Trends, Implications and Overview of Complex Organizations with a Focus on the Aerospace Industry

Jonathan M. E. Gabbai[1], W. Andy Wright[2], and Nigel M. Allinson[3], Member, IEEE

[1,3] Jonathan M. E. Gabbai and Nigel M. Allinson, EE&E Department, UMIST, Manchester M60 1QD, England, e-mail: j.gabbai@stud.umist.ac.uk, allinson@umist.ac.uk
[2] W. Andy Wright, Department, BAE SYSTEMS, ATC PO Box 5, FPC 267, Bristol BS34 7QW, England, e-mail: andy-src.wright@baesystems.com

Abstract—The Aerospace Industry is at the forefront of technological innovation, both at product level and manufacturing and support levels. We draw upon our experience in this sector to illustrate the increasing challenges that large scale complex organizations, exemplified by this sector, are facing. We examine why traditional methodologies are no longer globally appropriate and discuss how work on multi agent systems and emergence is promising the means to overcome the limitations of traditional approaches. Furthermore, we draw upon our research on relating organizational structure to performance to illustrate how such potential solutions can be applied to organizational complexity. Finally, we conclude by looking at the future of this industry and the technological solutions that may play a part in its evolution.

***Index Terms*—aerospace industry, emergence, complex systems, multi agent systems, organizational structure.**

I. COMPLEXITY IN THE AEROSPACE INDUSTRY

Information Technology is increasingly crucial to industries of all types. The aerospace industry, at the forefront of innovation, is embracing and shaping this industrial impact of IT. David Hughes, editor of Aviation Week and Space Technology, said in a 1998 editorial that “Information technology is becoming a key part of everything the aerospace and defense industry does for a living, and as the century closes it is computers and software that hold the keys to the future. The [aerospace] industry is being transformed from dependence on traditional manufacturing into something that looks more like IBM and Microsoft with wings.” [20]

Not only are new manufacturing systems computer controlled, they are controlled by networked computers, which, increasingly, are globally connected by public or private internets. Such advances in communication and information systems technology are causing global changes to market places. These advances have moved from the stuttered progress, seen in both world wars where mass production in the first and the introduction of aluminum in the second played key roles, into a continuous stream that the aerospace industry experiences today.

A most vivid example of how technology has impacted industries is in the world of defense. Technology has transformed warfare and will continue to do so. Gaining the upper hand now in what is called the *digital battle space* depends as much on the network of information systems around the battlefield as it does on physical platforms [12]. The label “Systems & Defense Industry” is perhaps more fitting than “Aerospace Industry” given these changes.

Technology is also having a major impact on the support structure for the creation and maintenance of these products. For example, aggressive targets were set for the reduction of lead-times, the time from requirements to operation of a solution; Military aircraft design and production traditionally takes around 15 years. This massive lead-time leads to ‘requirement creep’ – what was a requirement during a project’s initiation may have changed significantly several years later.

Another major factor that is affecting the Aerospace Industry is the UK, US and Australian moves advocating and exploring a transition towards what the UK Ministry of Defense terms “Network Enabled Capability” (NEC) [8, 13]. The long-term aim of NEC is to facilitate entities with degree of self-synchronization, meaning a high degree of self awareness within a global context through the “networking of knowledgeable entities that are geographically or hierarchically dispersed” [1].

Thus we find ourselves on the brink of change more fundamental than anything seen before, reaching into every area of industry. Sir Richard Evans, chairman of BAE SYSTEMS illustrated this with the following statement [12]. “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.” This critical issue can be applied not only to products but to entire systems and even organizations that exhibit high levels of interactivity and complexity. Looking at the aerospace industry, this includes:

The Organization and Infrastructure: The aerospace industry is experiencing a generally global trend in the products and services it provides – increased technological complexity requiring greater interaction between business units within an organization, compounded by the lower lead times demanded by customers.

The Products Manufactured: The defense and to a lesser extent civil markets are moving away from conventional products, placing the emphasis on capability requirements (e.g. anyplace, any environment, within a day) and information warfare instead of product specifications. This is leading to an emphasis on non-conventional product solutions that may potentially be autonomous, cheap and numerous instead of manned, expensive and resource intensive.

The Logistics, Manufacturing and Support Structure: As large organizations in the aerospace sector divest of noncore business and focus on the design and support of products, a large network of third party suppliers has emerged. This network is being increasingly integrated to aerospace companies through extranets such as Exostar and Partsbase, allowing transparency of information. Cross organizational collaboration is also on the increase. Furthermore, smart manufacturing and purchasing systems are being integrated into the design process.

It is clear that these three aspects encompass the entirety of the business. This should emphasize the importance of understanding what these trends will mean for the industry and how companies will tackle these realities that present increasing complexities. To paraphrase Sir Richard Evans's earlier quote; we may understand exactly how to build and operate a component, but how it interacts with countless other components remains a difficult question. This critical issue can not only be applied to products but to entire systems and even organizations that exhibit high levels of interactivity and complexity. Changes to industry emphasizing connectivity and knowledge sharing, encompassing the organization, products and support structure, will require a less clockwork-like reductionist view and a more holist perspective.

II. REDUCTIONISM VERSUS HOLISM

Science and engineering in particular, has developed out of the Newtonian paradigm of mechanics. In this worldview, every phenomenon observed can be reduced to a collection of atoms or particles, whose movement is governed by the deterministic laws of nature – this approach is called reductionism. Through this model, little room is left for the explanation of the spontaneous emergence of self-organization that has been observed in a multitude of systems including life itself. In this conventional view, observed complexity is broken down into simple rules that amass together to produce the initially observed complex behaviors [10].

Whilst this reductionist view is an enormously useful in looking at the intricate relation between simplicity and complexity, it is increasingly argued that this view is incomplete. Jack Cohen and Ian Stewart, authors of "The Collapse of Chaos" argue that the reductionist view is but part of a larger 'mechanism' that results in complexity [10]. They write "we think DNA controls biological development, but we don't know how; we think that appropriately arranged neurons generate consciousness, but we don't understand why." We observe the low level laws of nature but, in some important cases, lack the understanding of how they give rise to the observed behaviors at the top level.

To fill some gaps in the reductionist view, the subject of complexity and emergence must be approached in a very different way, looking for system properties applicable to all such collections of parts, regardless of size or nature.

However, this way of looking at systems is at odds with traditional engineering methodologies, where reductionism is at the forefront of problem solving. This poses a problem when one considers the trends companies will increasingly face with regards to increasing interactivity and complexity [9, 23].

This is not just a problem in the aerospace industry; it is a wider problem. Complexity produces unpredictable results from the interactions of a whole host of actions which, by themselves, seem simple. The 2001 UK fuel crisis can be cited as a simple example, where a protest outside a few oil refineries almost shut down the whole country with astonishing swiftness. The same is true for computer viruses, diseases affecting the food supply chain, failing transportation networks etc [29].

This emphasizes that as society and technology becomes increasingly interconnected and reliant on distant resources, the problems of complexity will increasingly come to the fore. Ironically, the only time it is appreciated how complex a system is, is when it fails. Because of this, it is the engineers, and to some extent management, that will be first having to deal with complexity head-on in real life situations.

It is necessary to say at this point though, that reductionism will be not replaced by the holist way of thinking. It is simply that certain situations merit a holist perspective, and that these situations will occur with increasing frequency. Intrinsic to the holist view, is the concept of emergence, where beneficial or indeed detrimental behavior emerges from local interactions.

III. EMERGENCE

An organization, 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 behavior. This emergent behavior is typically unintended and often detrimental. This includes flocking behaviors such as crowd surging, the spontaneous collapse of distributed networks and increased market volatility [29]. Examples of detrimental emergence in industry include well documented telecommunications outages. Router software upgrades, having passed scaled-down test-bed examinations, malfunction in real life causing large scale outages. Router timing errors only emerged during fully operational order of magnitude interactions – something test-bed examination could not pick up [26, 32]. Emergence is also a documented problem in increasingly utilized distributed control architectures. Van Parunak examines this in control plants and offers ways to detect emergence. Interestingly, predominantly homogenous systems tend to have a higher degree of resonance, leading to detrimental emergent behavior such as bottlenecks and biased workloads. Structural modification is one of the proposed solutions, an aspect our research is exploring, which is discussed in later sections [36].

Not all emergent behavior is unfavorable: positive emergence can be found in ant path planning, bird flocking and the Internet [10, 22]. An organization with positive emergence is usually described as "a whole greater than the sum of its parts" [4, 21, 37]. Organizations that are closely linked to their environment and display adaptability and robustness to change are known as Self-Organizing Systems (SOS) [4, 10, 43]. Examples of positive emergence used in industry include ant-foraging inspired routing of telephone calls [3, 5] and adaptive insect behavior based truck painting [30, 31].

One can argue that self-organization is a specific and 'good' emergent behavior in that it increases the fitness of the system in solving 'the problem', whatever it may be.

A more quantitative definition defines self organized behavior as one where the dynamical systems attractor of the behavior of n agents has an intermediate value. That is, an attractor dimension of between '1', where all agents acting in lock step, and a number related to n, indicating totally dissociated behavior [42].

Emergence is also associated with the capability of this self organization to change drastically, in response to a change in environment (e.g., the ability of a school of fish to dissociate themselves as a predator passes through, and then quickly reform into a self-organized state).

We define the terms emergence and self-organization as follows: Emergence is usually a negative phenomena found in complex systems, which can also be positively exploited to varying degrees. The full, or ultimate, positive exploitation of emergence is self-organization; a system aligns itself to a problem and is self-sustaining, even when the environment changes. Thus, the term 'self-organization' refers to a specific form of emergence.

Regarding "self-sustaining" systems, Maturana and Varela coined the term *autopoiesis* to characterize those systems which (a) maintain their defining organization throughout a history of environmental perturbation and structural change and (b) regenerate their components in the course of their operation [28]. Note that the first condition is a general property of a SOS, whereas the second is one that is a more specific subset meriting a specific label – autopoiesis; SOS maintain their organization, but do not necessarily regenerate their own components [41].

Emergent behavior is often observed in Multi Agent Systems (MAS) defined here as: "a collection of autonomous, social actors where, through local interaction and social communication, emergent global behavior occurs." From an organizational perspective, organizations can be described in terms of formal structure, policies and procedures and behavior of actors (people or agents). These aspects can also be ascribed to MAS, so it should also be possible for organizations to be described and developed around MAS [39]. These points should make MAS an appropriate tool in the understanding of complexity and emergence in organizations [42].

IV. MULTI AGENT SYSTEMS AND COMPLEX ORGANIZATIONS

Unfortunately the MAS field, while advancing research in the architecture for individual agents and agent communications has, according to Gasser and later backed by Odell and Van Parunak, placed the exploration of agent society and organization as a peripheral theme, "primarily a specific coordination technique – not really one of the central intellectual issues of the field" [18, 33]. However, by emphasizing the plurality of agents and the organizational structure that binds them, the focus is shifted from designing ((***intelligent agent***) *systems*) to (*intelligent* (***agent systems***)). This may initially seem to be counterintuitive, but as agents get smarter, their functionality in fact reduces [35]. The previous citations of beneficial emergence based systems in industry exemplify this.

We also have a limited principled methodology of how to organize complex, interdependent, heterogeneous, semi-autonomous agents – and the infrastructure to support them – into aggregates with predictable, reliable, and stable behavior at a very large scale [18]. According to Gasser and quoted at the start of Odell's journal article [18, 33], "We simply have hardly any real experience building truly heterogeneous, realistically coordinated multiagent systems that work together, and… almost no basis for systematic reflection and analysis of that experience".

We also lack a solid understanding of which types of organizational structures are appropriate to which organization. Generalizations, however, can be made; a centralized organization favors complex but static problems, whereas a decentralized system will work well for a dynamic problem when the costs of reconfiguration are low [2].

The increasing trends for complexity in the aerospace industry (and others) and the lack of explicit MAS research into organizations outside of coordination techniques is the basis for the following research questions:

1: An organization's behavior/performance primarily is a function of its environment, the composition of the individual agents and therefore the way they interact; how agents are connected determines the organizational structure [6, 16, 27]. How do we measure and relate the relationships between structure and performance?

2: Given (1) can we gain insight about organizational emergence and which organizational attributes are more suited to which performance requirement, how and why?

3: Given (1) and (2) are there any generalizations that can be made in the development of useful guidelines. Examples would include how to describe the cost/benefit trade off as a function of an organization's structure.

Of course, surrounding these three questions is the business case that needs to be made. From a business perspective, what will really drive the uptake and advancement of agent systems in industry, in our opinion, is that of necessity due to technical limitations (such as scalability, robustness, coping with decentralization, providing flexibility) posed by using traditional centralized and clockwork-type linear systems [38]. This is particularly the case in large industries and certain large infrastructures such as telecommunications networks. This suggestion can be backed up qualitatively by looking at industry sectors which place significant effort in researching and exploiting potential agent technology. No surprises that aerospace and telecommunications sectors feature heavily, as do small research firms looking to offer unique expertise to these industries. In many cases it is not to make things better or simpler, but to cross an invisible barrier placed by traditional methodologies and practices.

In order to explore the research questions raised above, we have developed a set of generic structural metrics and simulation specific performance metrics.

V. RELATING ORGANIZATIONAL STRUCTURE TO PERFORMANCE

Relating an organization's relationship with its environment, agents and structure with its position on the hierarchical complexity line is a possibility [7]. 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 [16].

If we measure an organization's structure, its entropy would show how much control there is in the system. This has been shown in flocking simulations, where the entropy is measured for flocks that exhibit crystalline behavior and compared to flocks that move in a more chaotic fashion [42]. While relating an organization's structure with its entropy is useful, it is even more useful from a design perspective to relate an organization's structure to performance. The problem is that performance metrics are less generic. While some performance measures may be relevant to many organizations (robustness, efficiency); others will be more specific (bureaucracy, response time). However, looking at predominantly generic performance metrics such as robustness, efficiency and optimality, we would expect that, regardless of application domain, similar organizations will behave in similar ways. It is for this reason that many researchers have looked to biological organizations for inspiration when engineering man-made systems [19, 31, 35].

An organization can be defined by two axes, namely horizontal and vertical specialization. Horizontal specialization refers to the operational aspect of the organization. A set of jack-of-all-trades agents will be homogeneous, whereas a set of simple highly specialized agents will be heterogeneous. We define capabilities through sets of capability. So an agent, j, will have one or more capabilities, i, defined as c_{ij} where $j \in \mathbb{N} \wedge j \leq N_a$, $i \in \mathbb{N} \wedge i \leq N_c$ and N_a and N_c are the total number of agents and capabilities in the organization respectively. c_{ij} describes the extent or quality of capability i; if no capability is present, c_{ij} is zero.

Vertical specialization refers to the management and coordination aspect of the organization. The centrality of communication and degree of hierarchy metrics determine the degree of vertical specialization [33].

A. Structural Metrics

To quantify these metrics in an organization, we need to measure the relationship between agents. Much work has been carried out in the MAS and Distributed Artificial Intelligence (DAI) community to formalize individual utterances [11]. These 'conversations' are retrospectively examined using methods developed for Social Network and Dooley Graphs, where nodes represent identities of particular agents as well as the state of information transferred [34]. We can chart the conversations between agents and the type of information conveyed. The graphs can be described in matrix form, which lends itself to further analysis of organizational structure. The interaction matrix, **M**, stores the time independent relationships between agents and their capabilities shown in (1). If agent x with capability $c_{a,x}$ has an interaction with agent y that requires a receptive capability or invokes a further capability $c_{b,y}$, the $c_{a,x}$, $c_{b,y}$ (*from*, *to*) value in **M** is incremented by '1'. Note that an agent can have an internal conversation between its capabilities. This allows a further layer of analysis, where internal agent structure can be explored.

$$\mathbf{M} = \begin{pmatrix} \begin{pmatrix} c_{1,1}, c_{1,1} & \cdots & c_{1,1}, c_{N_c,1} \\ \vdots & \ddots & \vdots \\ c_{N_c,1}, c_{1,1} & \cdots & c_{N_c,1}, c_{N_c,1} \end{pmatrix} & \cdots & \begin{pmatrix} c_{1,1}, c_{1,N_a} & \cdots & c_{1,1}, c_{N_c,N_a} \\ \vdots & \ddots & \vdots \\ c_{N_c,1}, c_{1,N_a} & \cdots & c_{N_c,1}, c_{N_c,N_a} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} c_{1,N_a}, c_{1,1} & \cdots & c_{1,N_a}, c_{N_c,1} \\ \vdots & \ddots & \vdots \\ c_{N_c,N_a}, c_{1,1} & \cdots & c_{N_c,N_a}, c_{N_c,1} \end{pmatrix} & \cdots & \begin{pmatrix} c_{1,N_a}, c_{1,N_a} & \cdots & c_{1,N_a}, c_{N_c,N_a} \\ \vdots & \ddots & \vdots \\ c_{N_c,N_a}, c_{1,N_a} & \cdots & c_{N_c,N_a}, c_{N_c,N_a} \end{pmatrix} \end{pmatrix} \quad (1)$$

Using this organizational structure matrix, we can quantify the type of structure based on a set of metrics. Generic structural metrics used include:

Centrality of communication: 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. We use this as a measure of the degree of centralisation. The degree of a point is defined by the number of arrows efferent or afferent to that point in a network graph [14, 40]. Conceptually, the degree of a point is the size of its neighbourhood and 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 which implies that nodes can only have single links between neighbouring nodes. Degree centrality scores can range from '0' to '1', with '0' relating to a completely decentralised network. However, this definition of the centralisation metric cannot cope with multiple connections.

The following relationship has been adapted from the concept of degree centrality to cope with multiple links. Rather than give the centrality of the entire organisation, it measures the centrality of communication; whilst the original method described above takes unconnected nodes into account, this method ignores them and instead weighs communication bias in a network. The centrality of communication, C_C, is given by:

$$C_C = \frac{1}{n} \sum_{j=1}^{N_a} \left(1 - \frac{\sum_{i=1}^{N_c} c_{ij}}{\max\left(\sum_{j=1}^{N_a} \sum_{i=1}^{N_c} c_{ij} \right)} \right) \text{ where } \sum_{i=1}^{N_c} c_{ij} > 0 \quad (2)$$

The denominator of the bracketed term refers to the largest number of connections afferent and efferent from an agent in the organization. n refers to the global number of connections between agents, and is incremented by 1 when

$\sum_{j=1}^{N_c} c_{ij} > 0$ for $\forall i$. This is regardless of the number of links between individual agents.

Degree hierarchy: Krackhardt [25] developed a measure of degree of hierarchy that indicates the extent to which relations among the nodes in a network are ordered and where there is little, if any, reciprocity. A measure of '1' indicates a fully hierarchical network. '0' indicates a flat organizational structure. Further details including equations and use for this and following metrics can be found in [17].

Specialization: The degree of specialization can be measured per skill type. For each particular skill type, we can measure the volatility of distribution in agents over the entire organization. A measure of '1' indicates a fully specialized skill, meaning only one agent has a particular skill. '0' indicates that all agents have said skill, and in equal amounts and/or quality (if applicable).

Heterogeneity of capabilities: The heterogeneity of capabilities measures how capabilities are distributed throughout an organization. '0' indicates that the sum of each capability throughout the group is equal. The greater the difference, the more this measure will tend towards '1'.

B. Performance Metrics

In order to explore the relationship between structure and performance, we developed a simulation test bed. The Java based Organizational Metrics Concept Demonstrator (OMCD) simulation is based on a two-dimensional grid which has no boundary conditions and where the agents have a simple "find and remove" objective. The agents move around the grid using a random walk searching for one or more 'targets'. When a target appears within an agent's search range, the agent communicates that a potential target has been found by placing a communication 'signal' around the target. The signal is strongest at the source, and tails off to zero at the edges. Agents that can remove targets and are inside the signal's region will travel up the signal gradient to the source. The communication is recorded in a relationship matrix outlined earlier. In the simulation an agent, *j*, will have one or more capabilities where $i = \{\text{search, remove, communicate}\}$. Validation of the model and further details about the simulation including capability resource allocation and weightings are covered in [15]. Two performance metrics are examined:

Normalized time taken: The termination condition of the simulation is defined as the removal of all targets in the environment. The time taken, τ, to remove all the targets is the average time taken from a set of simulations, or epochs ε, based on a single scenario configuration, but with random start positions.

Robustness to failure: Resistance and adaptability to failure (or changes to environmental factors) ought to be a major design consideration in large organizations. In our current approach we explore a single point failure of the most influential agent [17].

VI. DATA VISUALIZATION AND ANALYSIS

To explore the relationship between structure and performance of predominantly heterogeneous organizations, we examine a single premise in detail; namely, the materiel cost of the organization is kept constant with three agents and 37 unit^2 of capabilities (chosen for the best capability distribution for 3 agents) that are distributed in every possible combination to the three agents. Environmental conditions are kept constant; the unbounded environment size is 100 unit^2 and the number of targets is three. In all, over 6,000 scenarios were run. The high-dimensional measurement space that results from the use of numerous metrics thus requires the application of powerful data visualization tools. One such tool is the Self-Organizing Map (SOM), which permits an ordered two-dimensional representation of much higher dimensional input spaces [24]. In essence, a SOM employs unsupervised clustering techniques that can reveal meaningful groupings of parameters that may form distinct classes of organizations. Using the SOMine software package, a SOM trained output map for the data generated from this scenario is shown in Fig. 1

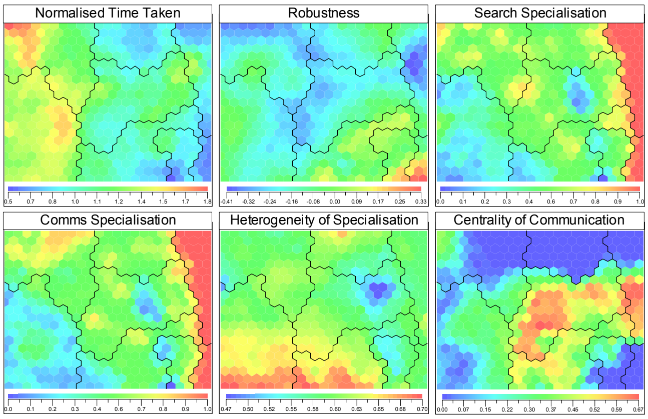

Fig. 1 SOM showing the two performance objectives (Time taken, and Robustness) and structural configurations that describe the organizations. Clusters are marked using boundaries.

Here we see how completely different organizational structures are suited to subtly different performance requirements. A small cluster exists where uncoordinated search heavy agents perform efficiently and are not too prone to failure. This is followed by a region where agents are far more specialized and rely a lot more on communication and coordination to be both efficient and robust. Although not as efficient as the search heavy organizational type, this organizational arrangement takes up a much larger area of the search space. For less trivial organizational scenarios, organizational types with this trait would be considered less than the theoretical ideal, but easier to locate and maintain.

VII. CONCLUSIONS AND FUTURE WORK

Our principal aims are to attain a better understanding of emergent global behavior in organizations and consequently, improve their design, and the design process itself. These aims are addressed through the use of MAS simulations of organizations. Our research program will be to extend the simulation and analysis framework so that corresponding organizational models can be incorporated into a feedback learning system with advanced cost-functions (incorporating procurement costs as well as operational ones) to find and maintain organizations at a required performance setting.

VIII. ACKNOWLEDGMENTS

This work is supported by an EPSRC studentship and BAE SYSTEMS, for an Engineering Doctorate (EngD) based at UMIST.

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