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Mapping the field of Complexity Theory: a computational approach to understanding changes in the field

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Abstract: The field of Complexity Theory research has grown considerably over the last two decades, but it is unclear whether the field is, or has ever been, an integrated whole. This paper uses Scientometric research techniques; a computational way to depict changes in Complexity Theory research as a whole. The field is mapped in terms of the geographic distribution of publications, the relationships between individual authors and the research fields to which they contribute, and the network of citations between publications and the sources they reference. This mapping has been used to address the question of whether there is a divide between Complexity Theory as applied to research in Mathematics and Computer Science, and Complexity Theory as used in Management research; an important consideration for those interested in the application of Complexity Theory in Management research past the level of explanatory metaphor.

Introduction

The field of Complexity Theory research is diffuse, bringing together a variety of associated models, theories and institutional research programs (Burnes, 2005: 73). There "…is no one identifiable complexity theory. Instead, a number of theories concerned with complex systems gather under the general banner of complexity research" (Manson, 2001: 405). Complexity Theory draws on diverse fields, such as meteorology, mathematics, physics, chemistry and biology (Burnes, 2005: 73). It has also been identified (Manson, 2001: 406) that the field builds upon a variety of earlier research including: the philosophy of organism (Whitehead, 1925); neural networks (McCulloch & Pitts, 1943); cybernetics (Wiener, 1961); cellular automata (von Neumann, 1966); and General Systems Theory (von Bertalanffy, 1968). This is a breadth of influence across disciplinary boundaries which makes it difficult to define the exact nature of Complexity Theory. Indeed, the study of complex adaptive systems has been referred to as "…the ultimate interdisciplinary science…" (McKelvey, 1999: 5).

The ideas of Complexity Theory have diffused through other research fields. Thrift (1999) has compared the spread of Complexity Theory through science, business and the new age communities. Of particular interest to this research is the way in which Complexity Theory is being used as an approach to understanding organisations. However, as the ideas of Complexity Theory have been translated into a management context, they have not always been applied in the same way. Organisational theorists "…do not appear to have moved beyond the stage of using it as metaphor rather than as a mathematical way of analysing and managing organizations" (Burnes, 2005: 73). In 1999, it was noted that "…complexity theory shows all the characteristics of a short-lived fad" (McKelvey, 1999: 6), and that "…the success of complexity theory has only been partial and its future as a new scientific paradigm – as opposed to the success of some of its individual elements – is by no means assured" (Thrift, 1999: 39). The purpose of this research is to examine whether evidence can be found in the field of Complexity Theory research as a whole to support the assertion that there is a divide between Complexity Theory as applied in mathematics / computer science and management research.

However, it can be difficult for the individual researcher, engaging with necessarily myopic research topics, local researcher collaborations, institutional boundaries, and the specific research papers that have appeared in response to their search terms, to gain an understanding of the field as a whole. The emergent behavior of the field is difficult to perceive from the perspective of a limited selection of its constituent elements. This research provides an overall analysis of the field of Complexity Theory research using scientometric techniques; "…the use of statistics to measure the activity of science…" (Latour, 2005: 6). Scientometrics is field which is also referred to as knowledge domain visualisation or domain mapping (Hook & Börner, 2005), and has been identified as a subfield of information visualisation (Hook, 2007: 442). It is a quantitative method of studying scientific communication, emerging from citation based domain visualisation (Chen, et al, 2011: 131). It aims to provide "…the graphic rendering of bibliometric data designed to provide a global view of a particular domain, the structural details of a domain, the salient characteristics of a domain (its dynamics, most cited authors or papers, bursting concepts, etc.) or all three" (Hook & Börner, 2005: 201).

Images of science provide necessary support for the communication and exploration of data, an increasingly significant activity given the volume of data available (Börner, 2012: 430). "Just like old sea charts, maps of science can help people to find places of interest while avoiding monsters. They complement local fact retrieval via search engines by providing global views of large amounts of knowledge" (Börner, 2007: 808-9). By contrast, while search engines are able to provide access to vast repositories of data, the outputs of searches are typically provided as lists, which leave the searcher to review data item-by-item; an approach leading to engagement with a small selection of detailed data, with little opportunity to perceive the dynamics of a field as a whole.

Research Methodology

A variety of authors have contributed to the early development of scientometrics. Hook (2007) refers to Bernal's work (1939) as one of the earliest maps of science, and to Eugene Garfield as "…a founding father of scientometrics…" (Hook, 2007: 443). By contrast, Latour points to De Candolle as "…the first person to create scientometrics…" (2005: 6). Readers interested in a detailed review of current "…approaches to collecting, interlinking, organizing, and making sense of scholarly knowledge and expertise…" are referred to Börner (2007: 808).

Scientometric techniques have been used to predict the conditions which lead to scientific developments and to identify the actors that are driving scientific advancement, whether they are institutions, research communities, or individuals (Scharnhorst, 2012: xii). These approaches have also been applied to a variety of research topics, including: visualising the growth of competing paradigms (Chen, et al, 2002); changes in melanoma research (LaRowe, et al, 2009); the topic space of the United States Supreme Court (Hook, 2007); and self-referentially even to changes in scientometric research (Chen, et al, 2011). Inversely to this research, Complexity Theory has also been applied to scientometric research in an effort to understand the how scientific disciplines develop (Scharnhorst, et al, 2012). Visualising Complexity Theory research as a whole provides an opportunity to develop a holistic account of the field; arguably a most appropriate way to examine a fundamentally anti-reductionist discipline.

The published literature on Complexity Theory provides tangible evidence of developments in the field, which can lead to conclusions about influential works, authors, and institutions, about the kinds of research that is done, and the areas in which this work is applied. In this paper, the literature on Complexity Theory has been analysed in terms of:

1. Geographical distribution of research conducted on Complexity Theory;
2. Links between authors of research and research fields; and
3. Links between publications on Complexity Theory and the publications they cite.

Discussion of the research methodology will be broadly structured in terms of Börner's (2010: 51) scientometric workflow design:

1. Data Acquisition
2. Preprocessing
3. Analysis / Modeling
4. Communication / Visualisation / Layout

Variations on the research methodology were required for each of the three analyses conducted on the data set. The research methodology will be discussed in general, before an each analysis is separately addressed.

Data acquisition for all analyses

LaRowe et al (2009: 221) have commented that as a great deal of scientometric research uses locally developed data sets, it can become "…very time consuming (in terms of data downloading, cleaning, and inter-linking) if not impossible (if data sets require access permissions) to replicate a certain study or to reproduce a given result." This is particularly problematic for scientometric research conducted on datasets that are not publicly available. In order to try to maximize the opportunity for reproducible results, the decision was made that this research would solely rely on data available through commercially available research databases.

This research used the Sci^2 tool (Sci^2-Team, 2009) which will import data in a variety of formats, including from the ISI Web of Science (ISI WoS), Scopus and Google Scholar. In order to create a comprehensive dataset, the researchers initially investigated the possibility of consolidating inputs from multiple research databases in one network. However, aggregation of data from different sources introduced irreconcilable errors in the datasets, making consolidation of data from different sources impractical.

As such, it was necessary to make a choice between research databases. Other authors (e.g. Bakkalbasi et al, 2006; Jasco, 2005) have investigated the overlaps between the ISI WoS, Scopus and Google Scholar. ISI WoS has been noted as one of "…the best sources of bibliographic entries on major, predominantly English journal publications" (Börner, 2007: 809), and that the ISI database is more standardized than the Scopus database (Leydesdorff & Persson, 2010: 1630). The authors, who found the ISI WoS database to be the most reliable in terms of repeatable data upload, encouraged this latter observation.

The ISI WoS was chosen as the source of research data. At the time of writing, this database includes over 12,000 journals, 110,000 conference proceedings, 87 million source items, and 700 million cited references, from 256 scientific disciplines (Thompson-Reuters, 2012). It has been identified as "…hard if not impossible to identify and compare the entities (records and authors) from all contributing domains" (Börner, 2007: 814) and it is acknowledged that the ISI WoS does not include all journals that contribute to Complexity Theory research. However, it was considered sufficiently comprehensive to justify broad conclusions about the development of the field as a whole.

Data was retrieved from the ISI WoS database using the search term "complexity theory" in the category "topic". This search delivered 2016 results from between the years 1900 and 2011, with the earliest paper in the dataset published in 1950, after duplicate records had been deleted. The citation details provided by this search formed the dataset for this research.

Different research techniques were used to conduct enquiry into the geographic distribution of Complexity Theory research, the links between authors and the fields to which they contribute, and patterns of co-citation. As such, methodological considerations for these techniques will be discussed separately and in turn below.

The geography of Complexity Theory research

Thrift (1999) has previously considered "…how we might construct a geography of complexity theory." Viewing Complexity Theory as a set of metaphors. He investigated "…the means by which metaphors of complexity theory are able to travel and gradually become a commonplace structure of intelligibility" (p. 35). Thrift considered the first factor in understanding the geography of the field involved mapping the specific sites where Complexity Theory is produced, "…which is, perhaps, best summarized by studies of citation counts" (p. 51). A geographic representation of the field also aligns with a common language understanding of mapping.

The research reported here has built upon Thrift's (1999) suggestion, developing a map of the locations for Complexity Theory research based on citation counts. Previous research (Leydesdorff & Persson, 2010: 1630) has identified that the geographic data provided by ISI WoS is "…highly comparable…" with Scopus data, suggesting that despite being based on a limited subset of all research on Complexity Theory research, mapping based on the ISI WoS is broadly representative of the field.

The WoS records include a field, which identifies the research address for the lead author of a publication. Of the 2016 records in the subset, 1767 records included a record in the Research Address field. Yahoo! Geocoder was used to identify longitude and latitude for these research addresses; a tool which has been previously used in comparable research (e.g. Leydesdorff & Persson, 2010: 1624). Of the 1767 records, 1679 returned valid results for longitude and latitude. These records were then consolidated, to produce a list of unique locations, recording the sum total of the citations of all publications produced at one address, resulting in 948 unique locations. The Sci^2 tool was then used to create a graphical representation of where Complexity Theory research is conducted (Figure 1). This image is broadly consistent with an earlier image of where Complexity Theory research is produced that was attributed to Gell-Mann (1994) in Thrift (1999: 52), although the distribution of Complexity Theory research appears to have become less localised, spreading more evenly across the globe.

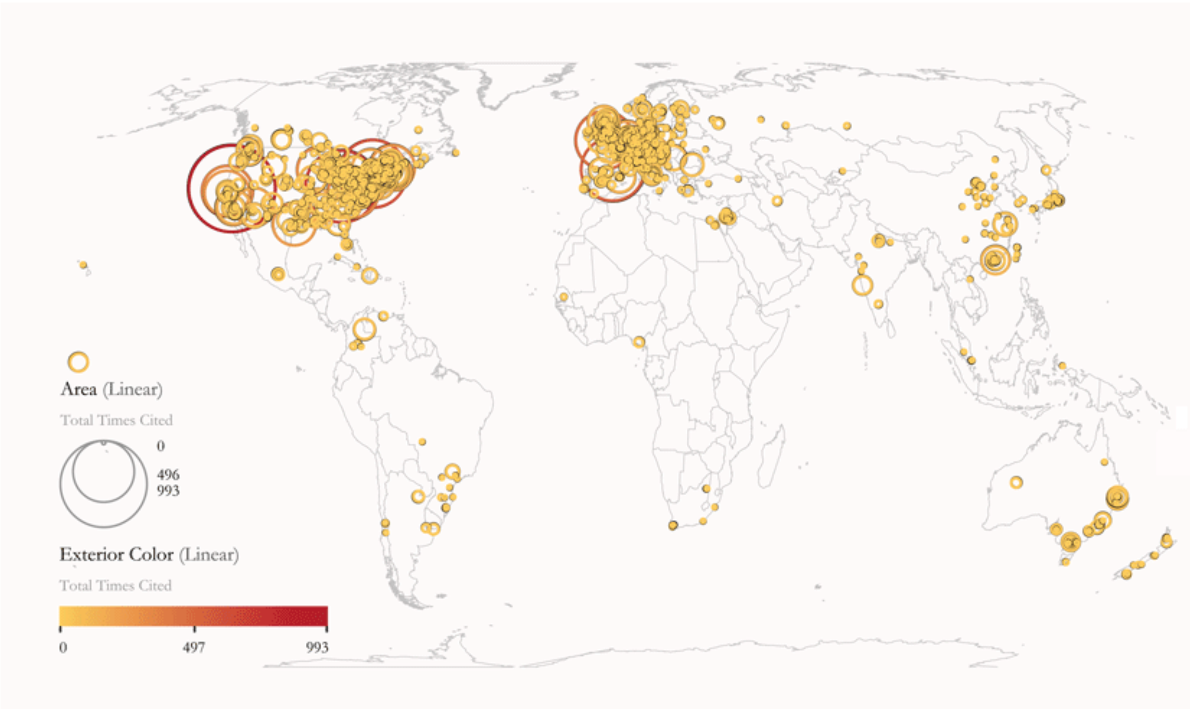

Figure 1: *Where complexity theory research is produced*

Burst analysis was also conducted to uncover periodic changes in the number of publications produced in one location (Figure 2). Burst analysis involves examination of the change in frequency with which nominated terms occur within a data set. Terms that rapidly increase in frequency over a period are considered to be ‘bursting’. Burst analysis of the affiliated institutions of lead authors can imply a sudden increase in the number of publications on Complexity Theory being produced at one institution.

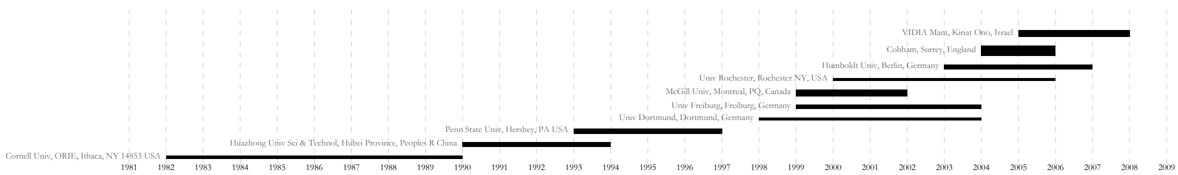

Figure 2: *Bursting institutions for complexity theory research*

Although of interest in understanding key contributors to Complexity Theory research, a geographic mapping does not provide much direct evidence to support an argument about how the content or focus of the field has developed. One finding from this analysis relates to the difficulty in isolating any centres of Complexity Theory research based on the affiliation location of publication lead authors. Complexity Theory research appears to be ubiquitous, with contributors across the globe; a finding which is consistent with the broad range of topics that both contribute to, and draw upon, the field.

The research fields of Complexity Theory research

As Complexity Theory has been identified as an interdisciplinary area of enquiry, spanning many different research fields, it was considered interesting to understand the different research fields in which Complexity Theory is being used. ISI WoS includes a broad categorisation of a publication's research field, and identifies the authors of that publication. These records can be used as evidence that an author has contributed to a particular research field, through a particular publication. This data was used to create a network representing the associations between individual authors and the fields to which they contribute.

Pre-processing, Data Preparation and Analysis

Of the 2016 records, 2015 included a valid entry for the Research Field, with many records identifying that a single publication contributed to multiple Research Fields. The output from the ISI WoS search was used to extract a bipartite network from the Author(s) of each publication to the Research Field(s) for the publication. A script was written for this network to add weights to network edges based on the number of times an individual author contributed to a particular research field.

Network isolates and self-loops were removed. An analysis was run on the network to detect duplicate nodes, with nodes automatically merged when over 95% similar. Nodes that were more than 85% similar were identified and manually merged as appropriate. All clusters other than the largest cluster in the network were then deleted for clarity in presentation. In this process 0.008% edges were deleted in this process, suggesting a highly interconnected network.

Modelling, visualisation and layout

A visual representation of the network from Authors to Research Fields was created using GUESS software, which is available as part of the Sci^2 tool, then edited with Photoshop for publication. The graph visualisation was created using the Graph EMbedding (GEM) algorithm (Frick, et al, 1994: 338). The GEM algorithm is based on spring embedder group of algorithms, in which "…vertices are treated as mutually repulsive charges and edges as springs connecting and attracting the charges." The GEM algorithm was chosen based on the relatively short processing time compared to other algorithms, and on the aesthetics of the output. This algorithm attempts to place notes so that edges are of similar length, with as few crossing edges as possible (Figure 3).

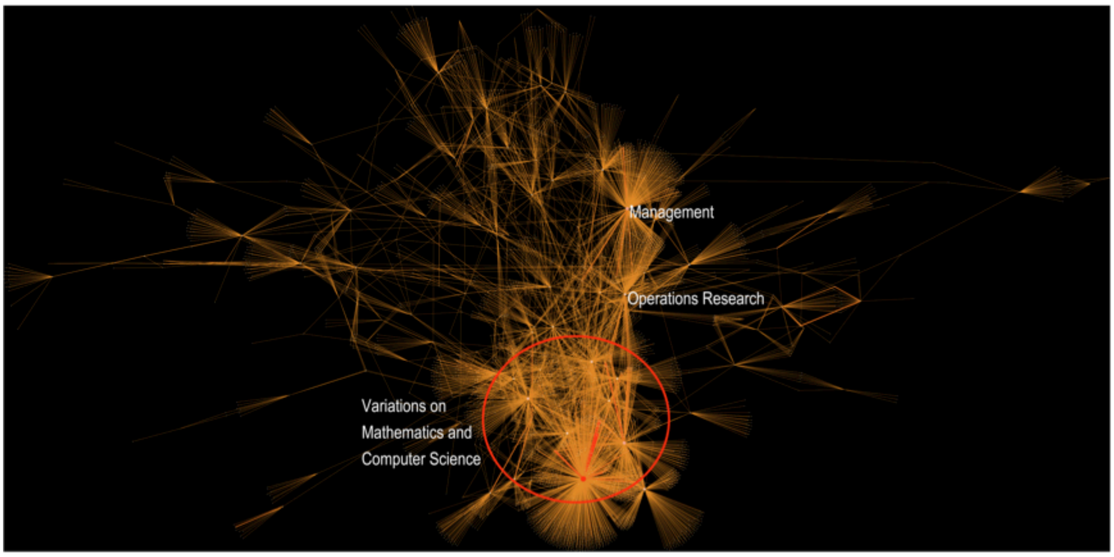

Figure 3: *The network from Authors to Research Fields*

The width and colour of edges represents the number of times a particular author has contributed to an application area. The size of Research Field nodes represents the number of Author's works that contributed to it. In this network there is a clear clustering of research around fields related to computer science and mathematics. Complexity Theory research applied to management sits quite separately, while operations research bridges the divide between these research areas.

A burst analysis of changes in entries in the Research Field record for the dataset was conducted, identifying periods when particular Research Fields became increasingly common (Table 1). The ten most common Research Fields within the data set were also identified. It should be noted that the burst of a Research Field does not guarantee its total frequency within the data set.

Bursting Research Field	Burst Period
Mathematics	1973-2002
Computer Science, Hardware & Architecture	1985-1987
Mathematics, Applied	1988-2003
Computer Science, Theory & Methods	1988-1993
Computer Science, Theory & Methods	1995-1996
Management	2002-2003
Telecommunications	2005-2010
Information Science & Library Science	2006-2009
Business	2009-2010
Education & Educational Research	2010-2012

Locally Frequent Research Fields	Frequency
Computer Science, Theory & Methods	596
Mathematics, Applied	236
Management	234
Engineering, Electrical & Electronic	149
Mathematics	137
Computer Science, Information Systems	132
Operations Research & Management Science	122
Computer Science, hardware & Architecture	94
Computer Science, Artificial Intelligence	83
Computer Science, Software Engineering	79

Table 1: *Burst analysis of Research Fields (gamma: 1.35, density scaling 2)*

The burst analysis of Research Field data shows a sustained increase in the number of publications that include reference to 'Complexity Theory' in the field of Mathematics research. The field of Computer Science, Hardware & Architecture research also shows an early and significant burst as a field that mentions ‘Complexity Theory’, with other variants on Mathematics and Computer Science also showing an early uptake. It is only after the year 2002 that bursts in research mentioning ‘Complexity Theory’ can be seen in research in the field of Management, and it is not until relatively recently (2009) that a significant burst is seen in the field of business.

The citation network of Complexity Theory research

The relationship between authors and research fields only provides one way of representing the development of the field. It is also possible to remove the individuals from the picture, and examine the direct relationships between publications through a citation network, linking publications to the sources they cite. This representation provides the opportunity to observe the dialogue within a field at a macro level, and uncover sources that have proved significantly influential within a population.

Pre-processing, data preparation and analysis

Development of the citation network for Complexity Theory research used the ISI WoS Cited References field and a unique publication identifier created by Sci^2 to mirror the Cited References field structure. Of the 2016 records, 1911 records contained valid entries for these fields. A bipartite network was created between these fields. A script was written to add weights to nodes and colour edges, based on the number of times a publication was locally cited. Network isolates and self-loops were removed. An analysis was run on the network to detect duplicate nodes, with nodes automatically merged when over 95% similar. Nodes that were more than 85% similar were identified in a report and manually merged as appropriate. Merging duplicates reduced the total number of nodes by 5.6% and edges by 1.2%. Network analysis revealed 52917 nodes and 71445 edges. The largest connected component consisted of 51177 nodes indicating that approximately 95% of all papers were connected in one network.

Modelling, visualisation and layout

This network was visualised using GUESS with a GEM layout, and the process was repeated multiple times to confirm that consistent results were being produced. Time slices of the network were taken, with cumulative visualisations prepared for each year from 1990 to 2011, three of which are reproduced in Figure 4. Publications focused on mathematical and computer science research are broadly bordered by the upper oval, while management and social research is broadly bordered by the lower oval. In these panels, it can be seen that by 1995 publications that mention Complexity Theory are almost exclusively grounded in mathematics and computer science. By 2000 management and social research in Complexity Theory had expanded considerably, reaching a comparable network size, while by 2011 this broad stream of research has arguably grown larger than the mathematics and computer science hemisphere. Although by 2011 there are some publications which sit between the hemispheres, they remain predominantly separate.

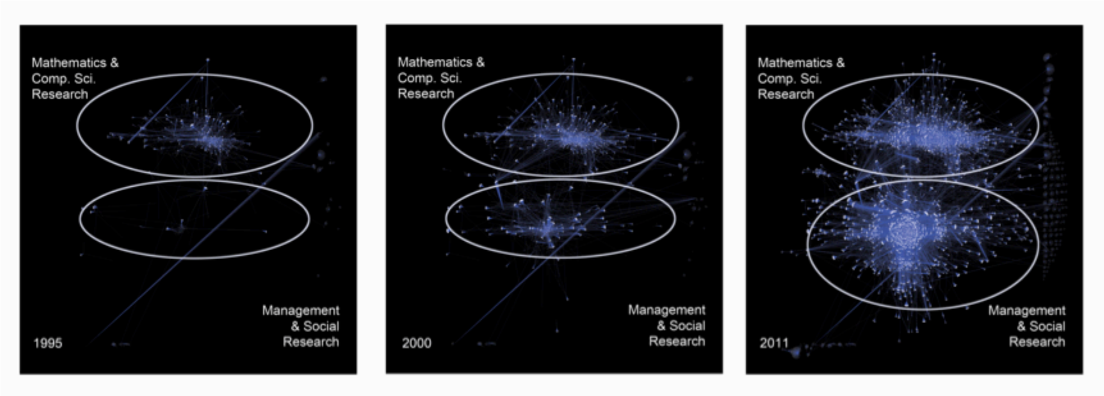

Figure 4: *Complexity theory citation network*

This network was also used to identify the publications that have been particularly influential within the data set. Table 2 compares the top ten citations identified through burst detection and the top ten citations identified by the local citation count, the frequency of citation within the data set. It is noteworthy that the only publication that has been detected as significant using both methods is by Garey and Johnson (1979), suggesting both the significance of this publication within the field and the differences between these two research techniques.

Bursting Cited References	**Burst Period (largest to smallest)**
Berman & Hartmanis (1977)	1986-1997
Ebbinghaus & Flum (1995)	1997-2004
Rogers (1987)	1973-1997
Baker, Gill & Solovay (1975)	1980-1999
Garey & Johnson (1979)	1981-2000
Cook (1971)	1982-1997
Hopcroft & Ullman (1979)	1982-1998
Stockmeyer (1977)	1984-1999
Immerman (1987)	1990-2000
Blum, Shub & Smale (1989)	1992-2003

Locally Frequently Cited References	**Local citation Count**
Garey & Johnson (1979)	131
Papadimitriou (1993)	83
Cilliers (1998)	80
Waldrop (1992)	73
Kauffman (1993)	69
Anderson (1999)	59
Kauffman (1995)	58
Holland (1995)	58
Brown & Eisenhardt (1997)	44
Gleick (1997)	44

Table 2: *Comparison of citation burst analysis and local citation count*

Discussion

Evidence that management researchers are a later adopter of Complexity Theory than mathematics and computer science researchers can be seen in Figure 4, representing the Complexity Theory citation network at different points in time. This is also supported by a burst analysis of the research fields of publications in the dataset (Table 1). Based on this evidence, earlier suggestions that Complexity Theory as applied to management would only be a short-lived fad (e.g. KcKelvey, 1999; Thrift, 1999) can be considered to have not yet come true. Management researchers appear to be continuing to investigate ways of applying Complexity Theory to management problems.

Other authors have commented that there is a divide between Complexity Theory as applied in management research, and as applied in mathematical and computer science research, and that this divide is to the detriment of management research. In 1999, the following comments were made about Complexity Theory as applied to management:

> "If we are to have an effective complexity science applied to firms, we should first see a systematic agenda linking theory development with mathematical or computational model development. The counterfactual tests are carried out via the theory–model link. We should also see a systematic agenda linking model structures with real-world structures. The test of the model–phenomena link focus on how well the model refers, that is, represents real-world behavior. Without evidence that both of these agendas are being actively pursued, there is no reason to believe that we have a complexity science of firms." (McKelvey, 1999: 24)

Six years later, it was noted that "…there is no indication that mathematical techniques used by complexity theorists in the natural sciences have been or can be applied to the complex and dynamic human processes in organizations…" (Burnes, 2005: 86).

The authors remain positive about the feasibility of using complexity theorists' mathematical techniques in organizational contexts. This research does however indicate that so far there has been little link in the literature between these two groups. This can be seen in the visualisation of the research fields to which authors contribute (Figure 3). This research indicates that it is rare for Complexity Theory researchers to contribute both management research and to research in mathematics or computer science.

Evidence of a divide within Complexity Theory research can also be seen in the publications authors cite (Figure 4). Evidence of predominantly separate literatures should be of note for those interested in greater unification in the diverse field of Complexity Theory research, and for those who advocate for the use of Complexity Theory concepts in management and organisational research at a level past that of explanatory metaphor. These separate citation networks, representing different literatures, suggest distinct virtual communities of research. Researchers contextualise their work through the works they cite. These predominantly separate literatures imply different research contexts, and suggest researchers who are potentially engaging in very different conversations about what Complexity Theory is, and how it relates to research.

Greater unification between these virtual communities may be of benefit to both sides of this divide. Indeed, there is a growing body of literature to suggest that pluralism, "... the use of different methodologies, methods and/or techniques in combination ..." (Jackson, 1999, p. 12), can provide many benefits that cannot be gained through the application of a single approach. Increased application of mathematical and computational techniques in organisational research would help to move the application of Complexity Theory in the management disciplines past explanatory metaphor to theory testing and model development, while increased use of sociological and phenomenological techniques may help in contextualising mathematical models. "A complex phenomenon often needs more than one method to investigate it adequately" (Cameron & Sankaran, 2013, pp.393-4). Complexity Theory is an interdisciplinary field, where findings are commonly transferred between otherwise disparate disciplines. It is possible that insight gained from theory development and testing in a management context might also add insight to researchers in the other disciplines, to the benefit of Complexity Theory as a whole.

The research techniques and the available data used in this study did not allow for a more detailed examination of the boundaries, key identifying characteristics, themes or significant contributors of these virtual communities of researchers. The authors suggest that examination of the differences and common points of reference between these communities could be a fruitful area of future research, which may facilitate development of a common understanding between these groups. In addition, a greater understanding of factors that have inhibited the transfer of ideas from the mathematical and computational aspects of Complexity Theory research to application in the management and social sciences may be of aid in further strengthening links between these communities. Cultural, institutional and funding barriers (Mingers, 2003, p. 246), differences in researchers'' skill sets (Munro & Mingers, 2002, p. 369), and their fundamental world views (Mingers & Brocklesby, 1997, p. 499) have all been identified as issues in developing pluralist practice in other fields, but their specific impact on Complexity Theory Research, and ways of mitigating these factors, would need to be examined through separate research.

Gregory (2003, p. 128) has noted that there are a number of forms of pluralism, while Cameron and Sankaran have identified a trend for the "…increased use of MMR [Mixed-Method Research] designs in research being reported in several fields…" (2013, p.398). Many other allied fields have moved from a division between qualitative and quantitative research techniques to exploration of opportunities for integration between otherwise distinct camps, and this pattern may be replicated here. To use Reed's (1985) classification of different forms of relationship between ways of conducting research, the field of Complexity Theory research may be moving from a period of isolationism to a greater acceptance of pluralism. The division between these virtual communities may already be eroding, although only time will reveal whether this will gain momentum.

Conclusion

The evidence presented in the paper suggests that the application of Complexity Theory to management problems is not a short-lived fad. Researchers continue to draw upon Complexity Theory to provide a level of insight on organizational issues that cannot be found elsewhere. Researchers contributing to Complexity Theory appear to be broadly spread across the globe, suggesting that group of ideas comprising Complexity Theory are valued across a broad range of cultures and research agendas, rather than being the focus of a limited core of specialised researchers.

However, a divide remains between the referencing patterns of authors who focus on management as opposed to mathematical or computer science related issues, suggesting the existence of distinct virtual communities of research, with potentially disparate interpretations of the field. Calls made by McKelvey (1999) and Burnes (2005) for an increased application of mathematical / computer science techniques to organizational issues, and for theory development and testing within an organizational context, appear to remain predominantly unanswered. Complexity Theory encompasses a range of ideas which have gained considerable popularity within the organizational research as a way of interpreting and understanding management activity. However, there remains a need for greater application of Complexity Theorists' mathematical and computational techniques in organizational contexts, to progress the application of Complexity Theory in management past explanatory metaphor to theory and model testing, and to contribute to a greater unification of the field.

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