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Perspective paper

Circular economy meets industry 4.0: Can big data drive industrial symbiosis?

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ABSTRACT

Cross-industry networks of multiple supply chains have evolved in the circular economy model using approaches such as industrial and urban symbiosis. However, the implementation of such sustainable industrial networks with matrix-like structures is not straightforward. Despite the clear benefits of big data-driven industrial symbiosis, corporates have noted that social, environmental and economic perspectives are also highly appreciated in the cross-industry networks. Moreover, gaps remain in operational data-driven and recycle, reduce and reuse optimization solutions, which may be the key components of industrial symbiosis practices.

Industrialization has resulted in rising standards of living but has also introduced adverse environmental impacts from unsustainable consumption and production patterns. This trend has led to research interest in examining the effect of emerging cross-industry networks that cut across supply chains, a structure increasingly prevalent in today's complex industrial systems. Traditionally, efforts to enhance industrial sustainability have focused on loop-closing strategies in linear production systems along one supply chain that involve only corporate decisions along vertically integrated systems. Instead, cross-industry networks of multiple supply chains have evolved in the circular economy (CE) model since the early 2000s, using approaches such as industrial and urban symbiosis. However, the implementation of such sustainable industrial networks with matrix-like structures is not straightforward. Closing the loop in these cases involves corporate decisions among multiple supply chain players across different industries that comprise the multiple-supply-chain network. To efficiently use resources according to preventive 3Rs (recycle, reduce and reuse) strategies in the matrix-like structure of these sustainable industrial networks with interconnected supply chains, the corporate world must now re-evaluate the triple-bottom-line (TBL) decision-making pattern among cross-industry corporate groups.

Over the past decade, there has been a clear trend in promoting sustainable production and consumption (SPC) considering the role of supply chain networks in sustainability (Tseng et al., 2016; Tseng et al., 2013). Many studies have proposed different concepts and tools such as industrial symbiosis, green operations and process integration; these concepts are often used to address the 3Rs in balancing the TBL to enhance corporate sustainability (Tseng and Bui, 2017; Shi et al., 2017; Tseng et al., 2018). Quantitative tools, metrics and indices have also been developed to support the decision-making process; however, such approaches are most easily applied to either single corporates or single supply chain systems. In such cases, decisions are made by a single corporate entity or a coalition of corporates with a clear history of cooperation and mutual trust because of direct supply chain relationships. Furthermore, although these principles can be applied to different corporates in the supply chain or cross-industry networks, such efforts are often hampered by data discrepancies, gaps, and confidentiality issues. These issues prevent the optimization of opportunities for sustainability enhancement, which naturally leads to the question of whether emerging technologies can be used to provide the necessary solutions. In other words, can Industry 4.0 tools, which include cyber-physical systems, the Internet of Things (IoT), cloud computing and cognitive computing and concepts, drive the deployment of a new generation of CE initiatives? Data-driven analysis can potentially be used to optimize the sustainable solutions intended to reduce the resource and emission intensities of industrial systems. Despite a massive volume of scientific work in these areas (e.g., separate queries in Scopus using "Industry 4.0" and 'Circular Economy' as keywords yield 4060 and 2452 published documents, respectively), there is plenty of growth potential for groundbreaking research in the nexus of these

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topics. A combined search using both 'Industry 4.0″ and 'Circular Economy' as keywords shows only three papers, all of which were published in 2017.

There is a notable contrast in data-driven analysis methods used in different industrial sectors. Despite the clear benefits of big data-driven industrial symbiosis, corporates have noted that TBL perspectives are also highly appreciated in their practices in the cross-industry networks. Moreover, gaps remain in operational data-driven and 3Rs optimization solutions, which may be the key components of industrial symbiosis practices. Furthermore, there are certain levels of interdependence and interrelationships among the sub-components and an inherent lack of operational data-driven and optimization solutions in supply chain networks that must be optimized to achieve efficiency and effectiveness (i.e., minimum-resource 3Rs and waste generation). To close these gaps, corporate operational data must be disclosed within supply chain networks, and data-driven and optimization solutions for an industrial symbiosis network should be further addressed. In highly integrated systems with high levels of cyclic linkages, the shortcomings of data-driven and optimization solutions will amplify a magnitude of disruptions in the industrial symbiosis practice.

The segment of the scientific community represented by *Resources, Conservation and Recycling* should leverage the technological innovations in Industry 4.0, using tools such as big data and IoT, to achieve gains across TBL perspectives. Some specific research opportunities that are immediately clear include the following:

- Empirical exploration of Industry 4.0 to identify sustainability gains that may not yet be fully recognized. For example, efficiency gains may be documented in terms of increased profitability, whereas there may be unreported reductions in resource consumption and waste generation, which translates to improved industrial sustainability.
- Mathematical and computer optimization models to provide decision-making support to optimize industrial symbiosis practices. The use of mathematical programming and multiple-attribute decision-making techniques is necessary for decision-makers.
- Operational data-driven analyses to produce liable information among the supply chain and industrial networks and to optimize resource usage or balance TBL perspectives, which is necessary for industrial symbiosis in an eco-industrial park.
- Understanding of resource usage optimization and disclosure of operational data to develop universally applicable metrics for industrial symbiosis. This opportunity may produce indices for resilience and reliability.
- Using the big-data driven analysis to benchmark the mutual trust, corporate culture, sustainable consumption or corporate behavior etc. in the supply chain or cross-industry networks to enhance the foundation of industrial symbiosis system and translates to improved industrial sustainability.

Regarding the gap in the literature, a search of the Scopus database using the keyword phrase "Data-driven on industrial symbiosis" yielded only 20 articles, few of which were related to industrial symbiosis. Thus, there is clear bibliometric evidence of the sparsity of scientific literature on this important topic. This gap presents an urgent challenge to the scientific community of industrial ecology as well as the scientific community of Resource, Conservation and Recycling to contribute concepts and tools to assist data-driven and optimization solutions in industrial symbiosis studies.

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