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■ *Research Note*

Strengthening the Structural Focus of Systems Thinking

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In their seminal book on directed graphs (or digraphs), published in the mid-1960s, Harary *et al*. (1965: 26) note the following:

> Digraph theory is concerned with structural properties of sets of abstract elements called points and lines, whereas the empirical scientist is interested in empirical structures made up of empirical entities and relationships. If an appropriate coordination is made so that each empirical entity is identified with a point and each empirical relationship is identified with a line, and if this is done in such a way that the axioms of digraph theory become true statements about the empirical world, then all true statements of digraph theory correspond to true statements about the empirical phenomena.

Harary *et al*. (1965: 22) offer a number of examples of empirical entities that may correspond to points, three of which are objects, events, and propositions. These are found in at least three systems approaches to managing change (Reynolds and Holwell, 2010): (i) *levels* in System Dynamics (SD) are *objects*; (ii) *activities* in the conceptual models/human activity systems of Soft Systems Methodology (SSM) are *events*; and (iii) *constructs* in the cognitive maps of Strategic Options Development and Analysis (SODA) are *propositions*. The relations corresponding to these entities may, respectively, represent 'flows into (the next level)', 'enables (the next activity to be done)', and 'causes or leads to (the next proposition)'.

In its concern with systems of interrelated parts, systems thinking may therefore be perceived as a field whose objects of interest are essentially digraphs or, in more synthetic terms, graphs. Graph theory, however, is not commonly adopted in systems thinking, even though systems thinking has been described as giving equal attention to, both, process *and structure* (Jackson, 2003: 13; 2006: 647).

Process is conceptually and analytically well-developed in systems thinking. For example, the flows in a SD model are analysed to understand their process of interaction (Forrester, 1968: 402, 414). SSM fosters a process of rearranging one's mental furniture (Checkland, 2000: S44). SODA maps facilitate the tracing of the process by which a proposition at the head of a map is the product of a series of propositional transformations earlier, and deeper, in the map (Eden, 1988: 5).

Undoubtedly, when discussing processes like these, systems thinking refers to the structures that underpin them. For instance, levels, flows, rates, and information channels constitute the structure upon which SD processes materialize.

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Transformation rules, CATWOE, root definitions, and human activity systems form part of the methodological structure upon which SSM is practiced. Psychological constructs have their own structural composition and are, in turn, the basic structural unit of SODA maps.

Conceptually and analytically, however, structure is not given as much attention as process. For example, SD might identify structural bottlenecks (Fung, 1999), but one is hard-pressed to find acknowledged comparative measures for weighing their constraining, or mediating, influence on flows. To take another example, SSM may produce large conceptual systems (Wilson, 2001), but no analyses are offered to identify the activities that sustain the internal coherence of such systems and, without which, any one such system disconnects into two or more independent subsystems. For these examples, a graph theorist or network scientist would draw on two analyses focusing, respectively, on 'betweenness' (Freeman, 1977) and 'cut vertices' (Aldous and Wilson, 2000: 222).

SODA illustrates a striking instance of undeveloped attention to structure. Its maps have long been acknowledged as reducible to digraphs (Armstrong and Eden, 1979: 22; Eden and Sims, 1979: 126). Given the plethora of structural analyses offered by digraph theory (Bang-Jensen and Gutin, 2009), one would therefore expect full use to be made of them by SODA. The discrepancy between actuality and potential, however, is visible in its associated software, Decision Explorer®. For example, although this software includes 41 structural analyses (Banxia, 2005: 156–158), only two concern centrality, that is, the central influence a construct may enjoy in a map. On the one hand, the software allows centrality to be calculated according to immediate degree (the number of links around a construct, separable into indegree and outdegree); on the other, according to the distances of all ancestors and descendants of a construct across the entire map. There exist, however, at least 108 centrality measures for models structured as graphs, all of them mathematically defined and open to translation into computer programs (Schoch, 2015: 12).

Overall, then, it is reasonable to assert that systems thinking should be looking to graph theory and network science to strengthen its attention to system structures. What, however, is the difference between graph theory and network science? And which of the two might be more effective in informing systems thinking?

Graph theory is an abstract, mathematical approach to analysing and understanding structural phenomena (Gross and Yellen, 2006; Gross *et al*., 2014). For the empirically inclined, it is made more enjoyable by studying it in easily conceptualized, anthropological contexts (Hage and Harary, 1984, 1991, 1996). Network science is the theory of undirected and directed graphs applied to empirical phenomena in general (Freeman, 2004): Network science is applied graph theory.

Since systems thinking is, on balance, concerned mostly with empirical phenomena, strengthening its own structural focus is best begun by consulting network science. This is not to leave graph theory aside, but to emphasize that, since the 1990s, network science, because of its analyses of empirical phenomena, has been able to extend innumerable graph theoretical concepts—for example, it has devised the aforementioned plethora of centrality measures. Network science has brought graph theory into the real world, so to speak. Its applications are too numerous to list, and the following is but a small selection with indicative references:

- Political and economic systems (Knoke, 1990, 2012; Goyal, 2007; Jackson, 2008; Easley and Kleinberg, 2010; Maoz, 2010; Kogut, 2012)
- Health systems (Valente, 2010)
- Academic systems (Andres, 2009; Moed, 2011; Carolan, 2013; Ding *et al*., 2014)
- Corporate and industrial systems (Mizruchi, 1982, 1992; Mizruchi and Schwartz, 1987; Murray and Scott, 2012; Heemskerk, 2007; Herrigel, 2000; Freeland, 2005; David and Westerhuis, 2014)
- Innovation systems (Moon, 2014)
- Urban systems (Giuffre, 2013)
- Criminal systems (Everton, 2012; Gerdes, 2015), and,
- Social capital systems (Burt, 1992, 2005, 2010)

All these are social systems—a major area of interest to systems thinking—and the indicative

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references are complemented by plenty of network science sources that tackle social systems as a general category (Wasserman and Faust, 1994; Carrington *et al*., 2005; Kadushin, 2011; Borgatti *et al*., 2013; McCulloh *et al*., 2013; Dominguez and Hollstein, 2014). Furthermore, Cambridge University Press publishes an ever-growing series of books under the rubric 'Structural Analysis in the Social Sciences' covering diverse applications from the automotive industry, to industrial relations, religion, emergent economies, and, of course, general introductions.

In light of this, what network science sources might best introduce a systems scientist to analytical skills for studying system structure? One could devise a ranking from the most basic (e.g. Prell, 2011) to the most advanced (e.g. Estrada, 2011), by way of the seemingly intermediate (e.g. Newman, 2010). But, given the complex nature of networks—and, by affiliation, systemic structures—any such study must be complemented by training in the use of specialized analytical software. As with books, there are numerous software packages available (Huisman and van Duijn, 2005; Huisman and van Duijn 2011; Cobo *et al*., 2011). Ackoff's (1967: B153) warning against using black boxes, however, casts a long and ever-relevant shadow: 'No [software] should ever be [used] unless the [user] for whom it is intended [is] trained to evaluate and hence control it rather than be controlled by it'. What is required is a source that offers a combination of sufficient theoretical knowledge with hands-on training in a software package that abides by Ackoff's maxim.

Such a source is now available in its third, revised and updated edition: de Nooy *et al*.'s (2018) *Exploratory Social Network Analysis with Pajek*. The apparent focus on social networks in the title should not be construed as limiting. Being a generally familiar context, conceptualization of complex structural issues of networks is made that much easier. Besides, the book covers issues applicable to the widest possible variety of contexts, from various ways to construe cohesive groupings, to the dynamics of diffusion, to social capital, and even bibliometric networks. As for *Pajek,* this refers to an award-winning, freely available[1] software package. This software is designed specifically as a network calculator that can handle billions of vertices, and their relations, irrespective of context. It is, therefore, useful for both, abstract and empirical analyses. Conforming to Ackoff's maxim, Pajek requires the user to structure an analysis in a manner analogical to the mathematical operations on networks; that is to say, in using the software, the user is encouraged to learn at least something of the underlying mathematics, thus affording precise operational oversight with consequent demystification of the black box. Furthermore, Pajek has a long history of published algorithms which are open to evaluation (Batagelj, 1991, 2003; Batagelj and Mrvar, 1998, 2008, 2014; Batagelj and Zaversnik, 2011; Batagelj and Cerinsek, 2013; Batagelj *et al*., 2014). All this enables users to maintain control of their use of the software instead of being controlled by it. In addition, the software provides outstanding graphics of networks, with multiple means for manipulating their aesthetic presentation, thus allowing for sophisticated visual appreciation to complement analytical results.

Adopting the insights of network science, for the benefit of enhancing structural analyses in systems thinking, requires an excursion into interdisciplinarity. The above has argued for the relevance of network science to systems thinking. Becoming familiar with network science, however, is not a trivial task. Social network analysis offers a viable path, no less due to its long history of theoretical and empirical advances that are generically applicable. Ultimately, software that engages the user, and allows for the evaluation of computational operations and results, is necessary to the learning process. Systems thinking and network science are two sides of the same coin. It seems an opportune time for systems thinking to engage with network science. It might even result in a new subfield of 'structural systems thinking', with its own conceptual discoveries and its own catalogue of system-specific analyses.

[1] http://mrvar.fdv.uni-lj.si/pajek/

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