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# Self-organising supply networks: a case study of the SA mining industry

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*Abstract*– For efficient operation, it is vital for supply chain management leaders and policy makers to recognize the nature of the system they deal with. Supply chains, are increasingly recognized as systems of systems, which are complex networks exhibiting self-organising properties. In large scale real-life networks, self-organisation manifests itself in distinctive structural patterns, such as Power Law connectivity distribution, scale-free, fractal, and nearly decomposable modular structure. Identification of such structural patterns in real-world supply networks may provide useful insights into their dynamics and functionality, and as a result, apply adequate governance frameworks to embrace structural complexity. To this end, the methods for identification of complexity traits in real-world industrial supply networks are of interest. A case study of the mining industry supply network in South Australia has been used to propose a method for identifying self-organisation patterns in regional industrial supply network structures. The approach combines network analysis and recent methods for testing Power Law distributions. The findings provide insights into the mining industry supply network functionality, including such operational characteristics as robustness, responsiveness, flexibility, and resilience.

*Keywords—supply networks, mining industry supply chain, structural patterns of self-organisation in complex systems*

## I. INTRODUCTION

The mining industry and its associated supply chains recently experience the need for new management frameworks to deal with increasing dynamism and complexity. However, mining industry supply chains are still traditionally viewed by scholars and practitioners as hierarchical or linear [1].

Increasing complexity of supply chains in various industrial contexts, lead to the development of new approaches to manage them effectively and efficiently. Industrial supply chains have been increasingly recognized as a system of systems, which is essentially a complex network [2]–[6]. Supply networks are seen as sets of intertwined supply chains that transmit the flow of goods and services from original sources of raw materials to the end customer [6], [7].

Supply chain management frameworks incorporating complex networks approaches have been mainly developed through application of modelling and simulation techniques [1], [2]. However, there are fewer empirical studies done that focus on examining structural properties of real-world supply networks that may vary significantly depending on the nature of the industrial relationships. There is a need for empirical validation of recently developed frameworks and methods that incorporate complex systems views in the supply chain context [2]–[4].

In this paper, we explore *whether regional supply networks (specifically, emphasizing the nature of the mining industry) exhibit structural patterns of self-organised complex networks and what are the implications for policy-makers and practitioners?*

To answer research questions, we are proposing a method for identifying structural patterns of self-organisation in the geographically bounded supply networks, that combines network analysis and Power Law (PL) testing tools [8].

As a case study, we will explore the structural patterns of the South Australian segment of mining industry supply network. Based on empirical data of 2794 companies and their connections in the South Australian mining industry supply chain, we have discovered that the supply network exhibits scale-free structure and self-repeating patterns in degree distribution in decomposition, which is similar to other real-world networks.

This has the following implications for regional policy makers and mining industry supply chain managers (1) regional mining industry supply chains are self-organising complex networks and relevant governance frameworks must be applied to manage them efficiently and effectively; (2) in order to incentivise resilient and responsive regional mining industry supply chains, structural aspects should be considered and monitored on a regular basis; (3) the proposed method could be used as a dashboard for assessing supply chains complexity and could be extended to other industrial contexts.

The paper is organized as follows. Section II describes the problem of supply chain management in the mining industry, Section III draws on theory of complex networks and self-organisation to explain structure and dynamics of complex supply networks; Section IV presents a case study of the SA mining supply network. A discussion of findings and practical implications are provided in Section V, which concludes the paper.

## II. THE MINING INDUSTRY SUPPLY CHAINS

Mining industry supply chains currently experience the need for adequate management frameworks to deal with increasing dynamism and complexity. The recent trends of flexible production incorporating outsourcing practices in the mining industry, significantly increased interconnectedness and complexity of the mining industry supply chains driving the them towards flat and decentralized structures. However, linear and hierarchical management models still dominate. Mining companies use hierarchical approaches, while supplier companies usually do not extend supply chain management beyond direct transactions [9]. Local policy-makers involved in the enhancement of regional supply chain efficiency, experience information uncertainty.

The majority of scholarly works also consider mining industry supply chains from linear [1], [10] or hierarchical [9], [11] perspectives. These models and frameworks do not provide adequate basis to deal with current complexity and networked structure of the mining industry supply chains. The network-level properties of supply chains such as responsiveness, adaptability and resilience could not be captured by linear methodologies and require approaches based on system of systems and complex networks views [4].

## III. STRUCTURAL PATTERNS OF COMPLEX NETWORKS AND THEIR APPLICATION IN SUPPLY NETWORKS CONTEXT

Supply networks are identified as sets of supply chains that transfer flows of goods and services from original sources to the end customer [6]. They are characterised by complex non-linear dynamic interactions between firms and organisations, existing in a multitude of different topologies, they are complex and bidirectional, having parallel and lateral links, loops, and exchanges of materials, finance, and information [7].

The complex networks approach has been mainly applied in three major themes in supply networks research: network structure, networks dynamics, and system network governance strategy. Network structure research focuses on supply network components, their connectivity and firm-level structural properties, flow types and tier strengths e.g. [10], [12]. System behaviour studies look at formation, change and evolution of supply networks considering network level parameters such as adaptability, responsiveness, resilience, and robustness from complex systems perspective e.g.[1], [13]. System policy and control studies suggest governance frameworks that allow to leverage and improve supply network performance e.g. [2], [4], [14]. The methods most commonly used are simulation and modelling e.g. [1]–[3] and Social Network Analysis [10], e.g. [15], [16].

Complex network structures have often been attributed to the dynamics of the interwoven web of relationships among multiple constituents, which interact with each other producing large-scale patterns. A generic property of complex networks is that they constantly grow and evolve over time due to process of self-organisation. The dynamic forces that act at the level of individual nodes, produce cumulative effects, that determine the network large-scale structural patterns [17]–[19]. These patterns could be discovered in real-world networks through

assessing a number of network structural parameters, such as degree distribution, network density and clustering, average path length, size of the largest connected component, small-world properties, modularity and self-similarity across all levels of decomposition .

- *PL distribution of nodes' degree in the network* reflects its *scale-free structure.* Such a structure means that the network evolution is driven by at least two coexisting mechanisms: 1) growth, implying that network continuously expands by adding new nodes; and 2) preferential attachment, implying that every incoming node tends to link to the nodes that already have a large number of links [20]. A quantity x obeys a PL if it is drawn from a probability distribution $p(x) \sim x^{-\alpha}$, where $\alpha$ is the exponent or scaling parameter of the distribution known [8]. *Scale-free structures* are to be considered resilient to random attacks and disturbances.

- Dense networks, characterised by *high clustering coefficient,* are seen to be flexible and adaptive to changes in external envirionment [17].

- *Short average path length* in the supply network is a sign of its responsiveness [21], [13].

- *The size of the largest connected component of a network* is associated with network robustness and resilience [21], [13].

- A *small-world property* exhibits in the network structure, when the average distance between nodes is a logarithm of the size of the network, whereas the clustering coefficient (or density) is larger than in a random Erdos-Renyi graph with the same size and average distance [17]. Small-world structure of any network could be identified as proposed by Watts and Strogatz by comparing: (1) the average number of links in the shortest path, and (2) the clustering coefficient. The randomised graph metrics $L_r$ and $C_r$ are compared to the $L_a$ and $C_a$ of an actual graph. If $L_a$ and $C_a$ are significantly greater than the random figures - $L_r$ and $C_r$, the network exhibits a small-world structure. *Small-world network topologies* are seen as resilient as scale-free structures.

- *Hierarchical modularity or decomposability*, is an ability of complex networks to be divided into a set of almost non-overlapping modules or clusters, which have high connectedness within a module, but relatively moderate amount of links between the modules [22]. In complex networks such modules are found at different hierarchical levels. Modularity in supply networks contributes to network resilience and ability to adapt to changing environment[5], [21].

- *Self-similarity* (similarity over different length scales) is property of self-organising networks to exhibit self-repeating patterns at all levels of

decomposition. Scale-free networks exhibit the absence of a characteristic degree (i.e. the number of connections for a network node). Self-similarity has been discovered in complex networks by applying methods, including k-core decomposition [23]. It contributes to complex networks robustness and resilience properties.

Identification of these structural patterns in industrial supply networks may provide valuable insights into dynamics and effectiveness of industrial relationships for practitioners and policy-makers. The authors applied network analysis and a recent method for identification of PL degree distribution proposed by Clauset et al. [8] to assess whether mining industry supply networks exhibit any of the structural patterns of complex networks.

## IV. ARE MINING INDUSTRY SUPPLY CHAINS SELF-ORGANISING COMPLEX NETWORKS? A CASE STUDY OF THE SA MINING INDUSTRY

### A. Network boundaries

To establish the boundaries of a network of interest, the authors consider the mining industry supply network as a set of firms that are engaged directly or indirectly in economic transactions within the SA mining industry (Fig. 1).
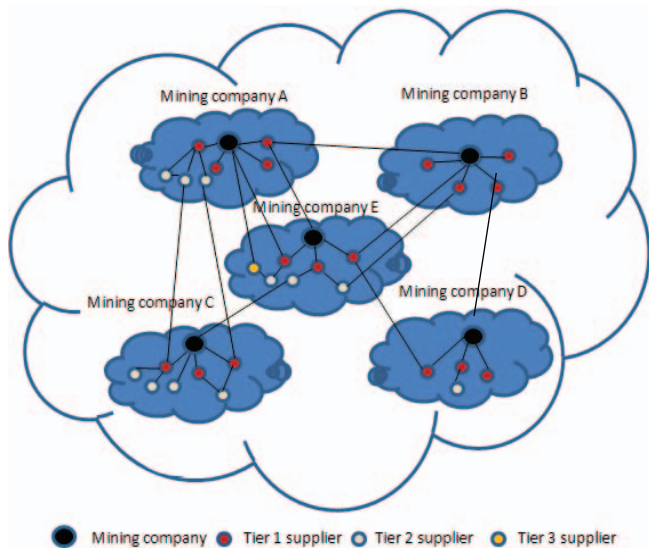


Fig. 1. The boundaries of SA mining industry supply network

Australian mining industry databases, Industry Capability Network (ICN) and Global Maintenance Upper Spencer Gulf (GMUSG), were used to identify companies operating in the state. Filter criteria have been applied to extract companies (1) who identified themselves as suppliers to the mining industry, (2) who identified themselves as operating in South Australia. The supplier-buyer relationships of these companies have been extracted to reconstruct the supply network.

### B. Analysis and results

The first step in identifying structural patterns of self-organisation in the supply network of interest was to calculate basic network parameters, including average degree, network density and clustering coefficient, average path length and the size of the largest connected component (Table 1).

To estimate whether the degree distribution fits the PL model, the procedure described in was applied [8]. The scaling exponent α of a PL probability density function – $p(x) \sim x^{-\alpha}$, and the lower bound of power-law behavior $x_{min}$ were estimated via Maximum Likelihood Estimation (MLE) and Kolmogorov–Smirnov (K-S) goodness-of-fit statistic. Smaller K-S values ≤0.1 indicate better conformity to a PL. A scaling parameter α represents the overall dynamics of the distribution: the closer it is to 1, the longer the tail, and the greater proportion of the total distribution is in the tail (i.e., a greater proportion of extreme scores. $x_{min}$ is a lower bound of power-law behavior in the data [8]. The results are presented in Table II.

Self-similarity has been tested through application of k-core decomposition procedure, which allows for identifying hierarchical properties in large scale networks [23]. Using a recursive pruning strategy this procedure extracts network regions of increasing centrality and connectedness (k-cores).

A subgraph $H = (C, E \mid C)$ induced by the set $C \subseteq V$ is a k-core if and only if the degree of every node $v \in C$ induced in $H$ is greater or equal than $k$, and $H$ is the maximum subgraph with this property. A vertex $i$ has shell index $k$ if it belongs to the $k$-core but not to $(k+1)$ - core. A $k$-shell $S_k$ is composed by all the vertices whose shell index is $k$. The maximum value $k$ such that $S_k$ is not empty is denoted $k_{max}$. The k-core is thus the union of all shells $S_c$ with $c \geq k$ [23].

In the case of the SA supply network the decomposition procedure has identified $k_{max}=10$. The number of nodes belonging to each kCore with shell indices 1-10 as well as the parameters of the PL probability density function are presented in Table II.

The kCores have revealed approximately the same shape of the PL distribution which has not been affected by the decomposition, thus showing hierarchical similarity. The degree distribution and kCores with shell indices 1-4 fit into a PL model with K-S values ≤ 0.10 [24]. However, the most densely connected part of the network with shell indices 5-10, show significant deviation from a PL distribution, with high K-S values, at the same time with only minor deviation in α and $x_{min}$, which is consistent with other studies in complex networks [23].

TABLE I.    SA MINING INDUSTRY SUPPLY NETWORK PARAMETERS

| Parameter | Value |
|---|---|
| Number of nodes | 2,473 |
| Number of connections | 7,069 |
| Average Degree | 5.28 |
| Density | 0.001 |
| Clustering coefficient ($C_a$) | 0.028 |
| Average path length ($L_a$) | 4.110 |
| Size of largest connected component | 2460 |
| Kmax (Kcore decomposition) | 10 |

TABLE II.    NETWORK PARAMETERS TESTED FOR PL DISTRIBUTION

| Measure | PL statistics | | | N |
|---|---|---|---|---|
| | K-S | $\alpha$ | $x_{min}$ | |
| Degree | 0.00 | 2.01 | 2 | 2794 |
| kCore 1 | 0.00 | 2.01 | 2 | 2597 |
| kCore 2 | 0.00 | 2.01 | 2 | 1139 |
| kCore 3 | 0.00 | 2.01 | 2 | 867 |
| kCore 4 | 0.00 | 2.04 | 3 | 715 |
| kCore 5 | -516.62 | 2.25 | 9 | 596 |
| kCore 7 | -516.62 | 2.25 | 9 | 365 |
| kCore 9 | -483.65 | 2.15 | 9 | 199 |
| kCore 10 | -147.54 | 2.71 | 31 | 145 |

## V.    SECTION 4. CONCLUSION AND FUTURE WORK

This paper proposes the method for identifying structural patterns that could be used to define complexity traits in the industrial supply chains. The method could be used as a dashboard to assess and monitor interconnectedness and complexity of any given geographically localised supply chain.

As a case study, this paper explores through empirical testing whether the connectivity of firms within the SA mining industry supply network exhibits structural patterns of self-organisation. The results show that: (1) the supply network connectivity parameters statistically fit a PL distribution, thus exhibiting scale-free structure, (2) the regional supply network reveals self-similarity in connectivity distribution when applying hierarchical decomposition procedure, (3) the path length and clustering coefficient do not allow to assert the presence of a "small-world" structure in the supply network.

These results could imply that regional supply networks are self-organising complex networks, or in other words, systems of systems [25]. As it is has been shown from insights into the mining industry supply network, these structural patterns are functionally related to its operational characteristics as robustness, responsiveness, flexibility, and resilience.

The  important insights for policy makers and mining industry supply chain managers are as follows (1) regional mining industry supply chains are complex systems or systems of systems and self-organising complex networks and relevant governance frameworks must be applied to manage them efficiently and effectively; (2) in order to incentivise resilient and responsive regional mining industry supply chains, their structure should be monitored on the regular basis; (3) the application of the proposed method could be extended to analysing supply chains in other industrial contexts.

Authors believe that governance frameworks have to be informed by an understanding of the true nature of regional supply chain networks in order to ensure development of efficient and effective strategies and policies for developing better to overcome current challenges of integration faced by mining sector supply chains.

Authors acknowledge the limitations of this study in terms of unavoidable measurement bias, as it has been acknowledged by other authors studying complex networks, e.g. [22], [23]. The database used in this study includes information about the most prominent firms within the SA mining industry, which may cause bias in parameter estimation. However, given the large sample size, nature of the research question and the level of analysis, it could be asserted that at a large scale the structural patterns attributed to self-organisation processes have been captured.

Further research will examine the interaction dynamics and decision-making mechanisms of firms operating in the mining industry supply networks.

## VI.    ACKNOWLEDGEMENTS

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