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Dijkema, Gerard P. J.; Xu, Ming; Derrible, Sybil; Lifset, Reid

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Complexity in Industrial Ecology

Models, Analysis, and Actions

Gerard P.J. Dijkema, Ming Xu, Sybil Derrible, and Reid Lifset

Introduction

This special issue brings together articles that illustrate the recent advances of studying complex adaptive systems in industrial ecology (IE). The authors explore the emergent behavior of sociotechnical systems, including product systems, industrial symbiosis (IS) networks, cities, resource consumption, and co-authorship networks, and offer application of complex systems models and analyses. The articles demonstrate the links, relevance, and implications of many (often emerging) fields of study to IE, including network analysis, participatory modeling, nonequilibrium thermodynamics, and agent-based modeling. Together, these articles show that IE itself is a complex adaptive system, where knowledge, frameworks, methods, and tools evolve with and by their applications and use in small and large case studies—multidisciplinary knowledge ecology.

In the special issue “Complexity and Industrial Ecology” (Volume 13, Number 2, 2009), Dijkema and Basson (2009, 157) propose that “. . . complexity theory and its tools has potential to shift the frontier of Industrial Ecology, by enhancing the quality of systems analysis and by underpinning recommendations for redirecting industrial development towards sustainability.” Indeed, in action-oriented IE (Nikolić et al. 2009), we arguably study “complex, layered and dynamic systems that interact with their environment and thereby perpetually affect one another” (Dijkema and Basson 2009, 157). Indeed, we study sociotechnical systems, where the social evolves the technical and vice versa (de Bruijn and Herder 2009). Both their evolution and impact occur at multiple spatial, temporal, and systems scales. Where it has been argued that “sustainability” is an anthropocentric, normative concept (Allenby 2009; Ehrenfeld 2007), from complexity science we may learn that sustainability is an emerging characteristic of the complex adaptive system of our planet earth and any subsystem or part thereof (Nikolić et al. 2009).

Taking a complex systems approach and applying complex systems methods can thus deepen and broaden our understanding of resource, production, and consumption systems. In fact,

“. . . beyond methods and tools, the articles in this special issue are proof that complexity science has provided IE an overarching knowledge paradigm that matches the continuously evolving resource, production, and consumption systems that are the object of study in the field.”

these methods can help us determine how these systems shape both the relation and the mutual impact between us humans and the planet. It provides information to underpin policy and strategy for sustainable development.

The articles, columns, and forums in this special issue, “Advances in Complex Adaptive Systems and Industrial Ecology,” reveal the frontiers of the application of complexity theory in IE, building on the success of the 2013 Industrial Society for Industrial Ecology conference in Ulsan, Korea (17–20 June 2013).

Figure 1 shows a word cloud from the titles, abstracts, and keywords of the articles, columns, and forums published in this special issue. Some expected terms appear, such as “industrial,” “ecology,” “analysis,” and “systems”; but one may observe the emergence of “network” analysis in IE, as well as “data” in this era of “Big Data,” and “resilience.” These new terms are, in fact, informative about the direction that the study of complex systems in IE is taking.

Overview of the Special Issue

The articles in this special issue reveal that, at both a conceptual and operational level, IE researchers are incorporating complex science theories and tools. We briefly discuss and frame the articles according to topical areas and methods.

The first group of articles discusses how complex systems theories and methods can address emerging needs in IE. Bettencourt and Brelsford (2015) argue that social and technical systems are increasingly global and interconnected. This leads to challenges of considering the two systems simultaneously when addressing sustainability issues in IE, because they require different strategies and tools. This challenge requires us to think of engineering systems that can adaptably respond to the growing social and economic knowledge and, at the same time, encode social and economic knowledge into engineering solutions. The authors concluded that this is the frontier of IE, and complex systems theories and methods can be most helpful.

Nikolić (2015) notes that IE as a field of study examines the evolution of the interconnected environmental, social, economic, and technical systems for solutions toward sustainability. While measuring the dynamics of structures and flows deals with the *what* question, the *how* question of exploring the

we must shed the siloed approach of past urban development, and rather address the urban “infrastructure ecology” (Xu et al. 2012) that examines connections and interactions within the UIS, and develop predevelopment policy tools. This is all the more relevant that “UIS are expected to double in the next 35 years, and it took 5,000 years to build the existing UIS.” A complex system is therefore paramount to view a system in its entirety. A water system therefore does not start at the water treatment plant, but at the very source where the water comes from.

Chandra-Putra and colleagues (2015) take industrial cities as their object of research. They investigated “how the environmental characteristics of firms affect the evolutionary pathway of their host settlement,” and by careful analysis developed an agent-based model to explore industrial and household location. Informing and positioning their work by, and related to, other scholars in economic geography and urban dynamics, they relate these to work in IS, urban planning, and urban metabolism. Focusing their model on real industrial-urban evolution—who and what settles on particular parcels of land, playing out their simulations in a virtual place that has characteristics matching the United States, they find that the model has four attractors—the isolated enterprise with commuters, the company town, the economic agglomeration, and the balanced city.

Agent-based modeling (ABM) has been an important tool to bridge complexity science and IE. The fourth group of articles provided case studies using ABM to understand industrial-urban evolution (Chandra-Putra et al. 2015) and rebound effect (Hicks et al. 2015). In particular, Hicks and colleagues (2015) develop an agent-based model to understand the energy-saving effects of adopting efficient lighting technology (light-emitting diode and compact fluorescent lamp). The authors note the actual energy savings realized through more efficient lighting technology depend on how consumers perceive available information of different lighting options. They conclude that efficiency increase in lighting technology can potentially save energy in the short term, but the rebound effect of increased lit space is likely to negate the energy savings realized through adopting energy-efficient technology.

The fifth group of articles studies the IE literature as an evolving, networked system. Kim and Perez (2015) analyze the IE community, notably, co-authorship in the body of articles of IE. Their analysis reveals a set of main topics of the field similar to Yu and colleagues (2014), as well as new information on the structure of collaboration in the IE community. They provide network metrics and visualization of author contribution to the *Journal of Industrial Ecology* and of the clusters of collaborating authors. From the analysis, they observe that some researchers in common or adjacent fields do not collaborate, whereas others do. Barriers preventing collaborations may include institution culture, geographic distance, and personalities of individual researchers.

Meerow and Newell (2015) examine the literature on resilience and complexity and offer prospects for IE. By analyzing the citation network of the reviewed literature, the authors identify five intellectual communities in the field of resilience,

and find that the resilience theory from ecology is especially influential. By examining IE literature, the authors conclude that IE resilience research is limited and underdeveloped. They argue that IE scholarship on complex systems can provide a foundation for expanding research efforts in resilience. The authors also propose two areas where IE can contribute to resilience research: testing resilience characteristics using quantitative methods and real-world industrial systems as case studies and developing a field of study on resilient urban metabolism to enable multidisciplinary collaboration.

The topical area that Meerow and Newell (2015) address, resilience, is the focus of the sixth group of articles. Pizzol (2015) notes that our product systems preferably are resilient, explores the implications for life cycle assessment (LCA), and conceptually develops directions on how one could deal with this in LCA. In general, resilience means how well a system can maintain functioning or quickly recover after disturbances. In two examples, the author demonstrates that the inclusion of an “option for storage” can help improve the resilience of a product system. The main reason is that the storage option provides alternative pathways for the product system to function even if one of the processes is disrupted. Core to resilient systems’ structure and content is that there exist such alternative pathways to fulfill the product system function, which come at an ecological and economic expense. Turning this around, this article points us to the fact that real systems are not in equilibrium and eco-efficiency is not the sole driver of their development. To bridge the real world of complex, dynamic systems with the equilibrium, static systems assessed in LCA, the author suggests to expand consequential LCA beyond studying the effect of small perturbations around an equilibrium.

Li and Shi (2015) analyze a large Chinese industrial zone using network analysis techniques to assess and learn about IS therein and determine resilience characteristics. By distinguishing between infrastructure and material exchange networks, they can determine components that are key to system resilience with respect to external disturbance. Interestingly, they take this further and point out an issue of IS, namely, that it may increase the likelihood of the zone experiencing cascading failures, and suggest remedies by companies and planners.

The network analysis techniques used by Li and Shi (2015), Kim and Perez (2015), and Meerow and Newell (2015) originate from network science (Newman 2010), a branch of complexity science. Together with two other articles, they are the seventh group in this special issue developing and applying network-based tools for IE. Liang and colleagues (2015) seek to augment traditional input-output (I-O) analysis (IOA) to extract new information out of I-O databases beyond structural path analysis. In traditional IOA, the goal is to attribute resource use to consumption. By developing a network analysis using data from a multiregional I-O database covering the entire world, the authors elucidate which parts, if not clusters, in the global production system are “hotspots” for global anthropogenic carbon emissions—to identify important transmission centers. Additional insights can be gained for developing policy interventions targeting those important transmission

centers with the potential to have the largest impact on global anthropogenic carbon emissions.

Ahmad and Derrible (2015) study U.S. public water withdrawal using a network approach. The main goal is to determine whether water withdrawal has increased or decreased in the past 30 years, because traditional statistical indicators were giving mixed signals. They use a U.S. Geological Survey database with a resolution to county level and gain novel insight into water withdrawal and distribution. Akin to the concept of “homophily” in network science, counties are linked if they have similar water withdrawal levels. By sorting counties per network metric, anomalies (if not outliers) in the data are detected. Together with straightforward statistical analysis, these can shed new light on water withdrawal characteristics. Analysis of 5-year intervals between 1985 and 2005 does not reveal significant changes or correlation between social or physical geography of counties and their water withdrawal, which hints that consumption is driven by other factors than population and local climate.

Finally, the special issue is enriched with three reviews by Derrible (2015), Seager and Snell (2015) and Ashton (2015) of recent books related to complexity as it pertains to urban geography, decision-making, and social network analysis for consumer marketing. These reviews further highlight the significance of complexity theory as an innovative and pertinent framework of study, and we expect many more books on complexity theory relevant to industrial ecology in the near future.

Conclusion and Outlook

We observe several trends in the intersection of complexity science and IE in this special issue as well as the broader literature. The first is the resurfacing of nonequilibrium thermodynamics in IE research. The initial connection between complexity science and IE was made around nonequilibrium thermodynamics (Kay 2002). Spiegelman (2003) argues that nonequilibrium thermodynamics can potentially help develop a more sophisticated analytical framework in IE to capture commonalities shared by industrial and ecological systems and go beyond the metaphor of IE. However, the IE community did not move in that direction until recent work that applies nonequilibrium thermodynamics to the study of sustainable urban systems (Bristow and Kennedy 2013), including one of the articles in this special issue (Bristow and Kennedy 2015). Cities have long been characterized as complex adaptive systems that are self-organized, open, and operating far from thermodynamic equilibrium. The integration of nonequilibrium thermodynamics theories and methods with urban metabolism might lead to a comprehensive framework for modeling and analyzing urban systems and their environmental implications.

The second trend is the cooling down of ABM. ABM has been seen as a tangible tool for applying complexity theories to IE (Kraines and Wallace 2006), especially when integrating with existing IE tools (Davis et al. 2009; Baynes 2009). Several case studies have been presented integrating ABM with traditional IE methods, including LCA (Miller et al. 2013),

material flow analysis (MFA) (Bollinger et al. 2012), and IS (Batten 2009). In this special issue, Hicks and colleagues (2015) use ABM to evaluate the rebound effect of adopting energy-efficient technology on energy savings; Chandra-Putra and colleagues (2015) model the emergence of industrial and household location in industrial-urban systems using ABM. Interestingly, ABM was not used in these studies as an addition to improve another IE method; instead, it was used as the main modeling technique to address an IE-relevant question. The cooling down of ABM in IE literature from the past decade might be because of the fact that traditional IE tools, such as LCA and MFA, are not straightforwardly compatible with ABM. Using ABM to improve these tools might be a misconception. Nevertheless, ABM has potential for addressing many long-standing and emerging research questions in IE. As hinted by Hicks and colleagues (2015) and Chandra-Putra and colleagues (2015), using ABM as the main modeling technique instead of as an add-on might be more effective in dealing with issues that emerge from the interaction of heterogeneous individual agents.

The third trend is the increasing popularity of network analysis. Indeed, in a recent review exploring options for social-material network analyses, Schiller and colleagues (2014) suggest that: “Network analysis can be seen as the most promising method to mediate between industrial ecology’s overall systems approach and the complex structures found in society.” In this issue, 5 of the 11 articles and forums use network analysis to study a variety of systems relevant to IE, including literature citation and co-authorship networks (Meerow and Newell 2015; Kim and Perez 2015), global anthropogenic carbon emissions (Liang et al. 2015), IS (Li and Shi 2015), and national water withdrawal (Ahmad and Derrible 2015). The increasing interest in network analysis in the IE community might be owing to the fact that many systems in IE studies have network structures (e.g., interconnected material cycles, I-O economies, and industrial parks). It is natural and relatively straightforward to use network analysis techniques to study particular dimensions of those systems using available data sets.

These trends and the research presented by articles in this special issue illustrate the evolution of the IE community in seeking better ways to understand complex adaptive systems. We would argue that beyond methods and tools, the articles in this special issue are proof that complexity science has provided IE an overarching knowledge paradigm that matches the continuously evolving resource, production, and consumption systems that are the object of study in the field. Because these systems are complex adaptive systems, we need to somehow let them evolve into sustainable systems. The special issue reveals the magnitude of the challenge before us to achieve sustainability and exposes the limits of our knowledge of how and when to intervene and manage—let alone control—complex adaptive systems in an interconnected world, where interaction, innovation, and development unfold across multiple temporal and spatial scales in often unanticipated, if not unimaginable, ways.

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About the Authors

Gerard P.J. Dijkema is a professor of energy systems and industrial ecology, Faculty of Mathematics and Natural Sciences in Groningen University in Groningen, the Netherlands. **Ming Xu** is an assistant professor in the School of Natural Resources and Environment and an assistant professor in the Department of Civil and Environmental Engineering at the University of Michigan in Ann Arbor, MI, USA. **Sybil Derrible** is an

assistant professor of sustainable infrastructure systems in the Department of Civil and Materials Engineering at the University of Illinois at Chicago in Chicago, IL, USA. **Reid Lifset** is a research scientist in the School of Forestry & Environmental Studies at Yale University in New Haven, CT, USA, and the editor-in-chief of the *Journal of Industrial Ecology*.

Address correspondence to:

Gerard P.J. Dijkema

Nijenborgh 4

9747AG Groningen the Netherlands.

Email: g.p.j.dijkema@rug.nl;

Web: www.rug.nl/research/energy-environmental-sciences/