrated into one or more higher-level holarchies, called domains of collaboration, thereby forming holarchies of level $n+1$; this is a property of the holon in terms of its expression as a part, for example the improvement through the SC based on vertical and horizontal synergies. This allows the holon to adapt to the environment.
- *Cooperation*: a holon can integrate other holons and processes in which a set of entities jointly make acceptable plans to develop a function, for example the improvement of the key performance indicators, from the TBL approach, at factory level.
- *Self-regulation*: a holon is endowed with the capacity to change its way of cooperating 1in order to develop a function, thereby gaining resilience. The holon evolves with the environment through the parameters established in the TBL.

The holon possesses a life cycle that is structured in three dimensions, as shown in Fig. 3. These three dimensions are: stages of the *life cycle* (vertical arrow), *views of complexity* (informational, material, energy, efficiency, etc.) and *degrees of specificity* as a particular, partial or general entity according to the degree of concretion or specialization. The holon, as an autonomous entity that interacts with the environment, has regulatory mechanisms in the form of filters and amplifiers, which exist in cooperation and collaboration domains. Through these mechanisms the holon establishes the necessary strategies to make both the adaptation to the variety of the environment and the integration into the environment of the managing organization. Depending on the direction these strategies can be top-down or bottom-up.

A strategy for the integration of the SSC can be structured in the following steps: (i) diagnosis and evolution of the SC; (ii) prospective analysis of the SC; (iii) strategic analysis of the SC; (iv) establishment of sustainable collaborative territorial axes for its implementation; (v) formation of synergistic collaborative clusters for vertical and horizontal integration from the frameworks of the circular economy; and (vi) proposal of indicators of sustainability for sustainable collaborative territorial axes, the SSC and their processes. These relationships are modelled as an emergent relationship of the cooperation domain (integration) that occurs in the domain of collaboration (adaptation).

4.3. Cyber-physical holon

According to the proposed framework for the connected AISSCM, holons are conceived as cyber-physical entities. Within the CPPS, a cyber-physical holon contains a virtual part and a physical part. The cyber part of the logical or informational processing of the holon is integrated with the knowledge regarding addressing the decisions according to the defined goals. Cyber holons are supported by digital enablers that allow real-time data acquisition, and the monitoring, simulation and control of the actions of the physical part through a decentralised control in a cloud environment. Physical holons are composed of technological enablers, such as physical equipment, sensors and actuators. Robots, machining tools and accessories are samples of a holon that has virtual and physical parts. Nevertheless, there are other holons in the manufacturing system, for instance those oriented towards design or calculation, which may be samples of holons that only has a logical or a cyber part.

4.4. Holonic network: the holarchy

The different entities, that constitute the biosphere and the technosphere, are conceptualized from the holonic paradigm as a set of holons and their interactions that constitute their holarchy. From the point of view of trophic chains (Liwarska-Bizukojc, 2009), the SC in the industrial ecosystem can be modelled from a bioinspired approach. This approach gives the composition of the ecosystem where organizations are classified as producers, consumers and decomposers and the relationships are defined. Analogically, a holonic network (SC) is considered as a trophic network, where entities have intra- and inter-specific relationships, whereby the intra-specific relationships are at the cooperation level, and the inter-specific relationships are at the collaboration level. Each holon has its own metabolism and its associated metabolism in the network (ecosystem).

According to the model of social metabolism (appropriation, circulation, transformation, consumption and excretion) (González de Molina and Toledo, 2014), it is necessary to optimize the processes of circulation, transformation and consumption (that occur in the technosphere) and reduce the processes of appropriation and excretion (that take place in the biosphere), with the aim of mitigating the metabolic rift that exists between nature and society.

The interaction network among holons is modelled and illustrated through a diagram in which nodes are the holons and the arrows describe the relationships between holons. The proposed network can be established into the holonic model at several levels: at holarchy level, at cooperation level, and even among different vertical levels. Bearing this in mind, the holarchy is established according to its holons and the relationships between holons (Esmaeili et al., 2017). Consequently, each holon in the same level is denoted by h^{n}_{j}, where n represents the level of the holarchy and j represents the holons that form the holarchy in level n. Eq. (1) defines the holarchy k at level n and the holons that it contains.

$$H^n_k = \left\{ h^n_1, h^n_2, h^n_3, \ldots, h^n_j \right\} \tag{1}$$

A holarchy level n is denoted as H^n, and is composed of k holarchies within the level, according to Eq. (2).

$$H^i = \{H^i_1, H^i_2, H^i_3, \ldots, H^i_j\} \tag{2}$$

Similarly, a holarchy composed of h holarchical levels is named H and described in Eq. (3).

$$H = \{H^0, H^1, H^2, \ldots, H^{h-1}\} \tag{3}$$

Each of these components and the relationships between the holons are detailed in the next section.

4.5. Behavioural self-organization based on ENA

The holarchy must be self-organized dynamically and in real-time in order to achieve mitigation and reversal of the metabolic rift. Within this aim, the concept of circularity, which exists in the circular economy (Lieder and Rashid, 2016), reaches a particular importance in the definition of a strategy to be carried out by the holarchy. The circularity of the resources, essential for achieving the improvement of economic, social and environmental aspects in emerging economies (Rashid et al., 2013), is closely linked to the process of circulation into the model of social metabolism for the SSC. Based on the flow of resources (substances, materials, energy, etc.), ENA is employed to analyze the relationships, from an ecological perspective (Fan et al., 2017), between holons in the holarchy. Therefore, natural, social and economic aspects of an industrial ecosystem can be conceptualized as entities in a network and the exchanges between these entities can be considered as pathways (Zhang et al., 2016). From the perspective of the analogy between natural metabolism and social metabolism, the relationship between each pair of holons is modelled as an interspecific relationship (Fath, 2007).

Consequently, the holarchy includes the information that ENA provides to identify and evaluate the metabolic paths. These relationships are established between holons into a holarchy or into several holarchies at the same level (i).

The model is described through the flow matrix F, which contains the direct flow (energy or material) from holon j to holon i (f_{ij}). T_i represents the total flow into holon i and the environmental inputs (z_i), as shown in Eq. (3).

$$T_i = \left(\sum_{j=1}^{n} f_{ij}\right) + z_i \tag{3}$$

The flow intensity matrix D is defined by normalizing the flow matrix F by total flow, whose matrix element is d_{ij}, as is shown in Eq. (4).

$$d_{ij} = (f_{ij} - f_{ji})/T_i \tag{4}$$

The integral flow intensity matrix N can be obtained by using the series described in Eq. (5).

$$N = D^0 + D^1 + D^2 + \ldots + D^m = (D^0 - D)^{-1} \tag{5}$$

Once the matrix N is obtained, the existing relationship between each pair of holons can be identified. According to the sign of each component, through the comparison of n_{ij} and n_{ji} elements of N matrix, the relationship of holon i with respect to holon j is obtained. Thus, positive and negative signs denote exploitation, negative and positive denote control, negative and negative denote competition, and positive and positive indicate mutualism (Martín-Gómez et al., 2018).

The holarchy has the capacity to evaluate various aspects of the ENA obtained in accordance with the KPI: economic (such as costs, and economic performance), social (such as work satisfaction, worker health and safety, and fair wages and treatment), and ecological (such as circularity, harmlessness, and efficiency). The selection of perspective would be based on the importance of the aspect to evaluate in a specific situation.

4.6. Ontology

The ontological model proposed under the holonic framework for AISSCM is shown in Fig. 4. This model describes the ontology and shows the classes, attributes and relations of the specific domain (Gruber, 1993; Raafat et al., 2013), which has been modelled using UML class diagrams. It is structured in accordance with the knowledge regarding the SSC to be shared by every entity involved in the system.

The main classes and sub-classes of the ontology developed are detailed below. *Resource* class contains the resources that are the inputs and outputs of the manufacturing process through the SSC. This class contains the sub-classes: *Resource_Type,* which indicates the type of material, *Nutrient_Type,* which defines a resource as natural or artificial according to its capacity to return to both cycles, *Obtaining_Phase* that describes the process necessary to achieve the resource, *Properties* defines the resource attributes of quantity, cost, location and composition and *Eco-properties* describes the ecological characteristic of the resource in terms of its circularity, harmlessness and performance.

The knowledge associated to the holonic framework must be transversal. Each holon shares knowledge of resources (raw material, product, by-product, recycled material, and recovered component) and of resource attributes (resource type, nutrient type, obtaining phase, properties, and eco-properties) that are the objective of distribution between companies/entities through the SSC. This distribution of resources between holons enables metabolic pathways related with the product life cycle to be identified, based on seeking the pathways that metabolize the resources into the ecosystem (artificial and natural) in an optimal way. In addition, specific knowledge is included, which covers the knowledge for product definition, where resources incorporated into the product are defined and validated. Furthermore, the process and associated flows (energy use, water use, energy source, emissions, and waste produced) for the manufacturing processes are defined.

Regarding KPI, three classes (ecological, social and economic) are defined according to the triple aspect of the TBL. Environmental parameters and associated indicators are included with the aim of enabling the establishment of the ENA and that of decision-making.

5. Case study

The process of annual manufacturing of a family of products of urban furniture through its SC (direct and reverse) is considered. The specification of a family of products is presented according to the ontology developed, where the product resource definition is identified, as shown in Fig. 5. Here, resources and quantities to be incorporated into the products are identified. A total of 89,100 kg of resources are needed for this family, including those for assembly and installation, according to historical data of the company. Its SC is divided into: (i) direct chain, comprised of the wood extractive plant, component manufacturing plant, product manufacturing plant, outbound logistics and consumer (local governments which have sustainable orientation based on the circular economy); and (ii) reverse chain, which is made up of resource classification plant, recycling plant and dump.

The holarchy is defined as *<Holarchy>::= <<SustainableSupplyChain_holon/w> <Symbiotic_relationships/p> <Circularity_of_resources>*, where the sustainable supply chain holon as a whole entity seeks to establish symbiotic relationships within its holarchy as a part of an entity, whose strategy is related to the circularity of resources from the principles of circular economy. Although the study is aimed towards the identification of cycles of material through metabolic paths and towards the analysis of the inter-specific relationships between the various entities that form the SSC, the model can also support social and economic criteria.

The sustainable supply chain holarchy is defined according to Eq. (1) as $H_1^1 = \{h_1^1, h_2^1, h_3^1, h_4^1\}$. Main links of the SC are identified within the holarchy: h_1^1 Extractive Holon, h_2^1 Urban Holon, h_3^1 Industrial Holon, h_4^1 Logistics Holon. The holonic network is developed as a trophic network, where holons are analogically identified as producers, consumers and decomposers. The extractive holarchy is defined as $H_1^0 = \{h_1^0, h_2^0, h_3^0, h_4^0\}$, where holons represent primary producers in the trophic chain (h_1^0 Wood Holon, h_2^0 Oil Holon, h_3^0 Gas Holon, h_4^0 Mining Holon). The urban holarchy is defined as $H_2^0 = \{h_5^0, h_6^0, h_7^0\}$, where holons represent consumers (h_5^0 Urban Transport Holon, h_6^0 Consumer Holon, h_7^0 Commerce Holon). The industrial holarchy is defined as $H_3^0 = \{h_8^0, h_9^0, h_{10}^0, h_{11}^0, h_{12}^0, h_{13}^0\}$, where holons represent secondary producers and decomposers (h_8^0 Component Manufacturing Holon, h_9^0 Product Manufacturing Holon, h_{10}^0 Maintenance Holon, h_{11}^0 Dump Holon, h_{12}^0 Classification Holon, h_{13}^0 Recycling Holon). The logistics holarchy is defined as $H_4^0 = \{h_{14}^0, h_{15}^0, h_{16}^0\}$, where holons represent tertiary producers and decomposers (h_{14}^0 Outbound Logistics Holon, h_{15}^0 Reverse Holon, h_{16}^0 Internal Logistics Holon). In order to simplify this case, only 9 holons are involved in the product life cycle. Firstly, h_1^0 Wood Holon is incorporated as the primary producers in the trophic chain. Secondly, h_8^0 Component Manufacturing Holon and h_9^0 Product Manufacturing Holon are identified as the secondary producers and h_{14}^0 Outbound Logistics Holon is identified as the tertiary producer. The h_6^0 Consumer Holon then represents the consumer. Finally, the decomposers are defined: h_{11}^0 Dump Holon incorporates and manages the waste in an eco-compatible way, h_{12}^0 Classification Holon directs each type of separated resource in order to transfer it to the adequate holon that possesses the capacity to manage that kind of resource, h_{13}^0 Recycling Holon coordinates the process of recycling and tenders recycled resources to other holons, and h_{15}^0Reverse Holon recoups the parts of disposed products to reuse them into other products.

Once the resources of the product and holons have been identified, the metabolic paths can be established in the socioeconomic ecosystem. The holarchy, based on its strategy of circularity, can establish the matrix flow from the associated ontology and the possible relationships at collaboration level. Table A1 in the Appendix shows the direct-flow matrix (*F*), where entries represent the flows from the holons that are indicated on the first row of the matrix to the holons listed in the first column of the matrix.

The direct and integral intensity matrix is obtained from the direct flows (Table A2 and Table 1). The analysis of the direct-flow intensity matrix reveals that eight of the twenty-six pairs identified possess a significant gap in absolute terms: $h_1^0 \rightarrow h_8^0$, $h_8^0 \rightarrow h_9^0$, $h_9^0 \rightarrow h_{14}^0$, $h_{14}^0 \rightarrow h_6^0$, $h_6^0 \rightarrow h_{12}^0$, $h_{12}^0 \rightarrow h_{13}^0$, $h_{12}^0 \rightarrow h_{11}^0$ and $h_{13}^0 \rightarrow h_8^0$. Following the organisation of the pairs, a path appears. This path has its origin at h_1^0 Wood Holon (extractive) and finishes at h_{11}^0 Dump Holon. The path between h_{13}^0 Recycling Holon and the h_8^0 Component Manufacturing Holon, $h_{13}^0 \rightarrow h_8^0$, should also be highlighted. These paths show the flow intensity through holons and set the principal path.

Through the comparison of the sign of each pair of nodes (n_{ij} and n_{ji},) the inter-specific relationships between holons are obtained from matrix *N* (Table 1). The following pair of holons have a relation of exploitation of *i* with respect to *j*: h_8^0 $(n_{8\text{-}1}, n_{1\text{-}8}) = (+,\text{-})$, h_8^0 $(n_{8\text{-}13}, n_{13\text{-}8}) = (+,\text{-})$, h_9^0 $(n_{9\text{-}8}, n_{8\text{-}9}) = (+,\text{-})$, h_{14}^0 $(n_{14\text{-}9}, n_{9\text{-}14}) = (+,\text{-})$, h_6^0 $(n_{6\text{-}14}, n_{14\text{-}6}) = (+,\text{-})$, h_{12}^0 $(n_{12\text{-}6}, n_{6\text{-}12}) = (+,\text{-})$, h_{13}^0 $(n_{13\text{-}12}, n_{12\text{-}13}) = (+,\text{-})$, h_{11}^0 $(n_{11\text{-}12}, n_{12\text{-}11}) = (+,\text{-})$. Inverse pairs identify holons that are controlled by other holons: $(n_{ij}, n_{ji}) = (\text{-},+)$. The main competition relationships between holons are found in: h_1^0 $(n_{13\text{-}1}, n_{1\text{-}13}) = (\text{-},\text{-})$ and h_{12}^0 $(n_{12\text{-}15}, n_{15\text{-}12}) = (\text{-},\text{-})$, h_{13}^0 $(n_{13\text{-}11}, n_{11\text{-}13}) = (\text{-},\text{-})$. h_1^0 Wood Holon (extractive) and h_{13}^0 Recycling Holon have a competition relationship because both try to provide resources to the SC. With regard to the main mutualism relationships, the related holons are: h_9^0 $(n_{9\text{-}1}, n_{1\text{-}9}) = (+,+)$, h_9^0 $(n_{9\text{-}6}, n_{6\text{-}9}) = (+,+)$, h_9^0 $(n_{9\text{-}13}, n_{13\text{-}9}) = (+,+)$. This analysis shows that an interesting relationship occurs between h_9^0 Product Manufacturing Holon and h_{13}^0 Recycling Holon, because this path is more suitable than h_1^0 through h_8^0 from an ecological perspective.

The evaluation carried out indicates the existence of a potential metabolic path that can enable technical cycles to be closed and therefore the establishment of a new path through the SSC based on the product life cycle. The ecological network generated between holons that are involved in the SC of the product shows that its circular pathway is: $h_8^0 \rightarrow h_9^0$, $h_9^0 \rightarrow h_{14}^0$, $h_{14}^0 \rightarrow h_6^0$, $h_6^0 \rightarrow h_{12}^0$, $h_{12}^0 \rightarrow h_{13}^0$, $h_{13}^0 \rightarrow h_8^0$, $h_{13}^0 \rightarrow h_9^0$. This path allows to reinforce the inter-specific relationship and reducing the use of raw material from biological cycles.

6. Conclusion

This work provides insights into the relationship between social metabolism, SSC, the circular economy, enablers from Industry 4.0 and the holonic paradigm, thereby providing a conceptual framework to achieve the AISSCM for social metabolism. The importance of the conceptual framework proposed lies in the integration of the SSC from the circularity and the pillars of sustainability. This is carried out from the holonic paradigm through a multilevel and multiscale framework which enables its instantiation in any territory. The incorporation of the cyber-physical holon allows the identification of the relationships between entities under the TBL concept with its ecological, economic, and social goals. This proposal enables operations to be carried out in real time and decision-making to be performed through the connected integration of the information processes. Furthermore, the common ontology developed allows the exchange of resources between entities, thereby helping to establish biological and technical cycles through the natural and social ecosystem.

According to the review carried out, the main implications are that the holonic paradigm is employed as an organizational enabler to manage the complexity of the SSC from the TBL perspective, by considering the SC simultaneously as the generator of the metabolic rift and as the framework for its mitigation and reversal.

The limitations of this work may lie in the fact that the framework has been developed considering the circular economy paradigm for the sustainability, and it therefore may fail to take into account aspects that exist in other paradigms, such as the green economy and bioeconomy. Likewise, the proposed framework only incorporates ENA as its quantitative method. Bearing this in mind, within the sustainable holonic framework and from the principles of optimization and self-organization, further directions may include the following approaches: data mining (Yerlikaya-Özkurt et al., 2014), machine learning (Silva and Zhao, 2016), system dynamics (Pedamallu et al., 2012), gene-environment networks (Kropat et al., 2016), interval uncertainty (Branzei et al., 2011), grey systems (Palanci et al., 2017), stochastic differential equations (Luo et al., 2017), Markov-switching models (Savku and Weber, 2017), decision-making by optimization, stochastic optimization, robust optimization (Özmen et al., 2017) and stochastic optimal control (Temoçin and Weber, 2014), among others. These approaches could be incorporated into the holarchy knowledge with the aim to widen the capacities of the holonic framework for the AISSCM described.

Declarations of interest

None.

Appendix A.

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