Relating Organisational Structure to Performance: An Initial Focus on Centralisation

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Abstract. This paper will focus on relating organisational structure with organisational performance. We first outline the motivation behind this research, from both industrial and academic perspectives. After defining the problem and the research aim, an outline of organisational performance metrics is provided, followed by a detailed look at the centralisation metric. Finally, using our test-bed simulation, the metric is applied and compared against the simulation's performance output, namely speed and robustness. We show that while the centralisation metric is a sufficient measure of performance, the implementation of further metrics should produce further promising results.

Keywords. *Agents, Organisations, Centralisation, Entropy, Stigmergy*

1 Background and Motivation

Organisations are the structured, patterned systems of knowledge, activity, memory, culture, history, and capabilities that are distinct from any single member or agent. They are 'supra-individuals', exhibiting behaviours independent of specific individual attributes [9, 12].

An organisation, be it a government health care system, a distributed (i.e. spatially and/or temporally separated) sensor array system, birds in a flock, or nodes in a telecommunications network, will usually exhibit emergent behaviour. This emergent behaviour is typically unintended and detrimental [18]; for vivid examples of this in telecommunication networks, see [11, 15, 20]. Not all emergent behaviour is unfavourable: positive emergence can be found in ant path planning, bird flocking and the Internet [5, 14]. An organisation with positive emergence is usually described as "*a whole greater than the sum of its parts*" [2, 13, 22]. Organisations that are closely linked to their environment and display adaptability and robustness to change are known as self-organising systems [2, 5, 28].

In the past, man-made systems and organisations for the creation and maintenance of products have been relatively easy to design, understand and alter. This, however, is changing [23, 24]. We can see this by comparing trends in agent function and use within current organisations and systems, with the challenge to our understanding of organisational behaviour. This is shown in ***table 1***, adapted from [9].

Furthermore, in traditional systems engineering, a sequential mechanistic approach was adopted. Cause and effect were clear. In management, centralised control – similar to classical control systems – was the preferred approach. Now, however, as systems, organisations and society as a whole expand in size, co-dependence and interactivity, their behaviour exhibits increasing emergence and complexity [25].

Table 1: *Trends in organisations increasingly challenge our understanding of them*

Trends in Organisations/Systems	Challenge to our Understanding
Increase in number of agents	As agents are social, they communicate; if every agent is connected to every other agent, they will have an 'information overload'. Agents may then spend more time processing information rather than acting on it. Building a system that balances information overload with global coordination is a challenge [21].
Increase in agent specialisation	It is easier to make agent skills domain specific, rather than build a generic agent. However, efficient and effective agent coordination is required if heterogeneous agent cooperation is required to solve a problem. Specialisation may also lead to centralised control.
Decrease in agent capability	Simple agents are easier to maintain. However, the desired behaviours in the organisation may have to be engineered to emerge out of the simple agents' interactions, rather than explicitly design it in [21].
Decrease in resources and resource slack	As resources in a system are reduced, the interdependence between the agents increases. This requires good resource allocation and agent coordination [3].

Perhaps as a coping strategy, there is a broad decentralisation trend that is sweeping through these domains [1]. This decentralisation trend has lead to a closer contact with the local environment, forcing systems and organisations to have faster responses to local environmental change, amplifying the decentralisation trend – a form of positive feedback if you will. This trend leads to increasing complexity, as described in ***figure 1***, where we see that as organisations get closer to their environment, complexity increases.

This trend is underlined by Sir Richard Evans, chairman of the defence company BAE SYSTEMS, stating "Systems capability has become more important than individual technologies and products. Obviously it's easier to make a single item, however sophisticated, than to integrate it into a large environment of complex devices and understand how it will perform" [6]. Unfortunately, we have a limited principled methodology of how to organise complex, interdependent, heterogeneous, semi-autonomous agents – and the infrastructure to support them – into aggregates with predictable, stable, and reliable behaviour at a very large scale [9].

We also lack a solid understanding of which types of organisational structures are appropriate to which organisation; a centralised organisation favours complex but static problems, whereas a decentralised system will work well for a dynamic problem when the costs of reconfiguration are low [1].

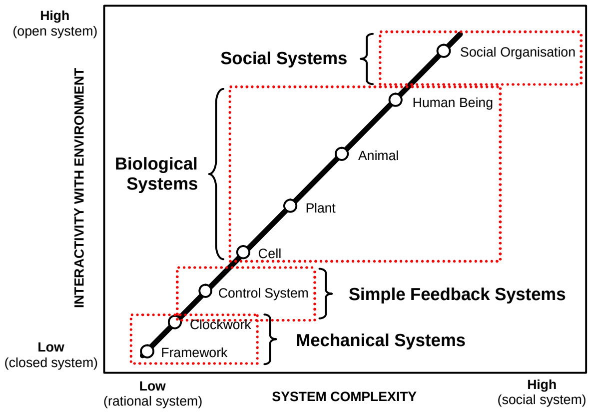

Figure 1: *Hierarchy of Complexity (Kenneth Boulding)*

While the centrality of an organisation is an important metric, there are many others. To fully understand and build a quantitative methodology of how different types of organisational structures perform in what way, which environment and how, we first need to measure the structure of the organisations and equate this with performance.

2 Organisational Metrics

An organisation's behaviour primarily is a function of its environment, agents and structure (how its elements are connected) [3, 16]. When looking at generic behaviours such as robustness, efficiency and optimality, we would expect that, regardless of application domain, similar organisations would behave in similar ways. It is for this reason that many researchers have looked to biological organisations for inspiration when engineering systems. See [10, 19, 21] for examples.

Relating an organisation's relationship with its environment, agents and structure with its position on the hierarchical complexity line in ***figure 1*** is a possibility. However, according to this conjecture, complexity is proportional to interactivity with the environment. However, the complexity of a system is also directly related to the level of control in a system which is a much more intuitive measure[1]. The continuum of control is shown in ***table 2***.

[1] While it is clear that the 'low-entropy' end of the continuum corresponds to a low level of interaction with the environment and therefore low complexity, it is less clear where the 'high-entropy' end sits. This is because the Hierarchy of Complexity in ***figure 1*** ends prematurely. Social organisations, the last category in the Hierarchy of Complexity, sit between 'control without controlling' and 'strange attractors' in ***table 2***. If the complexity axis were extended and the 'high point' redefined as 'irrational', both systems would fit. This makes sense, as a truly anarchic, individualistic system would be entirely dependant on its environment, and therefore very complex.

Table 2: *Continuum of control and order in systems*

	High Entropy ⟵			⟶ Low Entropy	
Description of Control	**No Control**	**Strange Attractors**	**Control without Controlling**	**Command/ Control**	**Total Control**
System Type	Random	Chaotic	Coherent	Top down Command	Mechanistic or Rigid
Relationships	Independent random relationship; anarchy	Random relationships with underlying regularities	Highly ordered interdependent relationships in which the costs of achieving order minimised, i.e. "order for free"	Predominantly dependent relationships. Order is controlled from above with significant added costs	Fully dependent, fixed and immutable relationships

If we could measure an organisation's behaviour, its entropy would show us how much control there is in the system. This has been shown in flocking systems, where the entropy is measured for flocks that exhibit crystalline behaviour and compared to flocks that move in a more chaotic fashion [27].

While linking an organisation's structure with its entropy is useful, it is even more useful to link this to an organisation's performance. The problem doing this is that performance metrics are less generic. While some performance measures may be relevant to all organisation (robustness, efficiency) others will be quite specific (bureaucracy, response time). Having said that, measuring an organisation's make up can be carried out in a non-specific manner if the required data is collated. Such metrics can include:

Table 3: *Examples of metrics used to measure an organisation's properties*

Metric	Description
Homogeneity / Heterogeneity	Degree of differentiation between agents. Linked to how specialised agents are. See [17] for work on measuring this in agent systems and its effects.
Degree of Hierarchy	Number of levels between agents where information passes in one direction.
Hierarchical levels	Number of cycles in an organisation, a cycle being defined as a complete circuit of one way links between three or more agents.
Sequentiality / Parallelism	Whether agent a_1 can function regardless of agent a_2, or if it can function only after a_2 has acted. There can be degrees to this measure – perhaps a_1 can function without a_2, but performs better if agent a_2 acts before a_1 does.
Hierarchical latency	A system or part of a system may not necessarily be hierarchical (a pyramid organisation is actually centralised; links between the levels are actually bi-directional) but the time taken for information from the bottom level to reach the top and back down again creates a hierarchical latency.

A metric to measure the level of centralisation in an organisation, an additional metric, is discussed in detail in the following section.

3 A Focus on Centralisation

Centralisation refers to overall integration or cohesion of a network graph, indicating the extent to which a graph is organised around its most central point [7, 26]. We use this as a measure degree centralisation. The degree of a point is defined by the number of arrows efferent or afferent to the point in a network graph [7, 26]. Conceptually, the degree of a point in a graph is the size of its neighbourhood. This is measured by the aggregate difference between the centrality scores of the most central point and those of all other points. It is the ratio of the sum of differences to the maximum possible sum of differences. Degree centrality scores can range from 0 to 1, 0 being the score for a completely decentralised network. The following equations have been adapted to cope with multiple links between agents as well as single ones. Rather than give the centrality of the entire organisation, it measures the centrality of communication; whilst the original method took unconnected nodes into account, this method ignores them[2]. The centrality of communication is given by:

$$C_D = \frac{\sum_{x \in E} \left(C_D(x^*) - C_D(x) \right)}{n-1} \qquad \text{where} \qquad C_D(x) = \frac{c_D(x)}{\text{highest degree}} = \frac{c_D(x)}{c_D(x^*)}$$

The denominator $c_D(x^*)$ is the highest number of arrows afferent and efferent from a point or points in the organisation. $C_D(x^*)$ is therefore always equal to 1, and n refers to the global number of connections between agents. Either agents are connected, and so $n = n + 1$ (regardless of the *number* of links) or not.

Figure 2 shows three examples of how the centralisation of communication metric can be applied. Note that the direction of communication does not affect the analysis – that is related to how hierarchical a system is. ***Example 2.3*** illustrates how having multiple connections between agents affects the centralisation score.

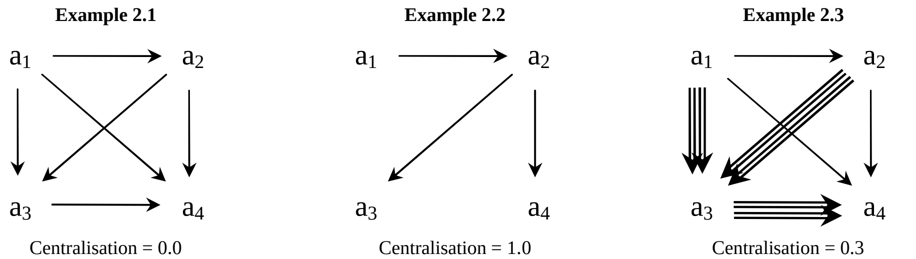

Figure 2: *Organisational structure diagrams with corresponding centralisation metric*

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[2] Having a completely unconnected node or agent represents a totally redundant agent. A specific measure to see how many redundant agents exist in an organisation can be applied simply, and would be far more useful for understanding and designing organisations.

Instead of using network graphs, we can use an organisational matrix which can be implemented computationally. This is a simple representation of connections from and to nodes in a chart. Using ***example 2.3*** above, the chart can be represented as show in ***table 4***.

Table 4: *A tabulated version of the organisational structure shown in* ***example 2.3***

		TO			
		Agent 1	**Agent 2**	**Agent 3**	**Agent 4**
F	**Agent 1**	0	1	4	1
R	**Agent 2**	0	0	4	1
O	**Agent 3**	0	0	0	4
M	**Agent 4**	0	0	0	0

The application of this centrality metric is applied to our simulation test-bed, discussed next.

4 Initial Concept Demonstrator

The Java-based Initial Concept Demonstrator (ICD) creates a multi-agent scenario to examine emergent organisational behaviour and apply organisational metrics. The ICD scenario is based on a two-dimensional grid operating a generic "seek, identify and destroy" objective. The agents move around the grid via Brownian motion searching for 'targets'. Agents have sensing capabilities, which determine the *sensor range* – the distance an agent can sense a target, and the *destroy range* – the distance an agent can destroy targets. Agents can have a single ability or a mix of the two.

When a target is within the sensor range, the agent communicates that a potential target has been found by placing a communication 'beacon' around the target. Agents that destroy targets and are inside a 'beacon' region will travel towards the centre of the beacon signal. This is a form on non-explicit communication that relies on stigmergy. Each simulation scenario is repeated with random start positions of agents and targets until the average time taken to find the target converges [4]. A typical heterogeneous agent scenario screen shot is provided in ***figure 3*** with explanations. A more detailed explanation and validation of this model can be found in [8].

To examine the effect of centralisation on the ICD, a simple question was posed – keeping the cost of the system equal, which organisation configuration will perform 'better'? The performance criteria are discussed later.

The many possible variations for the scenario were fixed, for illustrative purposes, as follows: environment size = 50 by 50 grid units, beacon radius = 10 grid units, number of agents = 10.

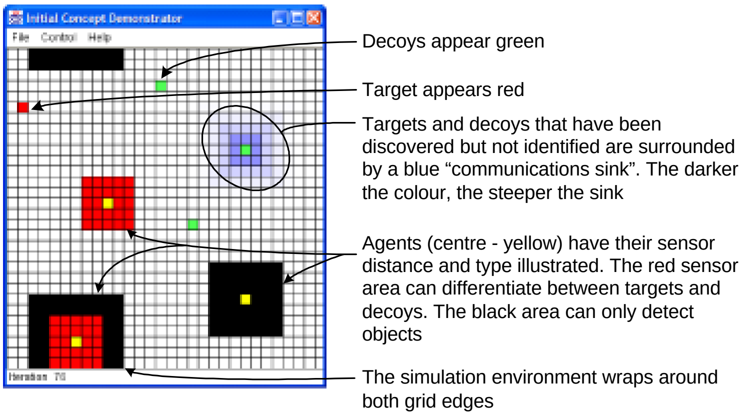

Figure 3: *A typical ICD scenario display*

The only parameter altered was the distribution of search and destroy squares between the 10 agents, although this was kept constant as far as possible in terms of global coverage, with 160 search (black) squares and 80 destroy (red) squares. The four configurations tested are shown in ***table 5***.

Table 5: *The four scenarios used to measure centralisation. The digits refer to the number of search and/or destroy squares around each agent*

	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**	
	Destroy	Search	Destroy	Search	Destroy	Search	Destroy	Search
Agent 1	8	16	24		8	16	8	
Agent 2	8	16	24		8	16	8	
Agent 3	8	16	24		8	16	8	
Agent 4	8	16	8		8	16	8	
Agent 5	8	16	8		24		8	
Agent 6	8	16		24	24		8	
Agent 7	8	16		24		24	8	
Agent 8	8	16		24		24	8	
Agent 9	8	16		24		24	8	
Agent 10	8	16		24		24		168
Global Sum	**80**	**160**	**88**	**140**	**80**	**160**	**72**	**168**

5 Results and Discussion

The performance criteria to determine which scenario configuration was superior were based on two measures, namely speed and robustness. Speed is defined as the average time taken (from the sample of the population mean) to destroy the target. Robustness is defined at the time taken to find the target after removing the most influential agent from the scenario – the worst case scenario. The most influential agent is the one with the most links to and from it. For instance, in ***example 2.3***, agent a_3 would be removed.

As shown in ***figure 4***, if speed is the required criterion, scenario 4 fares much better than others taking around half the time than the average of the first three scenarios. This is an intuitive result, as there is far greater centralised coordination (search agent 10 coordinating destroys agents 1 to 9). Using the centralisation metric quantifies this observation; scenario 4 has a centralisation value of 0.17, whereas scenario 1 has a much lower value of 0.0117

However, if robustness is the main criterion, the first two more decentralised scenarios suffer a similarly low performance hit, but as the original configuration (before removal of the most influential agent) increases in centralisation, the robustness of the system is reduced greatly. In fact, scenario 4 descends to the point of complete decentralisation and randomness.

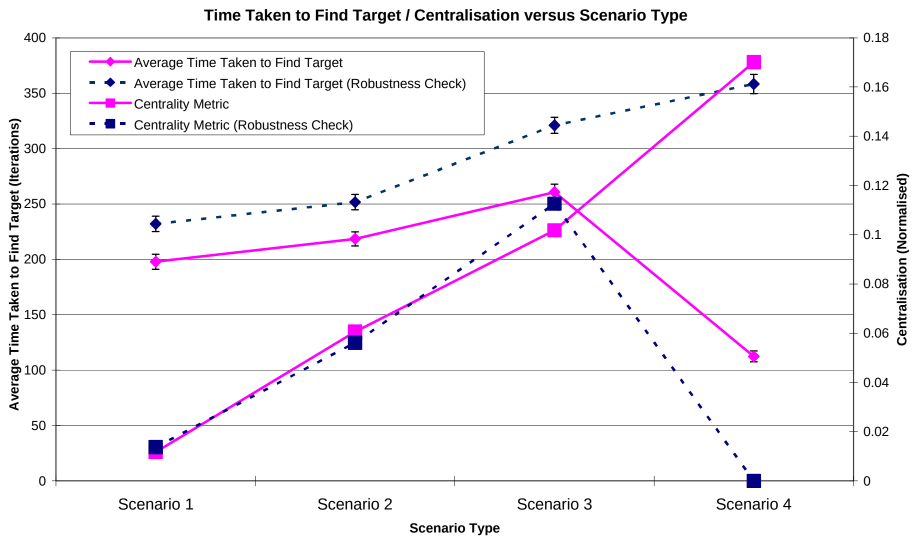

Figure 5: *Relationship between centralisation and speed / robustness*

6 Conclusions and Future Work

We have shown using a simple demonstrator that we can quantify intuitive organisational behaviours; decentralised organisations may perform worse than centralised ones, but they are far more robust. However, the decentralisation metric is not enough on its own. How heterogeneous and hierarchical the system is are also important descriptors of the organisation.

It is therefore the future aim of this research to incorporate further metrics and determine which ones act independent of others, using careful experimental design (such as Latin Squares) to cope with the multiple variable nature of this problem. Once achieved, a map of organisational make up to performance can be created to predict performance and recommend organisational make up based on performance requirements.

Such a model can be incorporated in a feedback learning system and a cost function (limiting the amount a system has to 'spend') to find and maintain an organisation at a required performance setting. This concept will then to be extended to more specific industrial issues, such as unmanned air vehicle (UAV) composition based on mission requirements and available inventory, as well as manufacturing lines. With further examples, we can examine the possibility of implementing a generic engineering methodology to link in organisational performance to organisational make up.

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References

[1] C. Anderson and I. John J. Bartholdi, "Centralized versus decentralized control in manufacturing: lessons from social insects," presented at Complexity and Complex Systems in Industry, University of Warwick, 2000.

[2] R. Ashby, "Principles of the self-organizing dynamic system," *Journal of General Psychology*, vol. 37, pp. 125 - 128, 1947.

[3] E. Bonabeau, G. Theraulaz, D. J.L, S. Aron, and S. Camazine, "Self-organization in social insects," *Trends Ecol. Evoll.*, pp. 188-193, 1997.

[4] T. F. Chan, G. H. Golub, and R. J. LeVeque, "Algorithms for computing the sample variance: analysis and recommendations," *The American Statistician*, vol. 37, pp. 242-247, 1983.

[5] J. Cohen and I. Stewart, *The collapse of chaos : discovering simplicity in a complex world*. New York: Viking, 1994.

[6] R. Evans, "Hard Choices," in *Aerospace International*, May 2001.

[7] L. C. Freeman, "Centrality in Social Networks I: Conceptual Clarification," *Social Networks*, vol. 1, pp. 215-239, 1979.

[8] J. M. E. Gabbai, W. A. Wright, and N. M. Allinson, "Centralised and Distributed Organisational Control," presented at Intelligent Data Engineering and Automated Learning, Manchester, 2002.

[9] L. Gasser, "Perspectives on Organizations in Multi-agent Systems," in *LNAI: Multi-Agent Systems and Applications*, M. Luck, V. Marik, O. Stepankova, and R. Trappl, Eds. Prague: Springer, 2001, pp. 1-16.

[10] R. Geake, "How simple ants can sort out BT's complex nets," in *New Scientist*, vol. 141, 1994, pp. 20.

[11] K. Gerwig, "AT&T Pinpoints Software Problem in Network Outage," vol. 2002: Internetweek.com, 1998.

[12] S. A. Herbert, *The sciences of the artificial*. Cambridge, Mass. ; London: MIT Press, 1996.

[13] S. A. Kauffman, *The origins of order : self-organization and selection in evolution*. New York ; Oxford: Oxford University Press, 1993.

[14] K. Kelly, *Out of control : the new biology of machines, social systems and the economic world*. Reading, Mass. ; Wokingham: Addison-Wesley, 1994.
[15] D. R. Kuhn, "Sources of Failure in the Public Switched Telephone Network," *IEEE Computer*, vol. 30, 1997.
[16] R. Lewin, *Complexity: Life on the Edge of Chaos*. London: Phoenix Paperbacks, 1995.
[17] L. Li, A. Martinoli, and Y. S. Abu-Mostafa, "Emergent Specialisation in Swarm Systems," presented at Intelligent Data Engineering and Automated Learning, Manchester, 2002.
[18] J. Meek, "Things Falling Apart," in *The Guardian*. London, 2001, pp. 2 - 3.
[19] R. Morley and G. Ekberg, "Cases in chaos: complexity-based approaches to manufacturing," presented at Embracing Complexity: A Colloquium on the Application of Complex Adaptive Systems to Business, Cambridge Mass, 1998.
[20] P. G. Neumann, "Cause of AT&T network failure," in *The Risks Digest*, vol. 9, 1990.
[21] V. Parunak, "Industrial Applications of Agents," presented at 2nd European Agent Summer School, Saarbrucken, 2000.
[22] I. Prigogine and I. Stengers, *Order out of chaos : man's new dialogue with nature*. London: Fontana Paperbacks, 1985.
[23] M. Resnick, "Beyond the Centralized Mindset," *Journal of the Learning Sciences*, vol. 5, 1994.
[24] M. Resnick, "Changing the Centralized Mind," in *Technology Review*, 1994.
[25] J. M. Sussman, "Ideas on complexity in systems - twenty views," 2000.
[26] S. Wasserman, and Faust, K., *Social Network Analysis: Methods and Applications*. Cambridge: Cambridge University Press, 1994.
[27] W. A. Wright, R. E. Smith, M. Danek, and P. Greenway, "A Measure of Emergence in an Adapting, Muti-Agent Context," presented at SAB 2000, Paris, 2000.
[28] M. C. Yovits, G. T. Jacobi, and G. D. Goldstein, *Self-organizing systems*. Washington, D.C.: Spartan Books, 1962.